Effect of process parameters to flexural strength of 3D printed anatomical bone part

T Tajarernmuang1,2,a, C Sawangrat3,b, and S Jomjunyong3,c

1Biomedical Engineering Institute, Chiang Mai University, Chiang Mai, 50200, Thailand
2Graduate School, Chiang Mai University, Chiang Mai, 50200, Thailand
3Department of Industrial Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, 50200, Thailand

*aCorresponding author e-mail: bchoncharoen@eng.cmu.ac.th,
tanapong.tajarernmuang@gmail.com, sermkiatf@gmail.com

Abstract. Training and practice on synthetic anatomical bone before perform real medical operation is useful and recently become part of medical procedure. Since there are various factors to considered, the attempt to imitate anatomical bone from medical image data of patient, using technology that based on Fused Deposition Modelling (FDM) is alternatively developed. Since durability and qualities of 3D printed model depend on process parameters which referred to 3D printer setting, this study aims to investigate effect of essential 3D printer setting parameters involve with mechanical properties of 3D printed anatomical bone part, focused on infill density and layer height, and determine regression model for mechanical strength prediction from selected printing parameters by using experimental design and statistical analysis that based on Design of Experiments (DOE). 2-levelled full factorial experiment was designed, 3 factors including layer height, infill density, and print speed were taken into account. After that, selected 27 Mid-section of femur bone from 3D medical image data were fabricated from filament of Poly-lactic acid (PLA). The models were underwent a three-point bending testing to investigate mechanical properties and statistical analyse to investigate the relationship of parameters.

1. Introduction
For medical student, training and practice on synthetic anatomical bone before perform real medical operation is useful and recently become part of medical procedure. [1-3]. Thus, the attempt to fabricate solid 3D anatomical model from medical image data of patient using a technology based on Fused Deposition Modeling (FDM) is alternatively developed [4]. FDM is one of additive manufacturing trends that work based on a layer-by-layer fabrication basis [5-7]. According to working principle, printing material for FDM must be able to liquefy above certain temperature and solidify upon cooling, for example, metal and thermoplastic polymer [8, 9]. The fabrication process of 3D printed anatomical model typically consists of several sequences [10, 11]; however, the quality and durability of model is mostly depended on 3D printer setting parameter adjustment [12, 13]. When focused on basic 3D printer setting, Infill density is a setting that determines a percent of material filling inside, layer height determine thickness of outer layer, and print speed was a speed of moving nozzle head. All of them consequently influence strength of an entire 3D printing model [13, 14]. However, geometric detail on
Each bone is different, resulting in varied mechanical properties of the 3D printed final product [12, 15]. Thus, the investigation of mechanical properties of bone-shape 3D printed model is required. Regarding the development of 3D printed anatomical bone, this study aims to investigate the effect and relationship between mechanical strength of anatomical model to withstand given load from transverse direction, referred to flexural strength, and process parameters, consisting of 3 parameters; layer height, infill density, and print speed, for additional information of 3D printed anatomical model and related study.

2. Materials and Methods

In this study, the experimental method was consisted of 3 part; test specimen preparation, design of experiment, and mechanical testing.

2.1. Test specimen preparation

Medical imaging data of mid-shaft of human left femur (size 33x52x150 mm) from Computer Tomography (CT) scan was selected from open-source digital library. After image segmenting, test specimens related to number of observation were fabricated in vertical direction. In addition, summary of 3D printer setting were represented in Table 1. The 3D printer was based on FDM and printing material in this study was focused on filament of PLA.

| Process parameter                  | Value          |
|------------------------------------|----------------|
| Nozzle temperature (°C)            | 210            |
| Bed temperature (°C)               | 60             |
| Printing orientation               | Triangle       |
| Infill density (%)                 | 40, 60, 80     |
| Layer height (mm)                  | 0.2, 0.15, 0.1 |
| Print speed (mm/s)                 | 50, 75, 100    |
| Wall thickness (mm)                | 1.2            |

2.2. Design of experiment

2-levelled full factorial experimental design, considering 3 factors; infill density, layer height, and print speed was selected. Each experimental runs was repeated 3 times.

2.3. Mechanical testing

3-point bending test was conducted by Instron5566 (0.2 mm/s head-cross speed, 10kN load). This study considered that shape of 3D printed model was identical to bone [16]. Thus, the equations based on beam theory that follow related study [17] consisted of bending moment, flexural stress, flexural strain, and flexural modulus were applied and calculated accordingly to equation 1, 2, 3, and 4

\[
M = \frac{FL}{4} \quad (1)
\]

\[
\sigma = \frac{Mc}{I} \quad (2)
\]

\[
\varepsilon = \frac{12c}{L^2} \cdot \Delta \quad (3)
\]

\[
E = \frac{\sigma}{\varepsilon} \quad (4)
\]

Where F is applied load, L is the distance between two bottom support (100 mm), c is a distance of the chosen point from neutral axis, I is the cross-sectional moment of inertia based on the geometric
entity \( c \) and \( I \) are 52.92 mm. and 175385.1 g/mm\(^2\), respectively, \( \Delta \) is the vertical displacement at the point of load application.

