Museum exhibitions of fossils into commercial products: Unexpected outflow of 3D models due to unwritten image policies

Kumiko Matsui[1,2] and Yuri Kimura[3,4]

[1] Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington D. C., the United States of America MatsuiK@si.edu

[2] The Kyushu University Museum, Kyushu University, Fukuoka, Fukuoka, Japan

[3] Department of Geology and Paleontology, National Museum of Nature and Science, Tsukuba, Ibaraki, Japan ykimura@kahaku.go.jp

[4] Institut Català de Paleontologia Miquel Crusafont, ICTA-ICP, Edifici Z. Carrer de les Columnes, s/n., Campus de la Universitat Autònoma de Barcelona, Barcelona, Spain

This manuscript has **not been formally accepted** for publication and is as such a **non- peer reviewed preprint**. If accepted in a peer-reviewed journal, the final version of this manuscript will be available via the Peer-review Publication link on the web page.

Feel free to contact us if you have any queries or comments; we welcome your feedbacks.

Museum exhibitions of fossils into commercial products: Unexpected outflow of 3D models due to unwritten image policies

Kumiko Matsui[1,2] and Yuri Kimura[3,4]

[1] Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington D. C., the United States of America

[2] The Kyushu University Museum, Kyushu University, Fukuoka, Fukuoka, Japan

[3] Department of Geology and Paleontology, National Museum of Nature and Science, Tsukuba, Ibaraki, Japan

[4] Institut Català de Paleontologia Miquel Crusafont, ICTA-ICP, Edifici Z. Carrer de les Columnes, s/n., Campus de la Universitat Autònoma de Barcelona, Barcelona, Spain

Corresponding Author: Yuri Kimura; e-mail: ykimura.research@gmail.com

Key words: photogrammetry; 3D-model, photograph; fossil-replica; museum; museum policy

ABSTRACT

Recent innovations and cost reductions in photogrammetry-based 3D modeling have enabled museum visitors to create 3D models based on photographs exhibited in galleries without breaking museum policies. While several museums make 3D museum data available on sharing platforms, museum visitors publish unofficial 3D data belonging to museum exhibits using a photogrammetry-based approach.

This study shows that photogrammetry-based 3D models can be generated without breaking conventional photo policies (i.e., no use of flash and tripods), and that museum visitors can create commercial products based on these models. 3D models can enhance the value of science and promote broader and deeper interests in the natural sciences. However, the rights of owners of museum pieces are ambiguous with regard to the dissemination of unofficial data, and this also makes information attributable to the original specimen unclear, which can potentially lead to revenue loss. We propose a set of best practices for museum photo policies, which covers the data use of visitor-generated 3D models of displayed objects.

museum exhibition/3D model/photogrammetry/museum policies

INTRODUCTION

Actual and scale-sized replicas of original fossils have greatly contributed to research and museum exhibitions in the field of paleontology and other disciplines. Since appropriately choosing molding compounds and casting materials can enhance the precision of fossil replicas, conventional techniques of duplication have supplemented paleontological research, especially for original fossils which are not easily accessible or have strict regulations on use and export. The benefits of molding and casting are clearly seen by the public in museum exhibitions. Many of us must have seen the casts of a complete *Tyrannosaurus rex* skeleton displayed in museums. Museum visitors can appreciate the scientific background of ancient organisms by seeing fossil replicas of original specimens which are otherwise stored in collection rooms. In addition, conventional duplication techniques (i.e., molding and casting) have shown great potential for innovative exhibition styles such as hanging casts of ceratopsian dinosaurs on a wall at the Natural History Museum of Utah (Figure 1A), where a phylogenetic tree is painted. Until a decade ago, fossil replicas for research and exhibition were almost exclusively created using molding and casting techniques [1]. In addition, this complex methodology has been limited due to copyright/ownership restrictions on fossil specimens because fossil replication was conducted internally in research, museum exhibitions, and education.

However, with recent developments in technology, 3D printing and digital models have increasingly risen as a new method for creating cheap and accurate fossil replicas [2,3]. This non-invasive technique is preferable especially for fragile specimens because 3D-printed replicas can be made more securely with a low risk of breaking the fossils during the replication process. An example of this is the life-sized *Triceratops horridus* fossil replicas based on 3D digital models displayed in the National Museum of Natural History, Smithsonian Institution (USA) (Figure 1B). 3D-printed replicas are also used as educational

tools [4,5]. The Florida Museum of Natural History compiled how to obtain and use 3D paleontological data [5].

Currently, photogrammetry-based reconstruction allows museum visitors to create digital models of museum displays and even share the models on online platforms. If the source photos were collected against museum policy (e.g., no flashlight or no selfie stick), creating 3D models based on these is considered a violation of museum policy. However, if model makers (i.e., museum visitors) follow the current museum photo policies while creating 3D models of museum displays, museums encounter an ambiguous situation because the copyright of the models technically belongs to the model makers even though the museums own the specimens. In general, 3D models are constructed through two processes: 1) capturing photos and 2) creating 3D models from the photos. In this case, photographers own the copyright of the photos used to create 3D models, while the copyright of the 3D models belongs to the model creators. Here, we demonstrate that photogrammetry-based 3D models can be created without breaking existing photo policies, and 3D-printed objects of the models are of decent quality and may be distributed commercially.

