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COMPARISONS OF FIDELITY IN THE DIGITIZATION AND 3D PRINTING OF VERTEBRATE FOSSILS

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ABSTRACT

3D surface digitization and 3D printing have increased in vertebrate paleontological research, teaching, and outreach as resolution increases and startup costs decrease. While the lowered cost and increased options for entry-level commercial printing and digitization units have led to their implementation in many research laboratories and classrooms, the question of fidelity and accuracy for their use as research and teaching aides has not been fully investigated. This study explores the quality of digitization and resolution of 3D printed specimens in quantitative terms to determine whether entry-level digitization and 3D printing units are feasible for the needs of most vertebrate paleontologists and educators. In order to test the fidelity of these techniques, resin casts of a *Tyrannosaurus rex* tooth and crocodilian osteoderm were digitized using two different techniques: white-light structured scanning and laser-texture scanning. Each resulting stereolithographic digital model was compared and statistically tested ($p < 0.05$) for significant differences in morphology based on point cloud volume and average triangle surfaces. Furthermore, the resulting digital models were printed on two commercial-grade fused deposition modeling printers. The resulting printed models were also compared and statistically tested ($p < 0.05$) for significant differences in shape and morphology. The results of this study suggest that while differences in digitization methods and 3D printed models do exist, they are virtually indistinguishable. However, observed differences were exacerbated by morphological variations of the original object; flat-shaped to tabular objects showed the greatest variability among digitization techniques. As such, even low-cost digitization and 3D printing systems are suitable for many paleontological research initiatives as well as the reproduction of high-quality teaching specimens.

Keywords: 3D printing, digitization, paleontology

RESUMO [in Portuguese]

A digitalização 3D de superfície e a impressão 3D aumentaram na investigação de paleontologia de vertebrados, no ensino e na divulgação, à medida que a resolução aumenta e os custos iniciais diminuem. Embora o custo reduzido e o aumento das opções de impressão comercial e unidades de digitalização tenham levado à sua implementação em muitos laboratórios de investigação e salas de aula, a questão da fidelidade e precisão para o seu uso como auxiliares de pesquisa e ensino ainda não foi totalmente investigada. Este estudo explora a qualidade da digitalização e resolução em espécimes impressos em 3D em termos quantitativos para determinar se a digitalização de nível básico e as unidades de impressão 3D são viáveis para as necessidades da maioria dos paleontólogos e educadores de vertebrados. Para testar a fidelidade destas técnicas, os moldes de resina de um *Tyrannosaurus rex* tooth e osteoderme de um crocodiliano foram digitalizados usando duas técnicas diferentes: *scanning* estruturado em luz branca e *scanning* por textura a laser. Cada modelo digital estereolitográfico resultante foi comparado e testado estatisticamente ($p <0,05$) para diferenças significativas na morfologia com base no volume de nuvens de pontos e superfícies triangulares médias. Além disso, os modelos digitais resultantes foram impressos em duas impressoras 3D comerciais de modelagem de depósito por fusão. Os modelos impressos resultantes também foram comparados e testados estatisticamente ($p <0,05$) quanto a diferenças significativas na forma e morfologia. Os resultados deste estudo sugerem que, embora existam diferenças nos métodos de digitalização e nos modelos impressos em 3D, eles são virtualmente indistinguíveis. No entanto, as diferenças observadas foram exacerbadas pelas variações morfológicas do objeto original; objetos de forma plana a tabulares mostraram a maior variabilidade entre as técnicas de digitalização. Como tal, mesmo sistemas de digitalização e impressão 3D de baixo custo são adequados para muitas iniciativas de pesquisa paleontológica, bem como a reprodução de amostras de ensino de alta qualidade.

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INTRODUCTION

Additive manufacturing (AM), including desktop 3D printing, is a relatively new technology that allows for the physical recreation of three-dimensional digital objects. Improvements in AM have reduced the significant overhead costs and complexities associated with the technology and expanded the user base beyond industrial purposes. Today, even non-professional hobbyists and enthusiasts have been able to use AM processes to create three-dimensional (3D) objects with relatively low costs and with little training. This ease of use has also created opportunities for professionals to utilize 3D printing to solve unique problems. In the field of paleontology, 3D digitizing and printing have already been used to provide a means of reconstruction, analyses, as well as unique and engaging forms of outreach and education (e.g. Mallison, 2011; Rahman et al., 2012; Hasiuk, 2014; Lautenschlager and Rücklin, 2014; Lautenschlager, 2016; Benoit et al., 2016; Thomas et al., 2016).

