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ARTICLE

3D Scanning to Enable 3D Printing in Ergonomics Projects

Escaneo en 3D para factibilizar la impresión 3D en proyectos de ergonomía

Josean L. **Vega-Feliciano**[1], Angelica P. **Vera-Torres**[2], Natalia A. **Rodriguez-Figueroa**[3]
Zairelys A. **Reyes-Rivera**[4], Clara E. **Isaza**[5], Mauricio **Cabrera-Ríos**[6]

[1]Universidad de Puerto Rico, PUERTO RICO
Recinto de Mayagüez, Industrial Engineering Department, The Applied Optimization Group
ORCID: 0000-0002-8383-4726 | josean.vega1@upr.edu
[2]Universidad de Puerto Rico, PUERTO RICO
Recinto de Mayagüez, Industrial Engineering Department, The Applied Optimization Group
ORCID: 0000-0003-4389-5556 | angelica.vera@upr.edu
[3]Universidad de Puerto Rico, PUERTO RICO
Recinto de Mayagüez, Industrial Engineering Department, The Applied Optimization Group
ORCID: 0000-0002-2104-7698 | natalia.rodriguez55@upr.edu
[4]University of Puerto Rico, PUERTO RICO
Industrial Engineering Department, The Applied Optimization Group
ORCID: 0000-0002-9737-808X | zairelys.reyes@upr.edu
[5]Universidad de Puerto Rico, PUERTO RICO
Recinto de Mayagüez, Biology Department, The Applied Optimization Group
ORCID: 0000-0001-5399-2566 | clara.isaza@upr.edu
[6]Universidad de Puerto Rico, PUERTO RICO
Recinto de Mayagüez, Industrial Engineering Department, The Applied Optimization Group
ORCID: 0000-0002-2845-7147 | mauricio.cabrera1@upr.edu

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Abstract

3D Printing is an ideal technology to support prototyping and invention. Its possibilities are, however, limited by the user's computer-aided modeling skills. Ergonomics would greatly enhance its practice with the adoption of the prototyping capabilities of 3D printers. For this to happen, Industrial Engineers who specialize in Ergonomics must adopt computer-aided modeling courses better suited to this end. Because curriculum modifications usually take a long time in colleges and universities to reflect a change of such nature, this work proposes the use of 3D Scanning to circumvent some of the difficulties in modeling and enable a more direct access to 3D Printing. The possibilities of this conjunction are demonstrated through the scanning and subsequent 3D printing of a human ear and a human skull.

Index terms: 3DPrinting, 3D Scanning, Ergonomics, Human Body Parts, Industrial Engineering

Resumen

La impresión 3D es una tecnología ideal para apoyar las actividades de invención y prototipaje. Sus posibilidades están limitadas, sin embargo, por las habilidades de modelación por computadora del usuario la ergonomía es un área que se beneficiaría con la adopción de las capacidades de prototipaje que ofrece la impresión 3D. Para que esto suceda, los ingenieros industriales especializados en ergonomía deben adoptar cursos de modelación por computadora más adecuados para este fin. Dado que la modificación de planes de estudio toma un tiempo muy largo en las universidades para reflejar un cambio de esta naturaleza, este trabajo propone el uso de escaneo 3D para cubrir algunas de las dificultades de modelación y facilitar así el acceso a la impresión 3D. El potencial de esta conjunción se demuestra aquí en el escaneo y la impresión 3D de los modelos de una oreja y un cráneo humanos.

Palabras clave: impresión 3D, escaneo 3D, ergonomía, partes del cuerpo humano, ingeniería industrial

I. INTRODUCTION

Additive Manufacturing has become an important part of the so-called industrial revolution 4.0 [1]. In consonance with this trend, the introduction of 3D printing in Engineering curricula is a critical step that all Engineering fields related to fabrication and construction must consider taking. This dynamic provides a valuable opportunity for Industrial Engineers (IEs) to get reacquainted with prototyping and manufacturing [2]. 3D Printing is a process that creates physical objects from a digital model by adding material in a layer-by-layer fashion. The creation of the digital model, with roots in traditional mechanical modeling, is now a computer-aided skill mostly incorporated into Mechanical Engineering curricula. IEs need this modeling skill to capitalize on 3D printing as a prototyping method [3]. Ergonomics in particular, one of the IE subfields, would greatly benefit from the adoption of 3D Printing. As the area of knowledge concerned with the interaction between humans and their diverse environments, the possibility of translating ideas into functional prototypes faster can be a great asset.