3D-MODEL OUTFLOW UNDER CONVENTIONAL PHOTO POLICIES

Currently, there is a major drive to make digital 3D models of natural history objects accessible and visible to the public. For example, the National Science Foundation-funded oVert is a research-driven project which shares digital 3D vertebrate anatomical models including high-resolution anatomical data of more than 80% of vertebrate genera to the public [6]. Major academic publishers such as Taylor & Francis also have an official account in Sketchfab [7], a major platform for sharing, buying, and selling 3D content, as well as archiving 3D models, such as in the case of *Journal of Vertebrate Paleontology* [8]. Several museums including the Natural History Museum of Los Angeles County, USA [9], and the

Natural History Museum, London, UK [10], have made their fossil collections available to users as open-access 3D models via Sketchfab. In addition to official 3D digital models uploaded and released by museums or academic publishers, many photogrammetry-based 3D models of museum displays have been uploaded by general users. On the Sketchfab platform, we identified the following user-uploaded 3D models: the *Tyrannosaurus rex* specimen ("Black Beauty," RTMP 81.6.1 at the Royal Tyrrell Museum), a nest of duck-like dinosaur *Maiasaura* (the Natural History Museum, London), and a specimen of the early Ceratopsian, *Protoceratops* (the American Museum of Natural History). These latter examples were "digital-snatched" models generated from photographs taken in the exhibition halls at the above museums. These 3D data have various Creative Commons (CC) licenses [11] defined by uploaders, and some allow them to be used for commercial purposes. These platforms are rapidly developing both in terms of users and model availability. Digitized museum exhibits are freely available online and their contents are used for various purposes. Occasionally, some models are sold under creator copyrights without an official permit by museums or specimen owners (i.e., national or local governments). Museums own their exhibitions; however, natural history specimens are not manmade. Thus, the museum has no copyright. The treatment of copyright holders of 3D files is still under debate, and these are considered uncopyrighted under current laws [12].

Discussions about the use of open 3D fossil specimen data have just begun. Some researchers have proposed the best practices for the quality control, publication, storage, and reuse of open data using digital morphology (e.g., [11]), and recent movements toward sharing 3D datasets of paleontological specimens are summarized in Weinberg et al. [12]. In this study, we summarized the photo policies of eight major natural history museums in North America, Europe, Asia, and Oceania, which receive more than two million visitors per year. We then made comparisons of the results of a demonstration of photogrammetry-based

3D models and products and suggested the best practices for museum photo policies for fossils which cover the data use of visitor-generated 3D models of displayed objects.

MATERIALS AND METHODS

Commercial Products

To test whether we could create good qualified photogrammetry-based 3D models under current policies, we photographed two specimens displayed at the National Museum of Nature and Science in Tokyo, Japan: a fossil of *Hyaenodon* (in Evolution of life – From the Earth's Origin through Human Existence, Global Gallery) and a cast of *Camarasaurus* skull (Evolution of Life, Exploring the Mysteries of Dinosaur Evolution, Global Gallery). They are displayed in strict accordance with the museum's current policies (i.e., no flashlight, no additional lighting, no selfie stick, no tripod/monopod) during open hours (Figure 2A). Notably, *Hyaenodon* is displayed behind a glass wall with lighting settings that automatically change from dawn to twilight mode, which is not ideal for professional photogrammetry. A smartphone (iPhone 8: Apple, Inc.) and an SLR digital camera (Canon EOS Kiss X9i: Canon) were chosen as they are popular photographic equipment for photogrammetry. We took photos of *Hyaenodon* with an SLR camera and Camarasaurus using a smartphone. HD movie videos along with 100-200 photos of still images which served as 2D images (Figure 2B) were obtained. The video files were converted to still images by a free video to the JPG Converter [13]. To create 3D models, we used Agisoft Metashape v. 1.5 [14], which is an affordable high-end photogrammetric program for small businesses. The default settings were set for the accuracy of the photography alignment and dense clouds. We further designed a smartphone cover with the *Hyaenodon* model and a cup of a *Camarasaurus* skull using the free 3D modeling software, Meshmixer [15], to serve as samples of potential commercial products.

Photo Policies

To compare photo policies, we compiled photo regulations and the number of museum visitors, which serves as an indicator of potential influence on people, from the webpages of these museums. We chose to compare the photo policies of eight major museums from North America, Europe, Asia, and Oceania, which receive 20 million visitors per year. The eight chosen museums were as follows: American Museum of Natural History, USA (North America), National Museum of Natural History, Smithsonian Institution in USA (North America), Royal Tyrrell Museum in Canada (North America), the Natural History Museum in UK (Europe), Muséum National D'histoire Naturelle in France (Europe), Museum Für Naturkunde in Germany (Europe), National Museum of Natural History in Tokyo, Japan (Asia), and Museum of New Zealand Te Papa Tongarewa (Oceania). The results are shown in Table 1.