Coupled with affordable, high-quality digitization methods, 3D digitization and replication have strong potential to revolutionize many of the obstacles in paleontology research methods such as digital preservation, widespread dissemination of digitized specimens (Tschopp and Dzemski, 2012), and challenges of working with large and/or fragile specimens (Schilling et al., 2013; Mitsopoulou et al., 2015; Das et al., 2017).

A variety of systems exist for the creation of digital representations of fossils, each with varying degrees of affordability, resolution, ease of use, and speed. Many of these methods are described in detail in Sutton et al. (2014). Surface-based techniques such as photogrammetry and laser-texture scanning have the capacity to create highly detailed digital representations of specimen exteriors without damaging the original material (e.g. Breithaupt and Matthews, 2001; Antcliffe and Brasier, 2008, 2011). Furthermore, in the case of computed tomography (CT) scanning, digital restoration can be completed even if the specimen is still embedded in matrix, or even inside of plaster jackets (e.g. Schilling et al., 2013).

With digital fossil reconstructions, collaboration and sharing of data between researchers can also be achieved electronically. Additionally, in cases where a physical, to-scale replica of the specimen is ideal, creation of a tangible 3D model from the digital file is considerably faster, easier, and potentially far less expensive than requesting a high-quality cast of the original.

Two commonly used techniques for fossil digitization are laser-texture scanning and structured-light scanning. While each technique has variations, smaller consumer-level laser-texture scanners that are commonly utilized in research laboratories and museum collections use a triangulation-based method. In such cases, a red laser is fired at a targeted object and its position on the object is recorded by a camera, triangulating the object's or point’s location in space (Sutton et al., 2014; Figure 1A). Depending upon the desired resolution, settings can be adjusted to modify the speed of the scanning laser, yielding more or fewer captured points per in^2. Projected structured-light scanning utilizes a projected black-and-white pattern beamed onto a targeted object. The displacement of the projected pattern is then captured by a pair of cameras aimed at the object, thus deriving a 3D point in space (Figure 1B). Depending on desired resolution, settings can be adjusted to modify the shutter speed of the cameras, yielding a faster or slower exposure time (milliseconds).

Additionally, 3D printed objects are typically more durable than fragile cast replicas of original fossil specimens (Tschopp et al., 2013). Analyses of anomalies in Egyptian mummies, replication of objects for science outreach and communication, the reconstruction of fossils from damaged field jackets, and investigations of water flow through the structure of a digitally-scaled blastoid are all situations in which 3D printing has provided unique perspectives of problematic or delicate physical specimens (e.g. Rahman et al., 2012; Schilling et al., 2013; Huynh et al., 2015; McKnight et al., 2015).

However, there are two major obstacles to face when adopting 3D printing as a research tool: investment price and printer resolution. For researchers with a limited budget, the initial investment in digitization and 3D printing may present an infeasible hurdle. While improvements and refinements in the technology have significantly reduced the costs associated with 3D printing, the initial investment price may still be out of reach for some researchers or smaller institutions.

A wide variety of 3D printing units exist in the consumer and industrial markets. High-end industrial units, such as selective laser-sintering (SLS) and stereolithographic (SLA) technologies use heat to fuse a thermoplastic powder (SLS) or