Traditionally, curriculum development is a lengthy process in colleges and universities; therefore, it is important to pursue a parallel effort to enable the adoption of 3D Printing in Industrial Engineering. With this in mind, this paper proposes the use of 3D scanning to enable the access to 3D Printing. 3D scanning captures the external shape of an object in digital form through the assembly of a set of electronic images of such object. In healthcare, it has been shown that 3D Scanning can be used to support the creation of implants and prosthetics as well as anatomic models for training purposes, among several other possibilities [4]. In the same field, 3D Printing has been used to manufacture not only the former [5] but also -with a higher level of sophistication- to replicate biological tissue [6]. Healthcare, then, provides proof of the capabilities that can be transferred to ergonomics if the dyad modeling-printing is fostered in the training of IEs.

This work seeks to demonstrate the plausibility of the idea of 3D scanning to enable 3D printing using two applications carried out by IE undergraduate students. The path of improvement on each application is included in qualitative terms in the narrative, as it is considered of value to potential practitioners looking to replicate a similar effort. The hypothesis is that creating a 3D printout of a complex human body part can be made feasible through cost-effective 3D scanning at a competitive resolution. In testing this hypothesis, an alternative to accelerate the immersion of Engineering students to 3D Printing and enhance their training in ergonomics shall become apparent.

II. METHODOLOGY

Two development phases are recognized in this work: (i) learning and (ii) testing. The total time took about one year, starting from just the basic idea. After the protocol was developed, the next projects took less than one month to result in workable prototypes. In the first phase, learning, it was necessary for the students to get acquainted with the 3D printer and select a suitable, affordable, 3D scanner. The 3D Printer is a MakerBot Replicator 2, shown in Figure 1 [7], and the 3D Scanner was a mobile app called Trnio [8], which had shown promising results in preliminary tests using an iPhone. The second phase, testing, was an iterative one where variations on materials, parameters, scanning conditions -among others- were essayed to obtain a feasible protocol for scanning and printing.

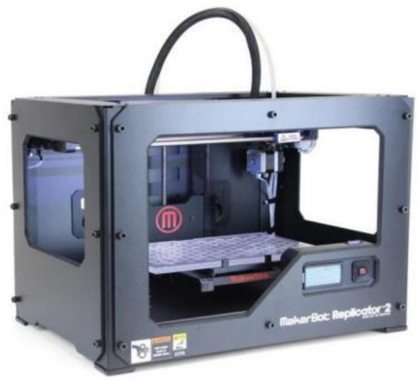

Fig. 1. MakerBot Replicator 2 3D Printer.

III. LEARNING EARNING PHASE

A human ear has a well-known complicated yet purposeful shape [9], [10]. Modeling it from scratch would require a considerable amount of skill. For these reasons, reproducing the shape of an ear was chosen as the first challenge. One of the students was the subject for scanning. It was recognized that variations on the scanning distance from the phone to the subject could have an effect on the images' quality, so to minimize this effect the phone was tied to a cord to maintain a constant radial distance. A total of six runs were executed sequentially as detailed in Table 1 and Figure 2. A general description of the scanning procedure used in the learning phase and the subsequent testing phase is presented in Appendix A.