"DIGITAL SNATCH" DISPLAYED OBJECTS

In the National Museum of Nature and Science in Tokyo, Japan, the photo policy is shown at every building entrance, booklets, and on its website [16]. We were able to obtain photos without violating any of the museum's photo policies of the National Museum of Nature and Science in Tokyo, Japan, and we used these to generate 3D models of decent quality and a virtual commercial product from the photogrammetry-based 3D model (Figure 3). We spent only a few minutes photographing the objects and used all the photo and video data to create the models. Based on photos and videos taken through a glass wall, we obtained 3D models of objects displayed below eye level at sufficiently good quality for printing, selling, or sharing (Figures 2A and 2C). On the other hand, complete 3D models were not acquired for large specimens or those displayed in high places because the dorsal/backside of the specimens could not be reached by visitors.

The *Hyaenodon* and *Camarasaurus* skull specimens were not displayed under suitable photographic conditions for photogrammetry. The exhibition hall had variable light conditions ranging from dark (dawn) to bright (daytime) modes. Even so, the software algorithms were able to align photos to generate 3D digital models that retain the extreme morphological details of the surface. Once the 3D models are uploaded to online data-sharing platforms, such as Sketchfab [17] or pinshape [18], they can be distributed rapidly. A third party can download them to make commercial products for profit. This "digital snatch" of a museum exhibition is easier than ever because of widespread advancements in photogrammetry techniques. Currently, the market price of photogrammetry software ranges from hundreds to thousands of dollars (e.g., Reality Capture [19], Agisoft Metashape [14], 3DF Zephyr [20], ReCap [21]). There are also free, open-source photogrammetry programs such as 3DF Zephyr Free (3D Flow) and smartphone applications (e.g., Qlone: EyeCue Vision Technologies). A "digital snatch" would potentially reduce museum profit, which

might be a critical issue for privately-owned museums. Although many natural history museums are managed as public properties, not all museums are publicly funded, as in the National Museum of Nature and Science, Tokyo, Japan.

MEGA NATURAL MUSEUMS PHOTO POLICIES

The photo policies of eight mega natural history museums in North America, Europe, Asia, and Oceania are listed in Table 1. We compared private use regulations, non-commercial use, and secondary use. All museums permit personal use of their exhibition photos and restrict commercial use by requesting application forms (along with monetary charges in some cases), whereas non-commercial cases are handled in various ways. Among the museums listed in Table 1, only two museums (the American Museum of Natural History and the National Museum of Nature and Science) state policies for secondary use. These say that museum visitors and the people who download photos collected by museum visitors must use them in a personal capacity (Table 1).

Importantly, we emphasize that there should be no conflict between public property and limiting data leakage. For example, the 3D model of the most famous dinosaur, the *Tyrannosaurus rex,* known as "SUE" (PR 2081), is officially available for education and creation on the official Sketchfab account of the Field Museum [23], but the data is not downloadable. This is an excellent example of releasing 3D data while retaining the copyright. Whether user-generated 3D data of displayed objects is appropriate, if museums prefer to control the secondary use of these data, conventional photo policies (e.g., no flash, no tripod stands) are insufficient.

CC 0 IN NATURAL SCIENCES

The Smithsonian Institution (including 19 museums, 12 libraries, nine research institutes, and one zoo) announced the launch of the Smithsonian Open Access wherein 2.8 million of their digital collection images were released into the public domain [24]. Under the CC0 policy, digital images including 2D and 3D data of the Smithsonian collections published by the Smithsonian Institution [24] can be used without permission and payment for any purpose [25]. Creative Commons (CC) licenses are standardized "communication tools" for creators to give various degrees of permission to share and use their creative work. CC licenses are standardized ways of granting public permission to use their work under copyright law. There are six different license types: CCBY, CC BY-SA, CC BY-NC, CC BY-NC-SA, CC BY-ND, and CC BY-NC-ND. CC refers to Creative Commons, BY means that the creator must give original credit, SA means that users must share Adaptations under the same terms, NC means that only noncommercial uses of the work are permitted, and ND means that no derivatives or adaptations of the work are permitted. In addition, CC licenses have a subcategory CC0. CC0 means "no rights reserved," waiving all rights of creators and placing their work as much as possible in the public domain in that users can reuse these works for any purposes without restriction under copyright or database law [26]. In the case of the Smithsonian, this effort has the imprimatur of its administration. Regarding the Smithsonian OA, Smithsonian Secretary Lonnie G. Bunch III stated that the institutional effort aimed for *"viewers to become collaborators to engage critically, to think expansively, to imagine freely"*[27]. Before the CC0 policy, the Smithsonian Institution allowed users to download their copyrighted data under their original policies: for non-commercial and educational uses, subject to fair use under copyright law. The new CC0 policy opens the door of the Smithsonian Institution to people in countries that do not declare fair use, such as Japan, where we are located. By becoming the first natural history museum to enact the CC0

247 policy for 3D datasets, they showed that museum collections belong to the public common
248 and removed economic and legal barriers which promote equity by permitting anyone in the
249 world to make creations based on their exhibited collections.
250 The Natural History Museum in London and the Field Museum also released 2D
251 images with limited data under the CC0 policy, but these do not include 3D models [28,29].
252 The former museum has released many downloadable 3D models of important specimens
253 (e.g., Darwin's fossil collection: The Natural History Museum, 2017) under the CC BY-NC
254 4.0 license, but not the CC0 license. Similar efforts have been undertaken by other small
255 museums (e.g., Western Science Center: [30] Charleston Museum: [31]; College of
256 Charleston: [32]).
257

DESIRABLE PHOTO POLICIES TUNED FOR 3D DATA

Open-access sharing platforms for 2D and 3D images are increasingly popular, and some of them explicitly state their copyright policy and other terms of use both for data authors and users. In some cases, uploaders (e.g., data contributors as well as data authors in most cases) can determine the copyright holder by selecting copyright options during the uploading process, which may become an issue as discussed below.