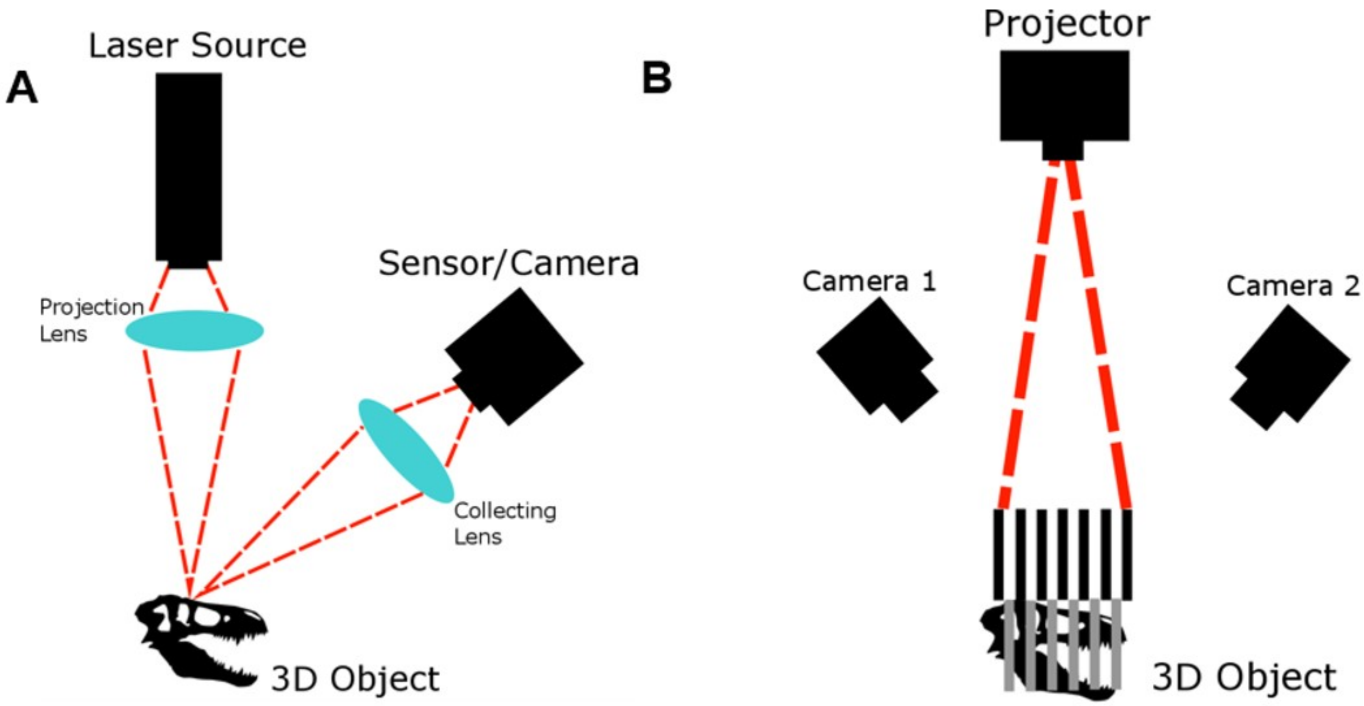

Figure 1: Utilized techniques of digitization. A) Principles of laser-texture scanning, where a laser is projected at an object, and the reflection is collected by a sensor; B) Structured-light scanning, where a light pattern is projected on an object, and a series of cameras triangulate the distance between points on the object.

liquid (SLA) to structure tangible models. These units produce very high-resolution products with build layers as thin as 20 µm and virtually no residual print artifacts. However, such units commonly cost up to tens of thousands of dollars (USD; Gibson et al., 2015). Alternatively, lower-end consumer models commonly use fused deposition modeling (FDM) technologies, where a thermoplastic filament composed of acrylonitrile butadiene styrene (ABS) or polyacetic acid (PLA) is extruded through a heated nozzle to build models of varying layer thicknesses, commonly between 100-400 µm. This frequently results in the production of print artifacts, such as ‘ribbed’ or ‘bumpy’ exteriors that may obfuscate minute features and require post-printing finishing. These units usually cost a fraction of the price of industrial units, making them attractive and accessible to many research laboratories, classrooms, and institutions. However, they typically lack the microscopic resolution of their industrial counterparts (Gibson et al., 2010).

Despite the differences in technologies, abilities, resolution, and costs of digitization and additive manufacturing systems, the level of accuracy needed is strongly dependent upon the research or educational needs of the users. For example, phylogenetic coding may require digitized or printed fossil reproductions of higher resolution than reproductions needed for classroom instruction or museum exhibition.

However, the fidelity maintained from digitization to 3D printing can be measured and compared to assess at which stages data may be lost, resulting in varying degrees of confidence in digital fossil reproductions. This study examines the fidelity of paleontological data created using common digitization techniques and commercial 3D printer systems. Digital models created by both projected structured-light scanning and triangulated laser-texture scanning were compared for deviation between specimens to determine differences in fidelity between both scanning methods. Additionally, these specimens were printed on different low-cost 3D printers and subsequently measured to determine differences in fidelity based on printer model and different printer settings. These measurements determine where and how much data is lost in both the digitization and reproduction processes.