Following Table 1, two types of filament material were used: (1) Polylactic Acid (PLA), which is rigid, and (2) Thermoplastic Polyurethane (TPU), which is flexible. This selection obeys to the variety of requirements in ergonomics endeavors, where sometimes rigidity is required -as in bone modeling- and other times, flexibility is required -as in tissue modeling-. Furthermore, a particular application might demand a combination of both properties. Indeed, PLA and TPU were used by themselves and, in the last two runs, combined to create a composite that capitalizes in their respective properties. In Figure 2, PLA is shown in white and TPU in green. Because 3D printing is a layer-by-layer material deposition process, the support for irregular shapes must be printed out simultaneously with the desired part and removed afterwards. This has important implications for the decision to either start printing out in one direction or another. In this case, the two positions essayed were termed "horizontally" or "vertically". The former refers to begin the process layering across the largest dimension of the ear (length), and the latter layering across its smallest dimension (width). The next to last column in Table 1 shows the relevant settings for the 3D Printer. In runs 1 thru 5 the settings were set as default by the manufacturer, a state that can be achieved by resetting the machine before a particular run. The only different setting was that of run 6, where infill was increased by 15%, looking for a more stable structure. The same effect was sought in runs 3 and 4 by augmenting the size of the printed object by 15%. Finally, the last column of Table 1 offers the key learnings on each run leading to the best results, which were achieved through the combined use of the different filament materials (runs 5 and 6).Success in the composite configuration had to do with using the rigid material first to build the support to then use the flexible material to build the actual ear. Although it is clear that no optimality can be claimed in this set of tests, the first aim here was feasibility: replicating an ear shape faithfully by 3D Printing based on 3D scanning. To this end, this series of learning runs were deemed successful. The implications to this point are that an intricate shape such as a human ear can be replicated to serve in ergonomics studies such as design of implants, design of objects that go in or around the human ear, or testing noise cancelling features, among many others.

TABLE 1
SIX RUNS IN THE LEARNING PHASE.

Run	Object	Filament Material	Position	Printer settings	Key learning/Observations
1	Human Ear	Flexible TPU	Horizontally	Default	Material is not strong enough to support the entire printout.
2	Human Ear	Rigid PLA	Horizontally	Default	No sufficient detail in ear's inner area due to printing position
3	Human Ear	Rigid PLA	Vertically	Default but object size was amplified	Vertical position and object size amplification result in a competitive configuration.
4	Human Ear	Flexible TPU	Vertically	Default but object size was amplified	Lost its precision resulting in irregularities and flexible material leaves hollow spots on the inside of the shell.
5	Human Ear	Composite PLA/TPU	Horizontally	Default	Composite material results in the best printout thus far.
6	Human Ear	Composite PLA/TPU	Vertically	Infill was increased by 15%	Vertical position allowed the support to reach the top of the ear. Equally as good as run 5.

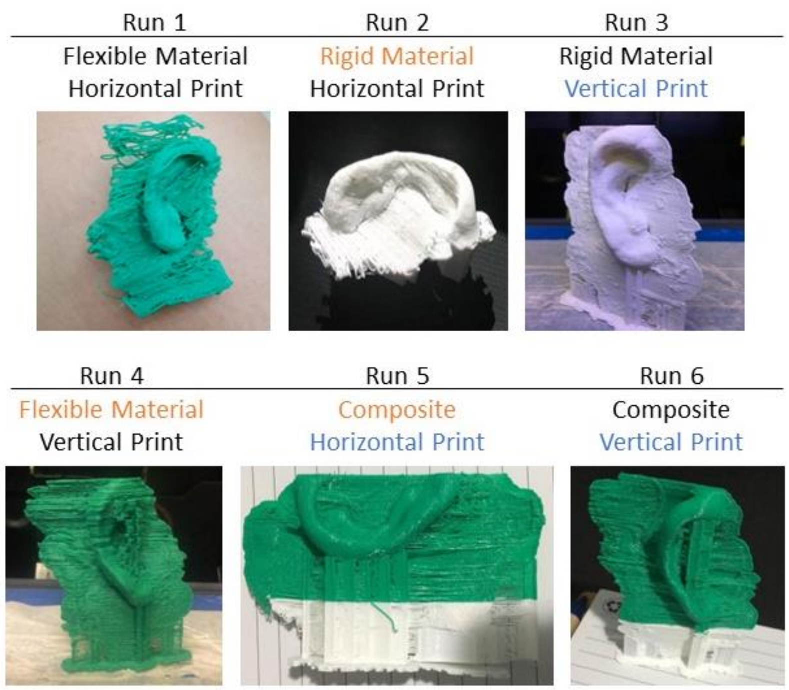

Fig. 2. Experimental runs in the learning phase. Changes on each run are indicated by the use of color: orange for material, blue for printing orientation.