In paleontological research, 3D digitization and imaging techniques have already been used as research tools (e.g., [33–36]); however, it is only recently that research-driven archives such as Digimorph [37] and MorphoSource [38] have become accessible to a more general audience who are curious to see 3D models of organisms, and allowed them to download the raw CT data. In MorphoSource, if *the restriction option* is set by data contributors (i.e., uploaders, data authors), data users are required to state the purpose of using the 3D data before they are permitted to download data or send a request for download directly to the uploader. All data contributors are required to obtain official permission from specimen owners before uploading (see [39]).

Nowadays, 3D digital models can be shared worldwide through major sharing websites, such as Sketchfab [17]. In Sketchfab, data contributors can set a Creative Commons license for each 2D or 3D object, but they are not required to obtain specimen owners' permissions. In this case, 3D data can easily lose important metadata attributes associated with the data and specimen, such as the location of the original specimen and specimen numbers.

Our results show that under general photo policies, visitors can generate photogrammetry-based 3D models of displayed objects and share these models without the authorization of museums. If museums desire to restrict unwanted duplicates while

displaying photos in their exhibition galleries, we suggest creating or revising handling policies for 3D models of displayed objects and stating these explicitly to visitors.

BEST PRACTICES FOR DIGITAL ASSETS OF DISPLAYED 3D OBJECTS IN NATURAL HISTORY MUSEUMS

Here, we propose the best practices for museum photo policies that cover the data use of visitor-created 3D models of displayed objects.

1) Creating models: State whether museums allow visitors to take photographs to convert them into 3D models. It is important for each museum to decide on the management of the 3D data of its exhibitions.

2) Copyright of 3D models: Clarify the ownership of any type of 3D model of displayed objects as a part of photo policies. During the COVID-19 pandemic (2020-ongoing), virtual reality or augmented reality exhibition could be considered as a new source of museum income. A statement about ownership is especially important when museums plan to sell 3D-printed replicas or other products,

3) Commercial versus non-commercial use: Clearly state whether visitors can publish their models for commercial or non-commercial use. For example, many museums display replica casts of fossil specimens from other museums. The copyright of the original specimens must be clarified before publication. Considering these circumstances, we recommend specifying whether a piece in an exhibit is CC BY-NC-ND. In some cases, museums that release 3D models on websites (e.g., the Natural History Museum in London and Charleston Museum, South Carolina in USA) retain the non-commercial use of their digital data in sharing platforms. The Smithsonian allows for the use of their published 3D models in CC0.

4) Sharing models: Whether museums allow visitors to share photogrammetry-based 3D models created by museum visitors with anonymous people on the Internet. If allowed, we recommend that museums request model creators to place the following in their 3D data files:

scientific information of the objects (e.g., scientific name, locality, housed institution, specimen number), data acquired to date, data acquisition equipment, and software.-The attribute information is easily lost during any allocation process of the 3D models when copying and pasting files. However, these metadata attributes are the most valuable information for museum specimens. If the 3D data retains its associated information, the data could be used for future educational and research purposes.

5) Clear notification: The above policies must be stated in plain language and easily spotted by visitors in museum galleries. It would be better to announce these repeatedly in multiple manners, such as through interactive kiosks, during the ticket-purchasing/reservation process, or on the museum's website. We believe that it is important to retain substantial museum-visitor relationships.

CONCLUSIONS

This study proposes handling policies for user-generated 3D models of displayed objects. Open access policies for the reproduction of museum specimens are becoming a global trend, being promoted and implemented at different rates and in different ways in countries across the globe. While some institutions have adopted fully open access policies for their 2D and 3D digital data, some museums maintain stricter copyrights. This issue has not been fully discussed in many contexts, including that of small museums. Cost reduction in 3D-scanning equipment and photogrammetry software will facilitate the creation of 3D models of objects displayed in exhibition halls. These “unofficial” models have already been uploaded to popular data-sharing platforms such as Sketchfab. Once 3D digital models of displayed objects are created by a third party, rapid online distribution cannot be controlled by museums that own original models.

Competing Interests

We have no competing interests.

Authors' contributions

Both authors equally contributed to the draft.

Funding

Financial support was provided by the National Museum of Nature and Science, JSPS KAKENHI Grant Numbers 21K14031, 19J0041, 18K13650, JP15H06884, and the Qdai-jump Research Program Grant Number Wakaba Project 02219 and 01220.