While the necessary level of reproduction detail is dependent on the scope of a study or exhibition needs, the results of these experiments suggest that entry-level and commercial-grade digitization and 3D printing units are useful for many paleontological research and educational outreach needs.

METHODS

For this study, we chose specimens that contain fine-detailed features in order to properly compare and contrast the quality of AM paleontological reproductions to their digital reconstructions. High-resolution resin casts of a shed tooth from *Tyrannosaurus rex* (FMNH PR2081) and a dorsal osteoderm from a Cretaceous crocodilian (FMNH PR3703) were chosen due to their relatively small size and the presence of multiple microscopic (e.g. tooth serrations) and macroscopic (e.g. osteoderms pits) surface features. Both specimens are housed at the Field Museum of Natural History in Chicago, IL.

Two techniques were utilized to digitize each specimen: laser-texture scanning and structured-light scanning (Figure 1A, B). Data were then processed into 3D surface models and finalized as STL (stereolithograph) files, a commonly used file format for many CAD programs.

Digitization Methods

Triangulated Laser-Texture Scanning

Triangulated laser-texture scans were conducted at the Department of Geology at the University of Wisconsin-Oshkosh in Oshkosh, WI (Figure 1A). Scans were made with a NextEngine 3D Laser Scanner, capturing data at seven scanning divisions in high-definition (2.0k points/in^2). Models were built with the NextEngine ScanStudio HD Pro (version 2.02), and exported as STL models.

Projected Structured-Light Scanning

Structured-light scans were conducted at the Field Museum of Natural History in Chicago, IL (Figure 1B). Scans were made with a 3D3 Solutions White Light Scanner, capturing data at twelve divisions in high-definition (exposure time of 1,688 ms), and models were built in FlexScan3D (version 3.1.9.109).

The resulting four STL model files were then imported into Meshmixer (Autodesk, version 10.0.297), in which the ‘Make Solid’ algorithm was utilized to prepare the models for printing by filling ‘gaps’ in the model meshes as well as the removal of artifacts from the scanning process. Digital models were then 3D printed on two different fused deposition modeling (FDM) printing units, resulting in eight printed models of the two objects.

3D Printing Methods

FlashForge Creator Pro Dual Extruder 3D Printer

Four printed models (both specimens digitized with both techniques) were produced on a Flashforge Creator Pro Dual Extruder 3D Printer utilizing FlashPrint (version 3.13.2) from 1.75 mm white Octave acrylonitrile butadiene styrene (ABS) filament. Prints were constructed in 180 µm layers extruded at 220°C on a heated bed at 105°C and a print speed of 60 mm/sec.

UP Mini 3D Printer

Four printed models (both specimens digitized with both techniques) were produced on an UP Mini 3D Printer utilizing UP Studio (version 0.0.10) from 1.75 mm white Octave acrylonitrile butadiene styrene (ABS) filament. Prints were constructed in 200 µm layers extruded at 265°C on a heated bed at 50°C and a print speed of 50 mm/sec.

Comparative Measurements

Printed Models

The four prints of FMNH PR2081 and PR3703 were measured with digital calipers along a series of landmarks and statistically tested for significant differences. Measurements were taken from prints produced from both methods of digitization, as well as their digital sources. FMNH PR2081 (Figure 2A, B) was measured from the tip of the tooth to the base of the crown (Figure 2A, measurement a-a’), the thickness of the middle of the crown height (Figure 2A-B, measurement b), and the thickness of the crown base (Figure 2A, measurement c). Measurements were also taken for the width of the crown at its upper ⅓ (Figure 2B, measurement d), its middle ⅓ (Figure 2B, measurement e), and its base (Figure 2B, measurement f).

Similarly, FMNH PR3703 was measured along the maximum height and length of the osteoderm (Figure 2C, measurements g-g’ and h-h’). Measurements were also taken of the internal diameter of four prominent pits on the surface of the osteoderm (Figure 2C, measurements i, j, k, l), and the thickness of the osteoderm in two locations (Figure 2D, measurements m, n).