IV. TESTING PHASE

With the learnings from the previous phase, it was decided to approach the replication of a human skull. This project is more challenging for scanning purposes, since it requires a higher level of detail fidelity including hollow features. A teaching model already existing in the ergonomics laboratory of our department (Figure 3), was used as the subject to be scanned.

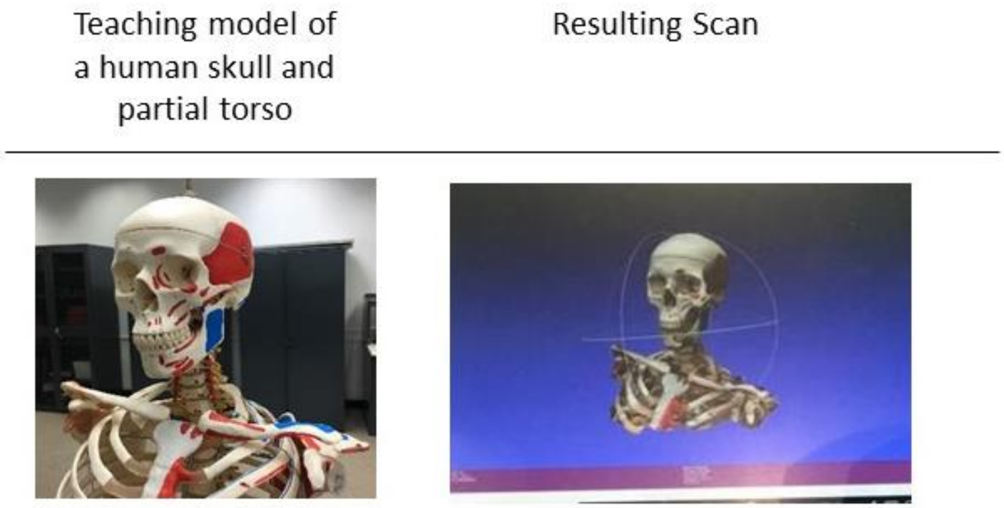

Fig. 3. The teaching model of a human skeleton (selected features) and the resulting scan.

The teaching model was placed under direct artificial lighting (white light), and two rounds of complete scanning were performed to capture all details. The resulting scan is also shown in Figure 3. The default settings were used for 3D printing using PLA filament to outcome a rigid prototype. Table 2 details the runs executed to result in a satisfactory printout.

TABLE 2
THREE RUNS IN THE TESTING PHASE.

Run	Object	Filament Material	Position	Printer settings	Key learning
1	Skull Model	PLA	Vertically	Default	3D Scan was not detailed enough.
2	Skull Model	PLA	Vertically	Default but object size was amplified 50%	Size too big for the printer.
3	Skull Model	PLA	Vertically	Default, three scanning rounds	The more scanning rounds, the better results.

The first run was considered satisfactory, but it lacked enough details in the printed features. The second run was an attempt to correct that by increasing the size 50%. This second run proved successful in providing better details, but exceeded the printing dimensions of the 3D printer. Thus, the third run needed to add more details while keeping the size feasible. It was decided, then, to try to improve detailing thru the scanning process by adding one round for a total of three. This additional round provided a better quality of details that transferred to the actual printing, as it can be appreciated in Figure 4.

Fig. 4. Experimental runs in the testing phase. Run 1 is shown to the left, followed by run 2 in the middle, and run 3 is to the right, in brown.

Figure 5 shows a side-by-side comparison of the original object and the 3D Scan-Print reproduction for the reader to assess the level of fidelity. Do note, however, that the actual model is smaller in this case. The testing phase lasted considerably less time than the learning phase, expectedly. It becomes clear that having a model in short time enables design innovation and evaluation of ideas, thereby completing a powerful pipeline for ergonomics projects.

