Error Analysis: How Precise is Fused Deposition Modeling in Fabrication of Bone Models in Comparison to the Parent Bones?

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Abstract

Background: Rapid prototyping (RP) is used widely in dental and faciomaxillary surgery with anecdotal uses in orthopedics. The purview of RP in orthopedics is vast. However, there is no error analysis reported in the literature on bone models generated using office-based RP. This study evaluates the accuracy of fused deposition modeling (FDM) using standard tessellation language (STL) files and errors generated during the fabrication of bone models. **Materials and Methods:** Nine dry bones were selected and were computed tomography (CT) scanned. STL files were procured from the CT scans and three-dimensional (3D) models of the bones were printed using our in-house FDM based 3D printer using Acrylonitrile Butadiene Styrene (ABS) filament. Measurements were made on the bone and 3D models according to data collection procedures for forensic skeletal material. Statistical analysis was performed to establish interobserver co-relation for measurements on dry bones and the 3D bone models. Statistical analysis was performed using SPSS version 13.0 software to analyze the collected data. **Results:** The inter-observer reliability was established using intra-class coefficient for both the dry bones and the 3D models. The mean of absolute difference is 0.4 that is very minimal. The 3D models are comparable to the dry bones. **Conclusions:** STL file dependent FDM using ABS material produces near-anatomical 3D models. The high 3D accuracy hold a promise in the clinical scenario for preoperative planning, mock surgery, and choice of implants and prostheses, especially in complicated acetabular trauma and complex hip surgeries.

Keywords: *Analysis, bone, computed tomography, error, model, printing, three-dimensional*
MeSH terms: *CAT scanners, x-ray, autograft, imaging, three-dimensional*

Introduction

Rapid prototyping (RP) is a manufacturing technology used in many industries to develop high fidelity three-dimensional (3D) structures from source image data. The RP technology has progressively developed over the years and is becoming increasingly important with widespread uses in the biomedical field.[1-10] The first reported use in orthopedic surgery was in 1979 when a polystyrene model of a pelvis was constructed to customize a metal implant for a patient with fibrosarcoma.[11] The majority of the reported literature on RP focuses on its uses in maxillofacial surgery.[12,13] However innovative uses in orthopedic surgery, especially in preoperative planning in spine surgery, deformity correction, and hip replacements have been reported.[14-18] Patient-specific instrumentation using RP techniques for total knee replacement was introduced by Biomet Orthopedics (Warsaw, Indiana, USA) with the signature knee system in collaboration with Materialize (Leuven, Belgium).[19,20] Other orthopedic applications apart from preoperative planning include teaching and patient counseling.[21,22] Recent advances in fused deposition modeling (FDM), a RP technique has made it a viable technology for application in orthopedic surgery. Use of FDM in the fabrication of skull and mandible with a high level of accuracy has been documented.[23]

To the best of our knowledge, no literature exists on an error analysis of the bone models generated by FDM in the orthopedic scenario. This study evaluates the accuracy of FDM using STL files and errors generated during the fabrication of bone models of nine different types of bones procured from anatomy department.

Materials and Methods

Model fabrication

A total of 38 measurements were made on nine different dry bones (7 femur,

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5 tibia, 3 talus, 2 calcaneum, 3 first metatarsal, 3 clavicle, 5 humerus, 5 radius, and 5 ulna) were procured from the anatomy department. All the bone models were computed tomography (CT) scanned with 0.625 mm thick slices using Siemens somatom perspective 64 slice CT scan system. From CT scan Digital Imaging and Communication in Medicine files were imported and 3D representation of the bone models was generated using InVesalius, version 3.0.0. beta 5 software [Centre for Information Technology Renato Archer, Campinas, SP, Brazil]. The data were then converted to STL (standard tessellation language) file format. The STL files were cleaned using mesh laboratory – advanced 3D mesh processing software, version 1.1.0[Meshlab, ISTI-CNR] and individual STL files of all nine scanned bones were made. From STL files 3D models were printed using Flash forge dreamer 3D printer (Flashforge dreamer dual extruder) with 1.75 mm Acrylonitrile Butadiene Styrene (ABS) plastic filament. Slic3r slice engine was used with standard resolution (layer height 0.2 mm, shells 3, infill 20%, print speed 60 mm/s, travel speed 80 mm/s, extruder temperature 230°, platform temperature 110°) [Figure 1].