2.4. Statistical analysis
After mechanical properties were calculated, Analysis of Variance (ANOVA) from software Minitab16 was used to analyze interaction of the process parameters.

3. Results and Discussion
Test specimens of 3D printed anatomical bone were fabricated as represented in Figure 1 relation to the full factorial experiment designed from Minitab2.

![Figure 1. Test specimens of 3D printed anatomical bone](image)

After testing, mechanical properties including flexural strength and Flexural modulus were represented in Table 2 and the statistical data was represented in Table 3.

| Infill density (%) | Group | Layer height (mm) | Speed (mm/s) | Flexural strength Mean (MPa) | STD | Flexural modulus Mean (MPa) | STD |
|-------------------|-------|------------------|--------------|-----------------------------|-----|-----------------------------|-----|
| 40                | 0.10  | 50               |              | 34.67                       | 2.13| 136.87                      | 13.04|
| 40                | 0.10  | 100              |              | 13.85                       | 0.34| 90.99                       | 7.95 |
| 40                | 0.20  | 50               |              | 14.53                       | 1.25| 38.74                       | 1.52 |
| 40                | 0.20  | 100              |              | 14.95                       | 5.13| 56.37                       | 39.22|
| 60                | 0.15  | 75               |              | 30.78                       | 0.72| 107.28                      | 1.06 |
| 80                | 0.10  | 50               |              | 36.88                       | 3.26| 125.94                      | 6.60 |
| 80                | 0.10  | 100              |              | 29.50                       | 0.07| 181.87                      | 16.79|
| 80                | 0.20  | 50               |              | 26.60                       | 0.73| 105.82                      | 3.76 |
| 80                | 0.20  | 100              |              | 21.63                       | 8.94| 165.10                      | 13.68|

| Source                              | DF | Seq. SS | Adj. SS | Adj. MS | F-value | P-value |
|-------------------------------------|----|---------|---------|---------|---------|---------|
| Main effect                         | 3  | 1478.73 | 1478.73 | 492.909 | 33.27   | 0.000   |
| Infill density                      | 1  | 490.36  | 490.36  | 490.364 | 33.09   | 0.000   |
| Layer height                        | 1  | 506.89  | 506.89  | 506.886 | 34.21   | 0.000   |
| Print speed                         | 1  | 481.48  | 481.48  | 481.476 | 32.49   | 0.000   |
| 2-ways interactions                 | 3  | 278.00  | 278.00  | 92.665  | 6.25    | 0.004   |
| Infill density*Layer height          | 1  | 0.67    | 0.67    | 0.665   | 0.04    | 0.835   |

3
In Figure 2(a), infill density (factor A) possess positive standardized effect meanwhile layer height (factor B) and print speed (factor C) possess negative standardized effect, in which clarified that when increase in infill density, decrease in layer height and print speed, maximum flexural strength was higher. The result was also in agreement with related study [14]. In Figure 2(b), the points of observation data were dispersed linearly in normal probability plot and were dispersed randomly in residual versus fits and residual versus order plots, these patterns showed that the parameters were normal and independent distribution. Accordingly, the regression model of 3 process parameters including infill density, layer height, and print speed could be described as

\[ Y = 24.022 + 4.520X_1 - 4.596X_2 - 4.479X_3 + 0.167X_1X_2 + 0.620X_1X_3 + 3.342X_2X_3 + 1.967X_1X_2X_3 \]

When \( X_1 \) is infill density, \( X_2 \) is layer height, and \( X_3 \) is print speed.

After 3-point bending test, the sample specimens were dissected and scanning electrons microscope (SEMs) was used to observe the difference of fracture between each group. In Figure 3, traces of transgranular fracture were seen in all groups of specimen. Rough fracture scars were seen in specimens with 40% infill density, 0.2 mm layer height and 100 mm/s print speed. The scars were slightly small when observe in high infill density, higher layer height, and low print speed. According to size of crack, outer layer or first layer of wall thickness of all specimens was affected from external force the most, and then the pattern of fracture changed in next layers. These behaviors corresponded to characteristic of thermoplastic material [18] that the model become more brittle when increase infill density, increase print speed or decrease layer height. Thus, when brittle model receive external force
from transverse side, a little rough scar was occurred on the fractured surface. More brittle specimens also related to higher flexural modulus from the result of 3-point bending test as well. In addition, inner layer of specimen contacted with many support structures that referred to triangle infill pattern in this study. When a number of support structures inside were increased due to high infill density setting, the received force could be good transferred through the contact area, resulting in several small cracks occurred through the layer.

Figure 3. Fracture surfaces of 3D printed specimens with 40% infill density, 0.1 mm layer height and 50 mm/s print speed (a), 40% infill density, 0.2 mm layer height and 50 mm/s print speed (b), 40% infill density, 0.2 mm layer height and 100 mm/s print speed (c), 60% infill density, 0.15 mm layer height and 75 mm/s print speed (d), 80% infill density, 0.2 mm layer height and 50 mm/s print speed (e), and 80% infill density, 0.2 mm layer height and 100 mm/s print speed (f)

Since 3D printed anatomical bone model typically use with bone saw and bone drill to perform medical training such as testing bone fixator [19, 20], when use a high infill density, the model will become too stiff that the machine is not able to cut or break. However, when use a low infill density, large cracks would be occurred and the fixator would be failed to attach the 3D printed model. Thus, using moderate infill setting and focus on the other setting should prevent the rough large fracture that lead to a low tolerance 3D printed model.