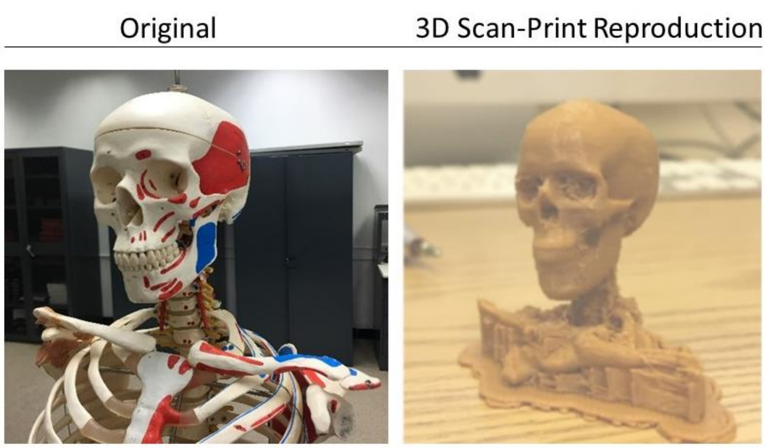

Fig. 5. Side-by-side comparison of original object and the 3D Scan-Print reproduction.

V. Conclusion

Technologies with the potential to enhance the practice of a field must find their way to thoughtful evaluation for adoption. Ergonomics -as a subfield of Industrial Engineering- can benefit from the adoption of Additive Manufacturing, and in particular of 3D printing to take ideas from inception to prototyping and, in the best case, to production. 3D printing, however, requires a high expertise level in mechanical modeling of 3D objects, not necessarily available to all Engineering fields. In this manuscript, 3D Scanning is proposed as an alternative to modeling 3D objects from scratch. The work discussed here shows how students from Industrial Engineering can enhance their ergonomics training by adopting 3D Scanning. The possibility of having the physical prototype of an idea in short time is indeed an important addition to the field that can be implemented faster than the necessary curriculum modifications, which will require longer times. It is clear that different combinations of resources (3D Printers, mobile apps, subjects, materials, training in Mechanical Modeling) can improve the results beyond the feasibility point achieved in this work. Formal experimental design and mathematical optimization are recommended in the future to such end.

References

[1] U. M. Dilberoglu, B. Gharehpapagh, U. Yaman, M. Dolen, "The Role of Additive Manufacturing in the Era of Industry 4.0," *Procedia Manufacturing*, vol. 11, pp. 545–554, 2017, doi: https://doi.org/10.1016/j.promfg.2017.07.148

[2] T. W. Simpson, C. B. Williams, M. Hripko, "Preparing industry for additive manufacturing and its applications: Summary & recommendations from a National Science Foundation workshop," *Additive Manufacturing*, vol. 13, pp. 166–178, Jan. 2017, doi: https://doi.org/10.1016/J.ADDMA.2016.08.002

[3] S. M. Villanueva-Pérez et al., "Reintroducing Industrial Engineering Students to Manufacturing through Environmental Pertinence," *Científica*, vol. 25, no. 1, pp. 47–53, 2021, doi: https://doi.org/10.46842/ipn.cien.v25n1a04

[4] A. Haleem, M. Javaid, "3D scanning applications in medical field: A literature-based review," *Clinical Epidemiology and Global Health*, vol. 7, no. 2, pp. 199–210, Jun. 2019, doi: https://doi.org/10.1016/J.CEGH.2018.05.006

[5] H. Dodziuk, "Applications of 3D printing in healthcare," *Kardiochirurgia i Torakochirurgia Polska, Journal of Cardio-Thoracic Surgery*, vol. 13, no. 3, p. 283, 2016, doi: https://doi.org/10.5114/KITP.2016.62625

[6] TRNIO, "Trnio 3D Scanner", 2022, https://www.trnio.com/ (accessed May 22, 2022).

[7] All3DP, "The Best 3D Scanner Apps of 2022 (iPhone & Android) | All3DP", 2022, https://all3dp.com/2/best-3d-scanner-app-iphone-android-photogrammetry/ (accessed Jun. 05, 2022).