Dimensional analysis

Definition of landmarks for measurement of individual bones was based on the "data collection procedures for forensic skeletal material" by Moore-Jansen *et al*.[24] Linear measurements were made using an osteometric board, and other measurements were made using a digital Vernier caliper (Mitutoyo Digimatic 150 mm/6 inch model: 500-196-30) [Figure 2]. Two observers (senior authors MVR and KKE) made the measurements on two different occasions on the bone and 3D model. The observers are practicing orthopedic surgeons with at least 15 years of experience in Orthopaedic surgery. Statistical analysis was performed to establish interobserver reliability for measurements on dry bones and the 3D bone models. Statistical analysis was done using SPSS version 13.0 [SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606-6412] software to analyze the collected data.

Results

Intraclass correlation coefficient (ICC) was calculated independently for the dry bones [Table 1] and the 3D printed models [Table 2] to assess the reliability of the observers. A high degree of reliability was found between the dry bone measurements and the 3D bone measurements between the two observers. The average measure ICC was 1 with a $P < 0.001$. Table 3 summarizes the variation between the 3D model and dry bone model for each of the bones. The mean of the absolute difference is 0.4 which is very minimal. Mann–Whitney U-test was performed to see the differences between the values of the two observers as the data are not continuously distributed. The "*P*" value (0.629) was more than 0.05 stating that there is no significant difference between the observations between the two raters. Box plot shows the difference between the dry and 3D modeling of first and second observer [Figure 3]. Compound bar diagram showing the difference between dry and 3D modeling of first and second observer according to the type of bone [Figure 4].

Discussion

A minimal difference between the measurements on dry bones and 3D bone models with significant interobserver reliability for either of the measurements signifies that RP in an office setup is a magnificent tool and provides near-anatomical specimens of the area of anatomical interest. Tibia (0.6340) and talus (0.5933) showed more variation in the absolute difference, whereas radius (0.1620) and ulna (0.1830) showed minimal variation. However, it

Figure 1: Near-anatomical three-dimensional printed bone models in comparison with the dry bones obtained from the anatomical department. (a) Femur. (b) Tibia. (c) Humerus. (d) Radius. (e) Ulna. (f) Calcaneum. (g) First metatarsal. (h) Clavicle. (i) Talus

Table 1: Intraclass correlation coefficient: Dry bone

Dry bone measurements	Intraclass correlation[b]	95% CI		*F*-test with true value 0			
		Lower bound	Upper bound	Value	df1	df2	Significant
Single measures	1.000[a]	1.000	1.000	651,585.430	37	37	0.000
Average measures	1.000[c]	1.000	1.000	651,585.430	37	37	0.000

Two-way mixed effects model where people effects are random and measures effects are fixed. [a]The estimator is the same, whether the interaction effect is present or not, [b]Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance, [c]This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise. A high degree of reliability was found between the dry bone measurements between the two observers. The average measure ICC was 1 with a *P*<0.001. CI=Confidence interval, ICC=Intraclass co-relation coefficient

Table 2: Intraclass correlation coefficient: Three-dimensional model

3D model measurements	Intraclass correlation[b]	95% CI		*F*-test with true value 0			
		Lower bound	Upper bound	Value	df1	df2	Significant
Single measures	1.000[a]	1.000	1.000	644,259.747	37	37	0.000
Average measures	1.000[c]	1.000	1.000	644,259.747	37	37	0.000

Two-way mixed effects model where people effects are random and measures effects are fixed. [a]The estimator is the same, whether the interaction effect is present or not, [b]Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance, [c]This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise. A high degree of reliability was found between the 3D bone measurements between the two observers. The average measure ICC was 1 with a *P*<0.001. CI=Confidence interval, ICC=Intraclass co-relation coefficient, 3D=Three-dimensional