Research Ethics

An ethical assessment was not required prior to conducting our research.

Acknowledgments

We thank Lauren Debussy and Nicholas D. Pyenson for providing constructive comments on our manuscript.

REFERENCES

1. Leiggi P, May P. Vertebrate Paleontological Techniques: Methods of Preparing and Obtaining Information. Cambridge: Cambridge University Press; 2005.
2. Falkingham P. Acquisition of high resolution three-dimensional models using free, open-source, photogrammetric software. Palaeontol Electron. 2012;15: 1T:15p. doi:10.26879/264
3. Das AJ, Murmann DC, Cohrn K, Raskar R. A method for rapid 3D scanning and replication of large paleontological specimens. Raia P, editor. PLoS One. 2017;12: e0179264. doi:10.1371/journal.pone.0179264
4. Johnson EH, Carter AM. Defossilization: A Review of 3D Printing in Experimental Paleontology. Front Ecol Evol. 2019;7: 1–7. doi:10.3389/fevo.2019.00430
5. Ziegler MJ, Perez VJ, Pirlo J, Narducci RE, Moran SM, Selba MC, et al. Applications of 3D Paleontological Data at the Florida Museum of Natural History. Front Earth Sci. 2020;8: 1–20. doi:10.3389/feart.2020.600696
6. Hoose N van. oVert. 2017 [cited 15 Mar 2020]. Available: https://www.floridamuseum.ufl.edu/science/overt/
7. Sketchfab. Sketchfab. 2021. Available: https://sketchfab.com/
8. Skechfab. Taylor & Francis. 2017 [cited 15 Mar 2020]. Available: https://sketchfab.com/taylorandfrancis
9. Obied C, Lopez S, Rhue V. 3D Digitization of the NHMLA Vertebrate Fossil Type Collection. 2019 [cited 15 Mar 2020]. Available: https://sketchfab.com/blogs/community/3d-digitization-of-the-nhmla-vertebrate-fossil-type-collection/
10. Skechfab. NHM_Imaging. 2016 [cited 15 Mar 2020]. Available: https://sketchfab.com/NHM_Imaging

11. Creative Commons. Creative Commons. 2021 [cited 18 May 2021]. Available: https://creativecommons.org/
12. Weinberg M. What's the Deal with Copyright and 3D Printing? Washington, D.C., USA: Public Knowledge; 2013. Available: https://www.publicknowledge.org/files/What's the Deal with Copyright_ Final version2.pdf
13. Digital Wave. Free Video to JPG Converter. 2020 [cited 15 Mar 2020]. Available: https://www.dvdvideosoft.com/products/dvd/Free-Video-to-JPG-Converter.htm
14. Agisoft LLC. Agisoft Metashape. 2018 [cited 15 Mar 2020]. Available: https://www.agisoft.com/
15. Autodesk. Meshmixer. 2017 [cited 15 Mar 2020]. Available: http://www.meshmixer.com/
16. National Museum of Nature and Science. General Information. 2020 [cited 31 Oct 2020]. Available: https://www.kahaku.go.jp/userguide/access/index.html
17. Skechfab. Skechfab. 2012 [cited 15 Mar 2020]. Available: https://sketchfab.com/
18. Pinshape. pinshape. 2016 [cited 28 Aug 2021]. Available: https://pinshape.com/
19. Capturing Reality. Reality capture. 2016 [cited 15 Mar 2020]. Available: https://www.capturingreality.com/
20. 3D Flow. 3DF Zeph. 2014 [cited 15 Mar 2020]. Available: https://www.3dflow.net/3df-zephyr-pro-3d-models-from-photos/
21. Autodesk. ReCap. 2020 [cited 15 Mar 2020]. Available: https://www.autodesk.com/products/recap/overview
22. EyeCue Vision Technologies. Qlone. 2017 [cited 28 Aug 2021]. Available: https://www.qlone.pro/

23. Sketchfab. fieldmuseumeducation. 2018 [cited 28 Aug 2021]. Available: https://sketchfab.com/fieldmuseumeducation
24. Smithonian Institution. Smithsonian Open Access. 2020 [cited 18 Feb 2021]. Available: https://www.si.edu/openaccess
25. Fisher A, St.Thomas L. Smithsonian Releases 2.8 Million Free Images for Broader Public Use. 2020 [cited 28 Aug 2021]. Available: https://www.si.edu/newsdesk/releases/smithsonian-releases-28-million-free-images-broader-public-use
26. Creative Commons. CC0 "No Rights Reserved." 2020 [cited 15 Mar 2020]. Available: https://creativecommons.org/share-your-work/public-domain/cc0/
27. Bunch III LG. Secretary Bunch's Reflections on Smithsonian Open Access. In: Smithsonian [Internet]. 2020 [cited 10 Nov 2021]. Available: https://www.si.edu/openaccess/updates/opening-doors-imagination-secretary-bunchs-reflections-smithsonian-open-access
28. Field Museum. Use of collections data and images. 2021 [cited 15 May 2021]. Available: https://www.fieldmuseum.org/science/research/use-collections-data-and-images
29. The Natural History Museum L. Digitising Darwin's Fossil Mammals. 2017 [cited 15 May 2021]. Available: https://www.nhm.ac.uk/our-science/our-work/digital-collections/digital-collections-programme/DarwinsFossils.html
30. Skechfab. WesternScienceCenter. 2021 [cited 15 May 2021]. Available: https://sketchfab.com/WesternScienceCenter
31. Skechfab. The Charleston Museum. 2020 [cited 15 May 2021]. Available: https://sketchfab.com/charlestonmuseum