4. Conclusions
This study presented the investigation of effect and relationship of process parameters including layer height, infill density, and print speed to flexural strength of 3D printed anatomical models. The result revealed that when layer height and print speed setting were decreased and infill density setting was increased, average maximum flexural strength and flexural modulus were higher relatively and the model also represented more brittleness characteristic. The author suggested that further progressive studies such as reinforced printing material development or analytical mathematic model should be considered.

Acknowledgment
The author would like to express gratitude to Asst. Prof. Dr. Dumnoensun Pruksakorn from Department of Orthopedic, Faculty of Medicine, Chiang Mai University, for his advice and guidance, to Graduate School, Chiang Mai University and Biomedical Engineering Institute, Chiang Mai University, for facility support.

References
[1] Berman, B. (2012). 3-D printing: The new industrial revolution. Business Horizons, 55(2), 155-162.
[2] Azer, S. A., and Azer, S. (2016). 3D Anatomy Models and Impact on Learning: A Review of the Quality of the Literature. *Health Professions Education*, 2(2), 80-89.

[3] AbouHashem, Y., Dayal, M., Savanah, S., and Štrkalj, G. (2015). The application of 3D printing in anatomy education. *Medical Education Online*, 20, 10.3402/meo.v3420.29847.

[4] Smith, M. L., and Jones, J. F. X. (2017). Dual-Extrusion 3D Printing of Anatomical Models for Education. *Anat Sci Educ.*

[5] Cui, X., Boland, T., D’Lima, D. D., and Lotz, M. K. (2012). Thermal inkjet printing in tissue engineering and regenerative medicine. *Recent Pat Drug Deliv Formul*, 6(2), 149-155.

[6] Hoy, M. B. (2013). 3D printing: making things at the library. *Med Ref Serv Q.*, 32(1), 94-99.

[7] Zhai, Y., Lados, D., and Lagoy, J. (2014). Additive Manufacturing: Making Imagination the Major Limitation (Vol. 66).

[8] Lim, L. T., Auras, R., and Rubino, M. (2008). Processing technologies for poly(lactic acid). *Progress in Polymer Science*, 33(8), 820-852.

[9] Hwang, S., Reyes, E., Moon, K.-s., Rumpf, R., and Kim, N. (2015). Thermo-mechanical Characterization of Metal/Polymer Composite Filaments and Printing Parameter Study for Fused Deposition Modeling in the 3D Printing Process. *Journal of Electronic Materials*, 44(3), 771-777.

[10] Mitsouras, D., Liacouras, P., Imanzadeh, A., Giannopoulos, A. A., Cai, T., Kumamaru, K. K., and Rybicki, F. J. (2015). Medical 3D Printing for the Radiologist. *Radiographics*, 35(7), 1965-1988.

[11] Wang, C.-S., Wang, W.-H. A., and Lin, M.-C. (2010). STL rapid prototyping bio-CAD model for CT medical image segmentation. *Computers in Industry*, 61(3), 187-197.

[12] Sood, A. K., Ohdar, R. K., and Mahapatra, S. S. (2010). Parametric appraisal of mechanical property of fused deposition modelling processed parts. *Materials & Design*, 31(1), 287-295.

[13] Luzanin, O., Movrin, D., and Plancak, M. (2014). Effect of layer thickness, deposition angle, and infill on maximum flexural force in FDM-built specimens (Vol. 39).

[14] Fernandez-vicente, M., Calle, W., Ferrándiz, S., and Conejero, A. (2016). Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing (Vol. 3).

[15] Lee, C. S., Kim, S. G., Kim, H. J., and Ahn, S. H. (2007). Measurement of anisotropic compressive strength of rapid prototyping parts. *Journal of Materials Processing Technology*, 187-188, 627-630.

[16] Oksztulska-Kolanek, E., Znorko, B., Michalowska, M., and Pawlak, K. (2016). The Biomechanical Testing for the Assessment of Bone Quality in an Experimental Model of Chronic Kidney Disease. *Nephron*, 132(1), 51-58.

[17] Sharir, A., Barak, M. M., and Shahar, R. (2008). Whole bone mechanics and mechanical testing. *The Veterinary Journal*, 177(1), 8-17.

[18] Ashby, M. F. (2011). Chapter 4 - Material Property Charts *Materials Selection in Mechanical Design (Fourth Edition)* (pp. 57-96). Oxford: Butterworth-Heinemann.

[19] Elfar, J., Menorca, R. M., Reed, J. D., and Stanbury, S. (2014). Composite bone models in orthopaedic surgery research and education. *J Am Acad Orthop Surg*, 22(2), 111-120.

[20] Lin, H.-H., Lonic, D., and Lo, L.-J. (2018). 3D printing in orthognathic surgery – A literature review. *Journal of the Formosan Medical Association*, 117(7), 547-558.