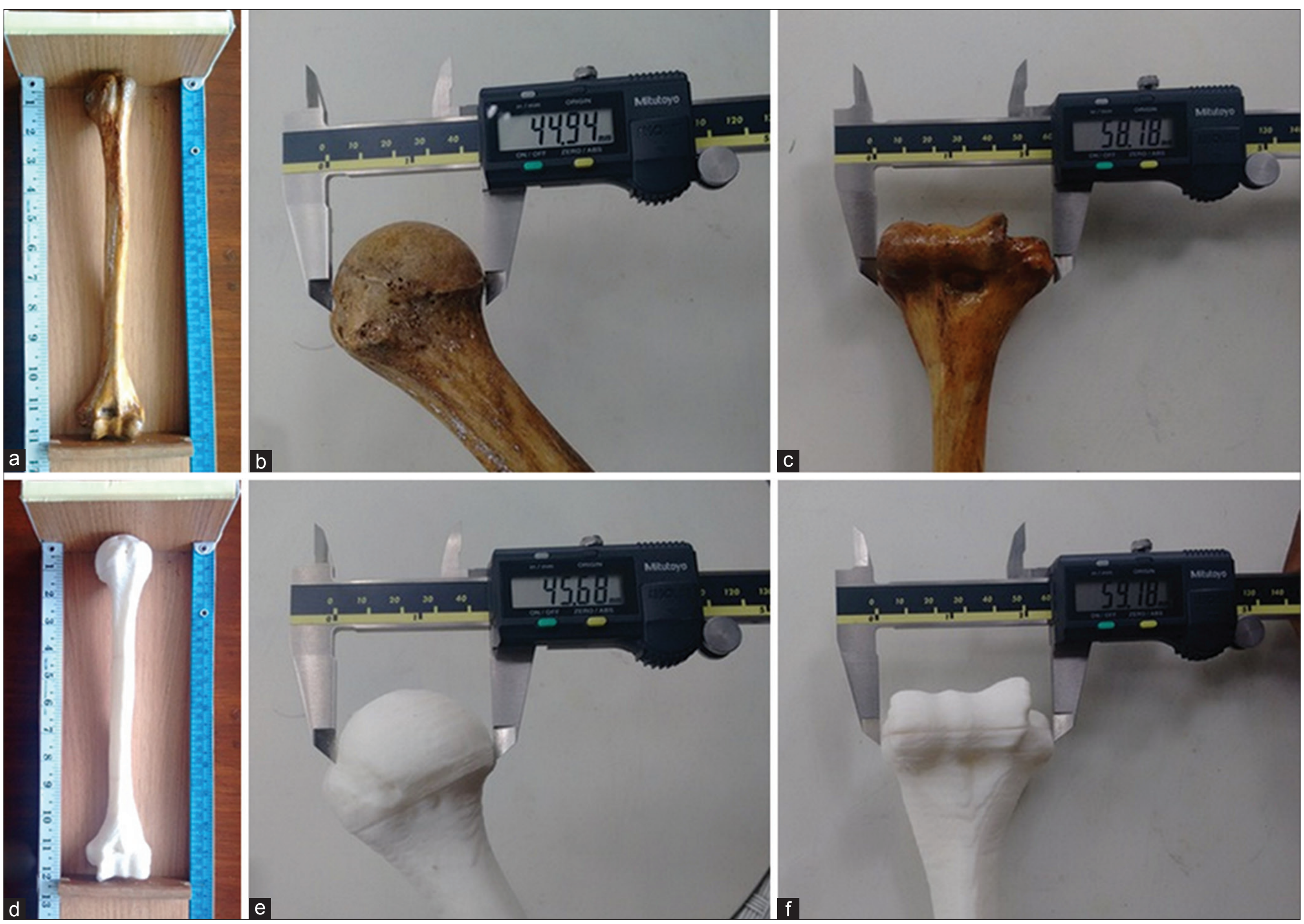

Figure 2: The comparative measurements of the humerus. (a and d) The measurement of length of the dry bone and the 3D model using the osteometric board. (b and e) The comparable values of the humeral head measurement using digital caliper for dry bone and the 3D model. (c and f) showing the comparable inter-epicondylar distance of the humerus for the dry bone and 3D model. 3D=Three-dimensional