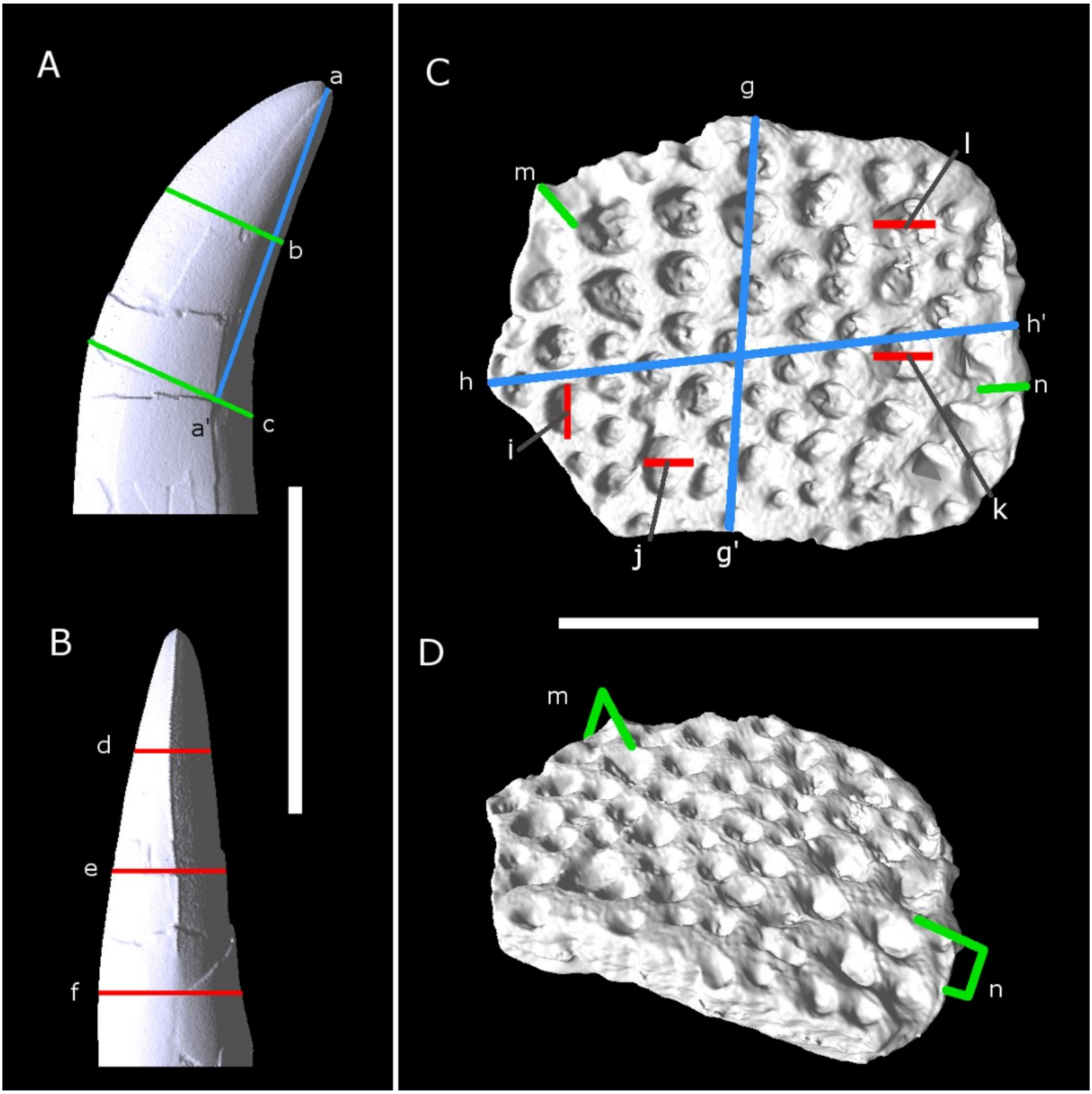

Figure 2: Lateral (A) and anterior (B) views of FMNH PR2081, and dorsal (C) and oblique (D) views of FMNH PR3703. Line a-a' measures the tooth crown height of FMNH PR2081, and lines b and c measure the mesiodistal crown thickness at the midpoint and base, respectively. Lines d, e, and f measure the labiolingual crown thickness at the upper third, middle-third, and base, respectively. Lines g and h measure the length and width of the scute specimen FMNH PR3703, respectively. Lines i, j, k, and l measure the internal diameter of surface pits of FMNH PR3703. Measurements for lines m and n annotate the thickness of the scute in two regions. Scale bars equal 5cm.