32. Skechfab. C of C Natural History Museum. 2019 [cited 15 May 2021]. Available: https://sketchfab.com/CofCNaturalHistoryMuseum)

33. Rowe T, Frank LR. The Disappearing Third Dimension. Science (80-). 2011;331: 712–714. doi:10.1126/science.1202828

34. Lewis D. The fight for control over virtual fossils. Nature. 2019;567: 20–23. doi:10.1038/d41586-019-00739-0

35. Matsui K, Karasawa T. 3D models related to the publication: Interacting with the inaccessible: utilization of multimedia-based visual contents of Japan's National Monument, the Taniwhasaurus mikasaensis (Mosasauridae) holotype for educational workshops at Mikasa City Museum. MorphoMuseuM. 2020;6: e106. doi:10.18563/journal.m3.106

36. Karasawa T, Matsui K. Interacting with the inaccessible: utilization of multimedia-based visual contents of Japan's National Monument, the Taniwhasaurus mikasaensis (Mosasauridae) holotype for educational workshops at Mikasa City Museum. Fossils. 2020;108: 3–10. doi:10.14825/kaseki.108.0_3

37. Rowe T. A National Science Foundation Digital Library at The University of Texas at Austin. 2002 [cited 28 Aug 2021]. Available: http://www.digimorph.org/

38. Boyer DM, Gunnell GF, Kaufman S, McGeary TM. MORPHOSOURCE: archiving and sharing 3-D digital specimen data. Paleontol Soc Pap. 2016;22: 157–181. doi:10.1017/scs.2017.13

39. Davies TG, Rahman IA, Lautenschlager S, Cunningham JA, Asher RJ, Barrett PM, et al. Open data and digital morphology. Proc R Soc B Biol Sci. 2017;284. doi:10.1098/rspb.2017.0194

FIGURES AND CAPTIONS

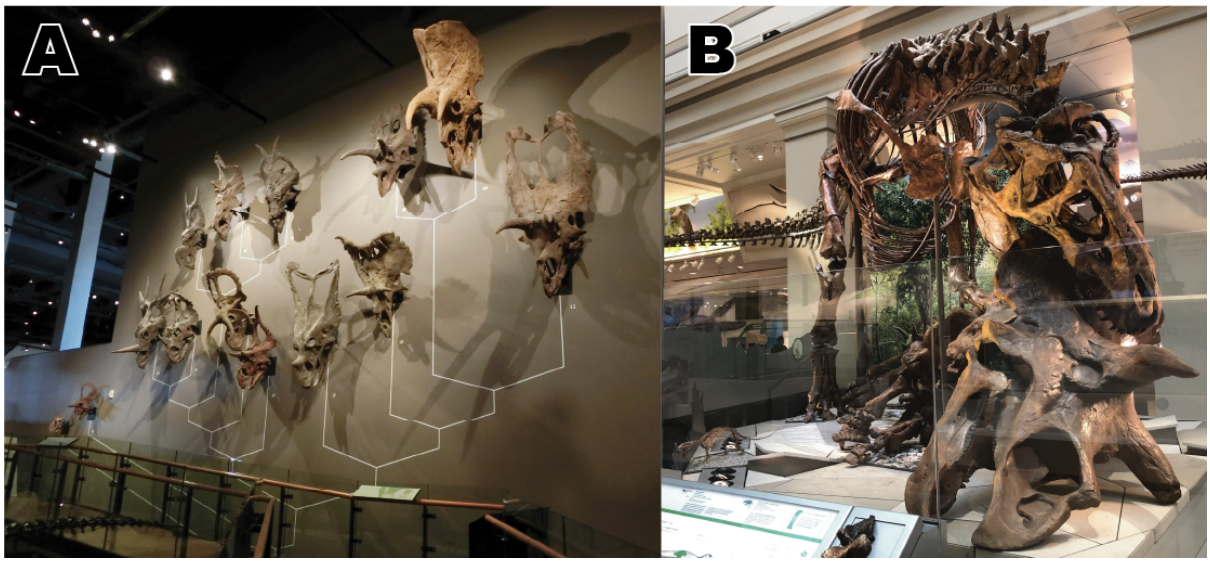

FIGURE 1 Museum exhibitions using replica fossils. A: An exhibition of the phylogenetic relationships of ceratopsian dinosaurs using giant ceratopsian dinosaur skull replicas at the Natural History Museum of Utah, USA; B: the nation's *T. rex* (*Tyrannosaurus rex* specimen, nicknamed Wankel' rex, USNM PAL 555000) decapitating a *Triceratops horridus* (USNM PAL 500000) at the David H. Koch Hall of Fossils – Deep Time, at National Museum of Natural History, Smithsonian Institution, USA.