Table 3: Depicting the median, minimum and maximum along with mean and standard deviation of the individual bones

Type of bone	*n* valid	Median	Minimum	Maximum	Mean	SD
Femur						
Dry bone mean	7	29.80	22.64	425.00	92.28	147.76
3D model mean	7	30.19	23.14	426.00	92.77	147.97
Absolute difference	7	0.39	0.27	1.00	0.50	0.27
Tibia						
Dry bone mean	5	45.17	32.18	386.00	113.93	152.86
3D model mean	5	45.61	33.01	387.00	114.56	153.06
Absolute difference	5	0.65	0.25	1.00	0.63	0.30
Humerus						
Dry bone mean	5	44.90	17.09	307.00	89.63	122.73
3D model mean	5	45.41	17.52	307.00	90.08	122.48
Absolute difference	5	0.50	0	0.80	0.45	0.29
Radius						
Dry bone mean	5	19.75	12.98	259.00	67.57	107.21
3D model mean	5	19.76	13.36	259.00	67.73	107.11
Absolute difference	5	0.19	0	0.38	0.16	0.16
Ulna						
Dry bone mean	5	16.67	11.22	265.00	109.81	132.30
3D model mean	5	17.03	11.51	265.00	110.00	132.14
Absolute difference	5	0.27	0	0.35	0.18	0.17
Clavicle						
Dry bone mean	3	12.44	8.62	140.00	53.69	74.77
3D model mean	3	12.77	8.94	141.00	54.24	75.16
Absolute difference	3	0.33	0.32	1.00	0.55	0.39
Calcaneum						
Dry bone mean	2	59.25	44.44	74.07	59.25	20.95
3D model mean	2	59.51	44.87	74.14	59.51	20.70
Absolute difference	2	0.25	0.07	0.43	0.25	0.25
Talus						
Dry bone mean	3	40.22	22.34	48.20	36.92	13.24
3D model mean	3	40.96	23.12	48.46	37.51	13.02
Absolute difference	3	0.74	0.26	0.78	0.59	0.29
First metatarsal						
Dry bone mean	3	29.14	19.32	65.54	38.00	24.35
3D model mean	3	29.62	19.67	65.76	38.35	24.25
Absolute difference	3	0.35	0.22	0.48	0.35	0.13

3D=Three-dimensional, SD=Standard deviation

should be noted that the number of measurements in each bone was different. The standard deviation was high as the measurements were different in nature (e.g., the length of a long bone is much higher than the breadth at the distal end).

FDM is comparable to other available RP technologies. Since it fabricates a 3D model using a layer by layer deposition, it does not require the use of machinery and tooling for the fabrication. This also reduces the wastage of the raw material, reduces the time for the generation of the models and is cost effective. The time required for fabrication of the bone models is less as compared to the other technologies, especially when models of greater complexity are required.[25] ABS material apart from having high impact and being heat resistant adheres to dimensional accuracy.[25] Research toward minimizing the errors in RP might improve the accuracy of the generated 3D models.[26,27]

Studies evaluating the error analysis of FDM in the orthopedic scenario are not reported in the literature to the best of our knowledge. Sun *et al*. evaluated the errors in unidirectional mandibular distraction osteogenesis in the treatment of hemifacial microsomia in six patients. However, they analyzed the errors of computer-aided design and manufacture.[28] Nizam *et al*. evaluated the accuracy of models obtained by stereolithography RP technology and found the errors acceptable for planning and application in the clinical scenario.[29] A study by Al-Katatny *et al.* demonstrated an exceptional accuracy using FDM process for the fabrication of anatomical replicas across sizes and