Digital Models

Digital 3D models were quantitatively compared by their digitization method in CloudCompare (version 2.7.0) to determine the degree of topographic deviation between each digitization technique. A point-cloud analysis algorithm for statistics computation were used to determine the size deviations between models digitized by the different scanning devices. The point-cloud analysis results were visualized with a scalar field color scale layered on the compared model (Figure 3A-D).

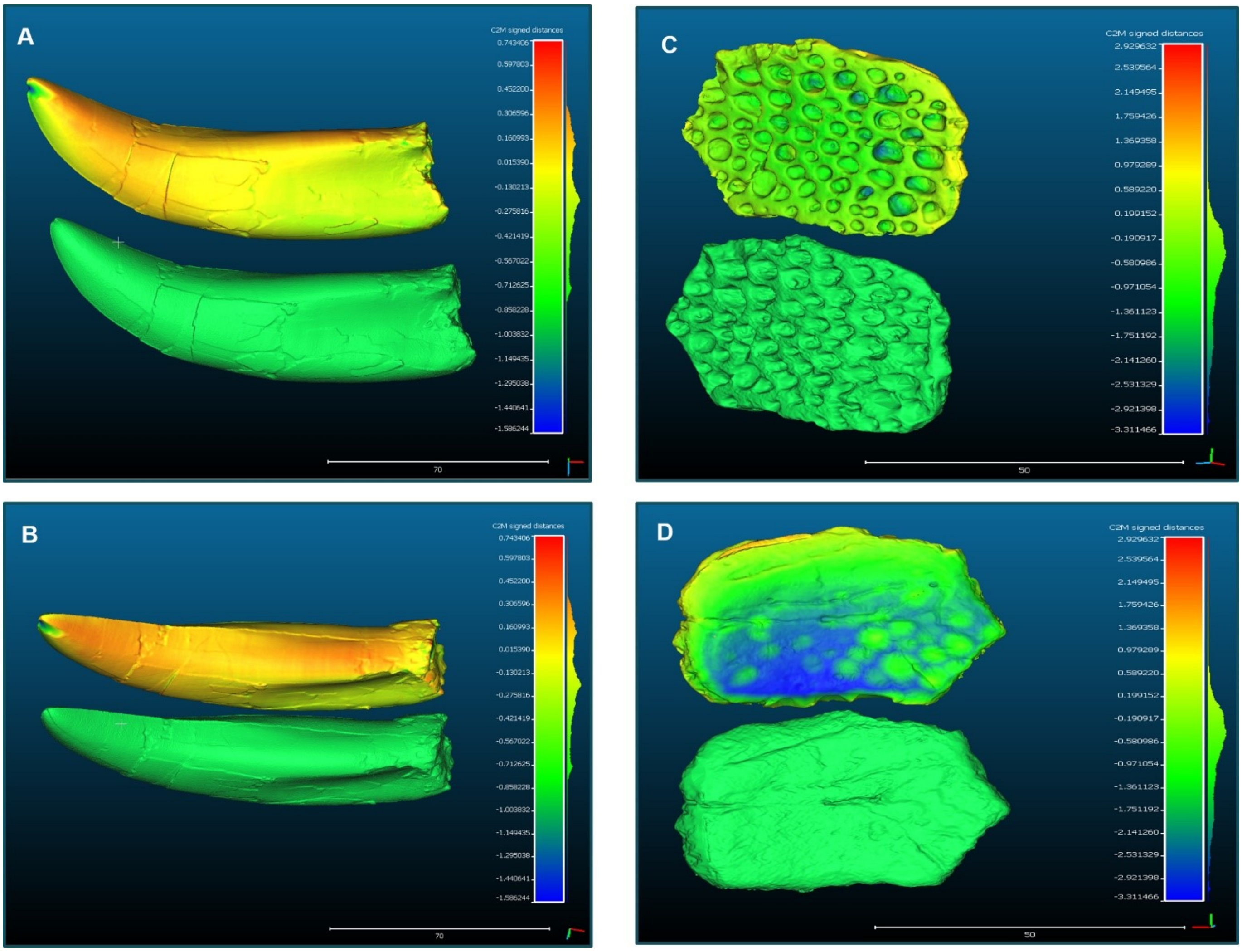

Figure 3: Heat maps depicting the topographic differences in digitized models between structured-light scans (solid green models) and laser-texture scans (gradient-colored models) of FMNH PR2081 in lateral (A) and oblique (B) views, and FMNH PR3703 in dorsal (C) and ventral (D) views. Warm (red) and cool (blue) color gradients indicate variation between models. Note the general even tone of color gradient in comparisons of FMNH PR2081, suggesting few differences between volumes, and the increase of blue coloration on FMNH PR3703, suggesting greater differences.

RESULTS

Upon visual inspection, all digital models appeared as accurate representations of the original specimens and were produced without the use of automatic "hole-filling" tools. Digital models of FMNH PR2081 were found to have volumes of 77,163.2 and 74,857.5 mm^3 between the laser-texture and structured-light scanning techniques, respectively, for a variance of 1.52%. Additionally, the mesh surface areas for these models were found to be 12,473.6 and 12,717.4 mm^2, for a variance of 0.97%.

For digital models of FMNH PR3703, mesh volumes were calculated to be 4,969.66 and 9,808.39 mm^3 between the laser-texture and structured-light scanning techniques, respectively, for a variance of 32.74%. The mesh surface area of these two models were found to be 5,056.68 and 4,970.17 mm^2, respectively, for a variance of 0.86%.