[8] Makerbot, "MakerBot ® Replicator TM 2", 2022, https://www.makerbot.com/es/3d-printers/replicator/

[9] G. Gomez, M. Baeza, J.C. Mateos, J.A. Rivas, F.J.L. Simon, D.M. Ortega, M. de los Ángeles, E.R. Del Campo, T. Gómez, J.L.L Guerra, "A three-dimensional printed customized bolus: adapting to the shape of the outer ear," *Reports of Practical Oncology and Radiotherapy*, vol. 26, no. 2, p.211, 2021, doi: https://doi.org/10.5603/RPOR.a2021.0030

[10] W. Lee, H. Jung, I. Bok, C. Kim, O. Kwon, T. Choi, H. You, "Measurement and Application of 3D Ear Images for Earphone Design," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 60, no. 1, p. 1053, 2016, doi: https://doi.org/10.1177/1541931213601244

APPENDIX A – *General scanning procedure in the present work*

Scanning can be understood as a system, where the inputs are the subject to be scanned and the mobile device loaded with the scanning app. The process is one where the mobile device is moved around the subject to capture as many details as possible. The output is a series of scans that are merged into a 3D model. For clarity, figure A1 illustrates the scanning process used in this study.

With these elements in place, there are controllable factors that immediately arise: illumination, angle of scanning with respect to subject, scanning distance to subject, trajectory of scanning device, position of the subject, and parameters associated to the scanning application.

In the scanning process, it is also expected to have non-controllable variables such as the initial quality of the subject, unintended variation produced during the scanning procedure, fluctuations in illumination or temperature, among many others. The response of interest is the quality of the resulting 3D model. This quality can be assessed qualitatively or quantitatively.

In the applications described in this work, it was decided to fix the mobile scanning device using a cord. The aim was to sufficiently control scanning distance, angle, and reduce scanning speed variation. In addition, the room with maximum indoor lighting available to us was selected to positively affect scanning. The scanning path was set radially using the mobile scanner tied up to the cord. At least two passes along the chosen scanning path were carried out. The larger the number the passes, the better quality of the 3D model, but also the more digital memory required.

In the series of tests described in this manuscript, the final 3D models were assessed through superimposition over the original subject´s image, qualitatively seeking for a satisfactory resemblance.

The results of the work described in this manuscript demonstrate the feasibility of this procedure, however, with larger resources it is possible to reduce the variance and undertake a formal optimization of the entire process.

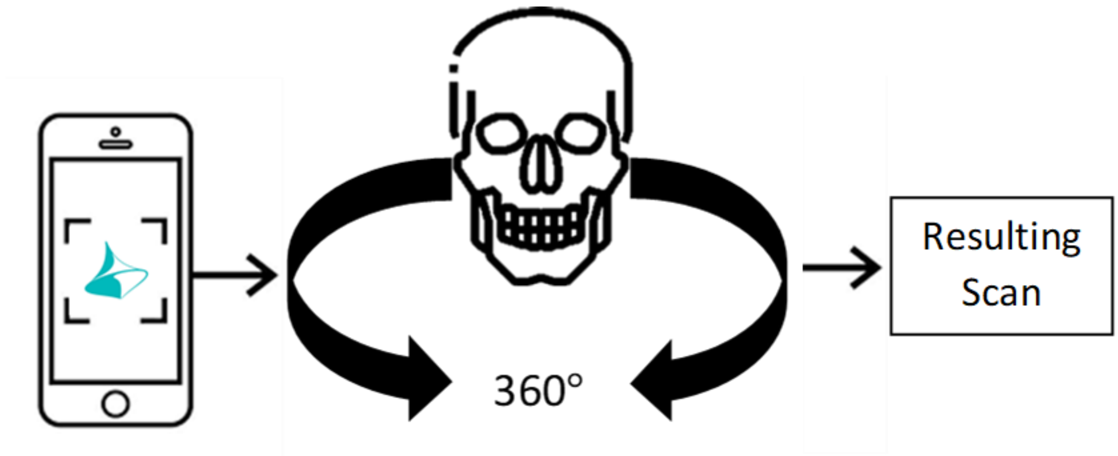

Fig. A1. Scanning process illustration.