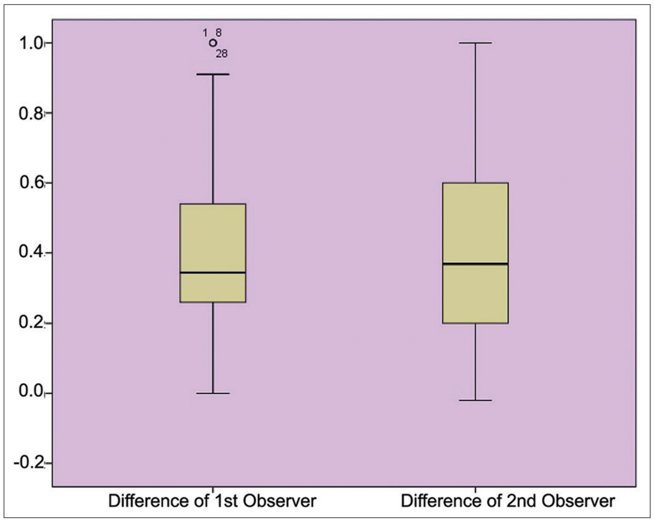

Figure 3: Box plot shows the difference between the dry and three-dimensional modeling of first and second observer

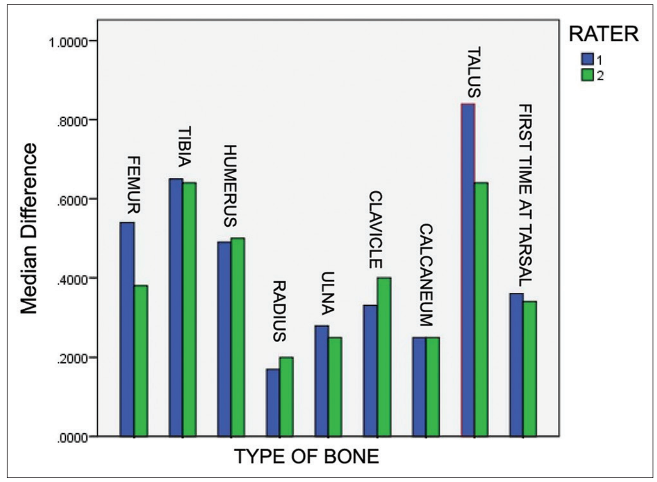

Figure 4: Compound bar diagram showing the difference between dry and three-dimensional modeling of first and second observer according to the type of bone

gender in comparison to other established RP techniques. They used skull and mandible specimens for error analysis.[30] The specimens were undersized and deviated from the original by an average of 0.24% demonstrating precision in measured bone thickness. The difference in the mean average deviation in comparison to our study might be attributed to the diversity of the bones used in our study. Dhakshyani *et al*. studied FDM models in surgeries for dysplastic hips and concluded that these models improved planning, decreased surgical time and improved surgeons confidence and aided rehabilitation protocol.[31]

The following were the limitations of our study. The sample size was limited and only selected bones representative of the skeleton were used. We did not compare FDM with other available RP technologies. We used ABS for FDM, and it was not compared with other materials. The number of measurements in each type of bone differed and could have altered the mean difference when each type of bone was considered separately. The nature of measurement (e.g., length vs. distal breadth of a long bone) leads to high standard deviation. In error analysis, the following aspects are usually evaluated-accuracy, precision, systematic errors, and random errors. Systematic errors were minimized as a digital caliper was used, and the observers independently measured the bones to minimize bias. The accuracy and precision were maximized by the experienced observers and the appropriate statistical analysis. The random errors could be minimized by increasing the sample size, but only representative bones were used in our study.

Despite the limitations, a mean average deviation of 0.4% is negligible and should not be a hindrance to the use of FDM in the clinical scenario. STL file dependent FDM using ABS material produces near-anatomical 3D models with a good co-relation between the bones and models procured by 3D modeling. Fabrication of these models, especially in the office set up is economical, time-saving, and convenient. The high 3D accuracy hold a promise in the clinical scenario for preoperative planning, mock surgery and choice of implants and prostheses, especially in complicated acetabular trauma and complex hip surgeries in orthopedics. These may be of value in training of surgeons in orthopedic surgery and patient education. Bone models may be fabricated easily in the event of a shortage of dry bones for educational purposes in the event of shortage of cadavers.

Conclusion

STL file dependent FDM using ABS material produces near-anatomical 3D models. The high 3D accuracy hold a promise in the clinical scenario for preoperative planning, mock surgery, and choice of implants and prostheses, especially in complicated acetabular trauma and complex hip surgeries.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form the patient(s) has/have given his/her/their consent for his/her/their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Conflicts of interest

There are no conflicts of interest.

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