Volume and surface area data for each digital model were also compared using a series of Two-tailed T-test analyses in order to determine the differences in model dimensions between the two digitization techniques. Digital models created for FMNH PR2081 resulted in a 0.9808 *p*-value, and digital models for FMNH PR3703 resulted in a 0.6431 *p*-value (Figure 3A-D, Table 1).

Between the structured-light scanned digital model of FMNH PR2081 and the 3D prints created on the FlashForge Pro and the UP Mini (Table 2A), crown lengths ranged from 48.58 to 49.96 mm, a variance of 2.76%. The base of the crown width measurements of these same models ranged

Table 1: Two-tailed T-Test statistical analysis of digital models and scanning technique. Note the high P-value in comparisons between FMNH PR2081 models, and the lower P-value in comparisons between FMNH PR3707 models.

Model	**Scanner**	**Mesh Surface Measurement (S)**	**Mean Tringle Surface**	**Mesh Volume**	**Two-tailed P value**
PR2081	**Laser-Texture**	12473.6	0.0124812	74857.5	0.9808
	Structured Light	12717.4	0.00653692	77163.2	
PR3703	**Laser-Texture**	4970.17	0.00138549	4969.66	0.6431
	Structured Light	5056.68	0.00307501	9808.39	

Table 2: Chi-Square analysis of FMNH PR2081 3D printed models. A) Models printed from structured-light scanning, and B) models printed from laser-texture scanning. All measurements are in mm. Note the general similarities among printed models of FMNH PR2081 from the two different digitization methods.

A Printer	Length a-a’	Thickness b	Thickness c	Width d	Width e	Width f		
Digital	49.96	27.09	24.54	23.75	18.37	12.30	D. F.	10
Flashforge	48.58	29.67	25.65	23.42	18.68	12.73	*p* value	1
UP Mini	49.69	29.82	25.68	23.51	18.42	12.06		

B Printer	Length a-a’	Thickness b	Thickness c	Width d	Width e	Width f		
Digital	50.09	28.42	26.10	23.96	18.82	12.74	D. F.	10
Flashforge	48.14	31.30	26.90	24.20	19.11	11.75	*p* value	1
UP Mini	49.81	31.17	27.04	24.38	19.08	11.77		

from 23.42 to 23.75 mm, for a variance of 1.38%. For models based on the laser-texture scanning process (Table 2B), crown length ranged from 48.14 to 50.09 mm, a variance of 3.89%. For these same models, the base of the crown widths ranged from 24.38 to 23.96 mm, for a variance of 1.72%.