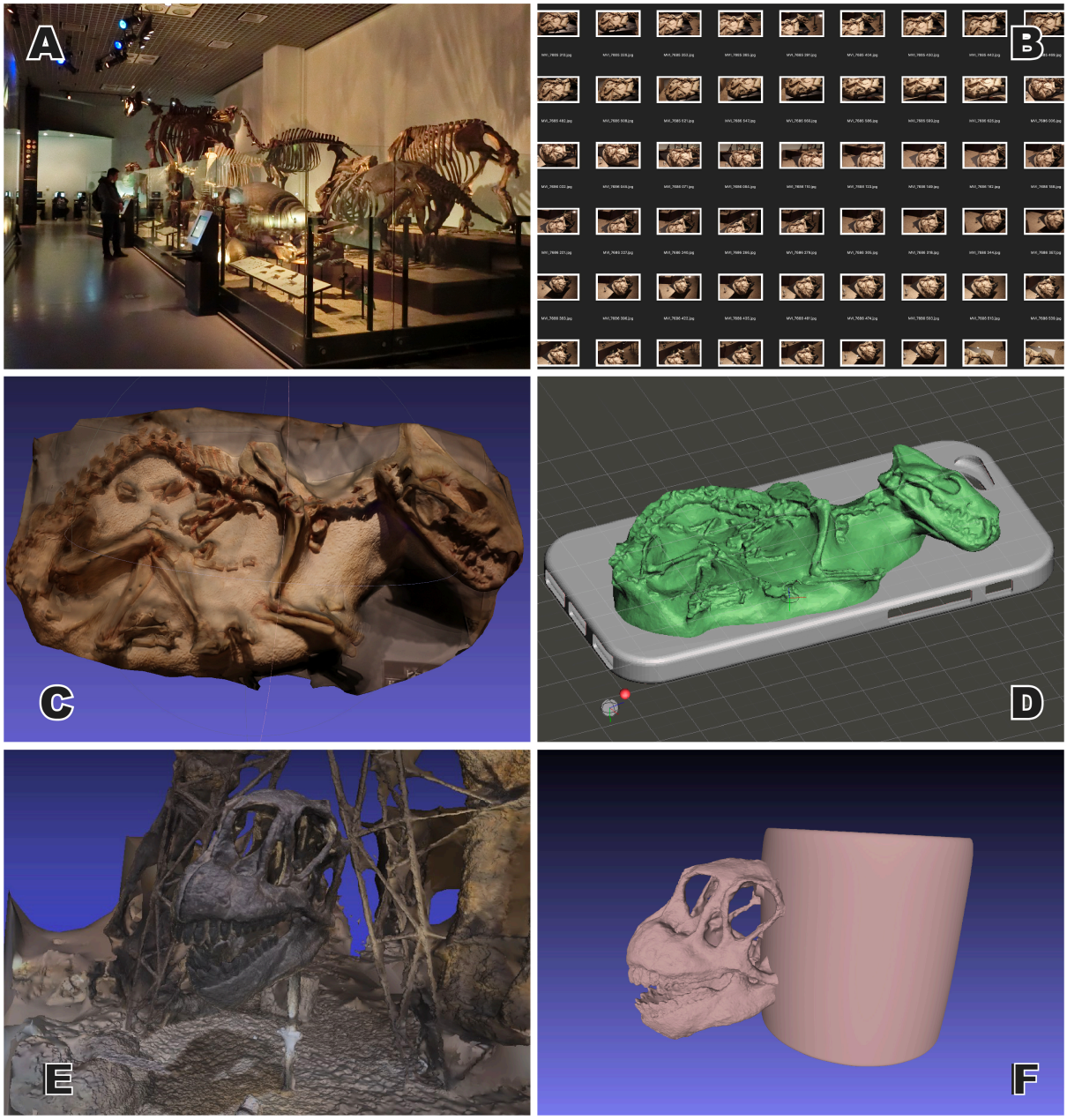

FIGURE 2. Photogrammetry-based 3D models of the *Hyaenodon* and *Camarasaurus* skulls, and their virtual products.

A: Exhibition gallery at the National Museum of Nature and Science, Tokyo, Japan. Fossils were displayed behind the glass walls. Lighting conditions changed from dawn to twilight; however, walkways are dim. These conditions are generally not ideal for photogrammetry [14]. B: Photos of *Hyaenodon* displayed in a permanent exhibition gallery. These were taken under museum photo policies and later used to create a photogrammetry-based 3D model. C: Photogrammetry-based 3D model of *Hyaenodon*. It was constructed using the Agisoft

Metashape [14]. D: Original smartphone cover as a virtual product made using the *Hyaenodon* model. E: Photogrammetry-based 3D model of *the Camarasaurus* skull. It was constructed using the Agisoft Metashape [14]. F: Original mug as a virtual product made using the *Camarasaurus* skull model. We merged the *Camarasaurus* skull model and a 3D model of a mug in the Meshmixer [15].