For FMNH PR3703, measurements were taken along all three spatial dimensions as well as the width of four prominent pits (Table 3A, B). Model lengths varied by a total of 1.81% and 2.12%, respectively, between the structured-light scanning and laser-texture scanning techniques. Heights varied by 0.75% and 2.08% for the same models, while thicknesses varied by 2.64% and 7.78%. Pit widths varied by 2.55% and 0.23% for pits i & j of the structured-light scanned models, and these same pits had variances of 0.30% and 6.70% for the laser-texture scanned models.

The resulting print measurements were then compared using Chi-Square statistical analysis, with resulting *p*-values of 1.0, indicating that differences in model dimensions attributed to the 3D printing process were not statistically significant.

DISCUSSION

This experiment demonstrates that, when used to digitize small-size, high-detail paleontological specimens, both structured-light scanning and laser-texture scanning create accurate digital representations with fidelity typically on the order of 1 mm or less average surface deviation for objects in the 5-15 cm range. Differences in model fidelity for prints created on low-cost 3D printers such as these are statistically insignificant, with differences typically on the order of 1 mm or less.

The fidelity of digitized specimens depends more on the specimen morphology rather than the technology used to digitize or reproduce them. Very thin specimens (<1 cm in thickness) produced a great deal of digital artifacts or deformation during the digitization process, regardless of technology used. For the non-contact digitization processes used for this experiment, digital models have a higher chance of error when the projected light or laser beam is far from the point of origin (as is the case for very long objects), or is projected onto a very thin surface.

Table 3: Chi-Square analysis of FMNH PR3703 3D printed models. A) Models printed from structured-light scanning, and B) models printed from laser-texture scanning. All measurements are in mm. Note the small differences among printed models of FMNH PR3707 from the two different digitization methods.

A Printer	Length g-g’	Height h-h’	Thick-ness m	Thick-ness n	Pit i	Pit j	Pit k	Pit l		
Digital	50.86	39.70	8.11	4.91	5.08	5.02	4.55	4.35	D. F.	14
Flashforge	52.49	39.93	7.93	5.08	5.06	4.53	4.63	4.99	*p* value	1
UP Mini	52.73	40.30	8.36	5.09	5.05	5.18	4.46	4.63		

B Printer	Length g-g’	Height h-h’	Thick-ness m	Thick-ness n	Pit i	Pit j	Pit k	Pit l		
Digital	53.26	41.92	5.04	3.73	5.92	5.25	5.65	5.75	D. F.	10
Flashforge	54.87	42.70	5.83	4.09	6.10	5.19	5.22	5.52	*p* value	1
UP Mini	55.57	43.70	5.89	3.26	6.23	5.50	5.11	5.45		

In most cases, these digital artifacts could be modified with post-processing software. However, as was the case with the digitization of specimen FMNH PR3703, the thin nature of the cast resulted in two digital models with a wider variance in thickness - approximately 8mm with the structured-light scanner compared to 5.5mm with the laser-texture scanner. As such, the variance in volume suggests that thinner specimens digitized with either of these techniques must be used with caution for research purposes. However, the resulting models would still be useful as teaching and outreach aids.

Future Directions

Fused depositional modeling is the most common form of additive manufacturing in the commercial and research sectors and a very useful tool for paleontology research, education, and outreach. However, many other forms of additive manufacturing exist with varying degrees of cost, ease of use, and fidelity. As the technology develops, such alternative forms of additive manufacturing may become more commonplace.

While the specimens utilized in this experiment are within the size range typical for the digitization devices used, a wider variety of specimens of larger and smaller sizes should be digitized to fully gauge the extents and limits of digitization processes. Furthermore, this experiment does not fully explore the fidelity of digitization processes available for paleontology research and outreach, such as photogrammetry. Additionally, a wider variety of printers would be ideal to more accurately gauge the fidelity of reproduction techniques, such as photopolymerization or laser sintering.

For a true test of the potential benefits of digitization and additive manufacturing for the field of paleontology, a study into the use of digital models and AM reproductions for phylogenetic coding would be ideal. If digital and AM reproductions of paleontological specimens can be used for accurate and reliable phylogenetic analysis, then these technologies may be considered adequate substitutes for traditional resin casts. The ability to accurately and reliably conduct research on paleontological specimens through the use of digital models or reproductions created through AM techniques has the potential to be significant for paleontology research as well as education and outreach opportunities.

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