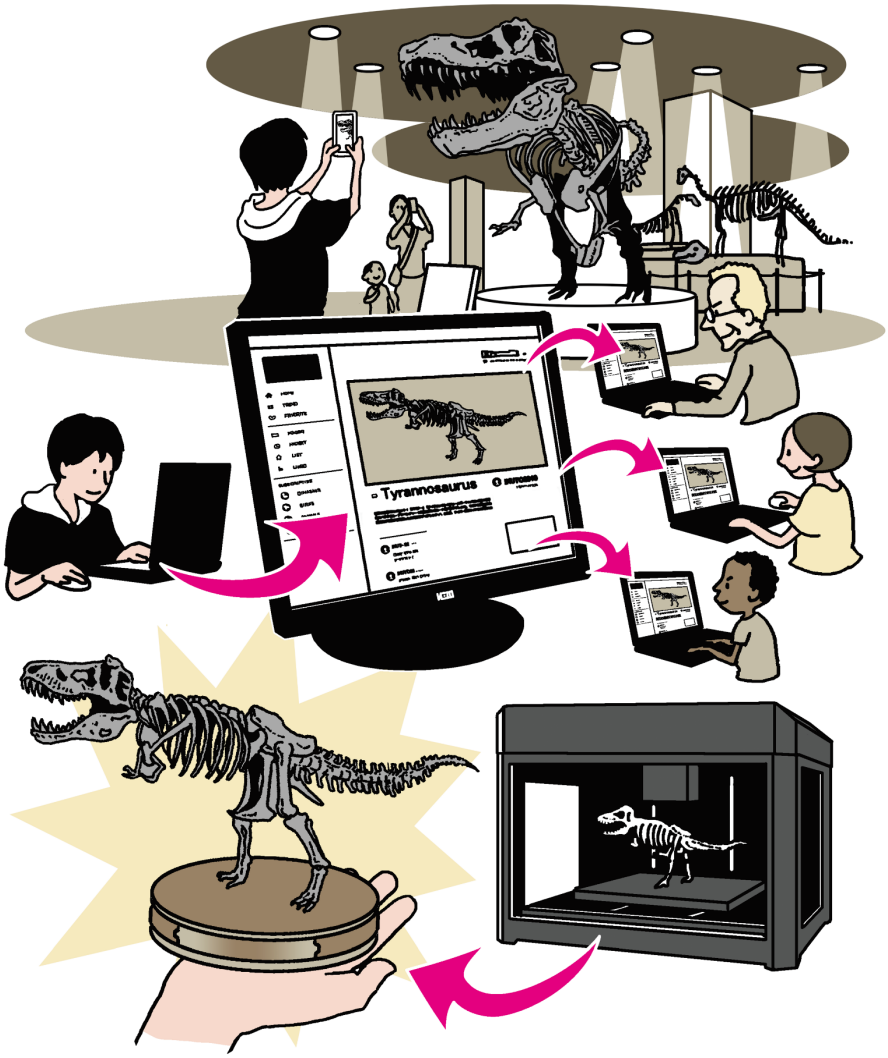

FIGURE 3. From photographs of a museum exhibit to a 3D-printed product in hand. Innovation and cost reduction of photogrammetry can assist museum visitors in making 3D digital models based on photographs taken in the exhibition hall without breaking museum policies and allow them to publish these to sharing platforms. Illustrated by Hayanon, Hayanon's Science Manga Studio (https://www.hayanon.jp/).

485 **Table 1** Policies about photography in major natural history museums worldwide.

486

MUSEUM NAME	PERSONAL USE	NON-COMMERCIAL USE	COMMERCIAL USE	SECONDARY USE	NUMBER OF VISITORS (2019)	REFERENCES
American Museum of Natural History, USA	Permitted	Application required	Restricted	Restricted	5,000,000	American Museum of Natural History (2020), Rubin (2019)
National Museum of Natural History, Smithsonian Institution, USA	Permitted	Permitted	Application required	Not mentioned	4,200,000	National Museum of Natural History, (2017, 2020), Rubin (2019)
Royal Tyrrell Museum, Canada	Permitted	Permitted	Application required	Not mentioned	1,300,000	Royal Tyrell Museum (2020), Royal Tyrell Museum (2020b)
The Natural History Museum, UK	Permitted	Application required and/or Charge required	Application required	Not mentioned	5,424,000	The Natural History Museum (2020a, 2020b), Rubin (2019)
MUSÉUM NATIONAL D'HISTOIRE NATURELLE, France	Permitted	Application required and/or Charge required	Charge required	Not mentioned	3,325,000	Muséum national d'Histoire naturelle (2020a, 2020b, 2020c)
Museum Für Naturkunde, Germany	Permitted	Permitted	Charge required	Not mentioned	737,000	The Museum für Naturkunde (2020), Museu

						m für Naturkunde Berlin (2020)
National Museum Of Natural History, Tokyo, Japan	Permitted	Application required	Charge required	Application required	2,460,000	National Museum of Nature and Science (2020a, 2020b), Rubin (2019)
MUSEUM OF NEW ZEALAND TE PAPA TONGAREWA	Permitted	Permitted	Application required	Not mentioned	1,548,000	Museum of New Zealand Te Papa Tongarewa, (2019, 2021a, b)

487

488