Development and Analysis of Three-Dimensional Printed Hand Cast: Finite Element and Comfortability Analysis

A U A Aziz\textsuperscript{1,2}, N A Yassin\textsuperscript{1,2}, G H Seng\textsuperscript{3}, and M H Ramlee\textsuperscript{1,2*}

\textsuperscript{1}Medical Devices and Technology Centre (MEDITEC), Institute of Human Centered Engineering (iHumEn), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
\textsuperscript{2}Bioinspired Devices and Tissue Engineering (BIOINSPIRA) Research Group, School of Biomedical Engineering & Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
\textsuperscript{3}British Malaysia Institute (BMI), Universiti Kuala Lumpur (UniKL), Batu 8, Jalan Sungai Pusu, 53100 Gombak, Selangor, Malaysia

\*muhammad.hanif.ramlee@biomedical.utm.my

Abstract. Bone fracture treatment aims for restoring the function of a broken bone, and for scaphoid fracture, the conventional cast is an example of commonly used treatment. However, due to its downsides, the development of customized three-dimensional (3D) printed hand cast is getting more attention. It is lightweight, easy to manage, has good ventilation and hygienic properties. Hence, this study aims to fabricate customized 3D printed hand cast in treating scaphoid fracture. Three designs were made and analysed accordingly based on three different tests, including Finite Element Analysis (FEA), comfortability, and clinical effectiveness test. Design 2 was chosen as the best design as it produced lower stress and displacement in FEA and higher total mean score for clinical effectiveness. In conclusion, the fabricated casts were proven to help in restoring the broken bone besides providing comfort to the patient.

1. Introduction
Scaphoid is an obliquely oriented bone located on the radial side of the wrist, and significantly contributing to the wrist stability and biomechanical function [1]. Fracture of the scaphoid bone is common among carpal bone fractures [2] with statistic of approximately 12 per 10 000 in the population as a whole [3]. It includes proximal fracture, middle fracture, and distal fracture (distal tubercle and distal articular surface fracture) [4]. A scaphoid fracture may result in two situations which are displaced and nondisplaced fracture. For displaced bone fracture, surgery treatment is needed through the fixation and plaster cast whereas, for nondisplaced fracture, usage of plaster cast has been the treatment of choice [5, 6] where the healing will take about 4 to 6 weeks or more depending on the fracture acuteness [7].

In medical practice, the conventional method of casting are splint and cast. Both methods help in sustaining the surrounding joint as well as reducing the swelling at the fracture area. The materials used for the treatments are plaster and fiberglass. Splinting and casting are two different methods in restoring the function of the fractured bone [8]. Splinting is not as hard as casting. It is easier for the injury site inspection. However, the fractured bone is not totally immobilized. There could be motion at the fractured area and hence, affecting the healing time of the broken bone [8, 9]. On the contrary, the
application of casting is to give full immobilization to the area of the fracture. Casting takes a longer
time to be applied to the patients. Even though it provides extreme immobilization, casting also has its
disadvantages including thermal injuries, ventilation problems, swelling, joint stiffness, and skin
infection [9, 10]. A 3D printed hand casting is an alternative way to escape from the conventional hand
cast that is not so comfortable for the patient. It aims in providing comfortability to the patient through
good ventilation, and reducing skin infection risk, but at the same time, it still assists the healing process
[11].

Research had been conducted to investigate how the patients react toward this technology and based
on the research study, most of the feedback were positive, in which the custom designs were able to
maintain the bone alignment. In terms of comfortability, neither pressure sore nor compartment
syndrome was present, and no loss of reduction was found on the patient [12]. An assessment of clinical
effectiveness of the 3D printed cast had also been made based on several criteria including the stability
of immobilization, blood circulation, wear pressure-related pain and pressure sore as well as the
assessment to the patient’s satisfaction. According to the mean score for clinical efficacy, about 81%
claimed that the 3D printed hand cast helped in the bone healing whereas, for patient satisfaction, 76%
from the patient agreed that 3D printed hand cast was comfortable based on skin itchiness, cast odour
and smell, patient preference and patient compliance [12]. Apart from that, there were also reported
literature on the computational study of the 3D printed cast. For example, a study by Lin H. et al. had
proposed a rapid design technique in creating patient-specific cast fabricated by 3D printing technology
[11]. They claimed that their 3D printed cast was able to provide comfort and hygienic properties due
to the ventilated structure. Besides, the FEA conducted also revealed its mechanical performance
validation as the stress and displacement it produced were below the safe limit. However, these studies
are still limited. Thus, more research should be performed to further certify the use of a 3D printed cast.

Following the current trend, this study aims in comparing three different designs of hand cast through
a computational method by using FEA, as well as comfortability and clinical effectiveness tests by using
a designated questionnaire. Custom 3D printed hand casts were fabricated based on three subjects. For
the FEA, stress distribution and displacement were observed. As for the comfortability test, the
evaluation includes the patient satisfaction while wearing the 3D printed hand cast such as patient
comfort, patient compliance, patient preference, cast odour, and skin itchiness. As for the clinical
effectiveness, it the stability of immobilization, blood circulation, wear pressure-related pain, and
pressure sore. These criteria are evaluated and compared through total means score.

2. Methodology
This study includes the finite element analyses for prediction of mechanical behaviour, and
questionnaires for clinical and comfortability assessment.

2.1. Development of 3D printed hand cast
In creating a customized 3D printed hand cast, the first step was to obtain a 3D model of a human hand.
Every angle of the human hand is needed to ensure the success of hand cast fabrication [13]. For that,
Sense 3D scanner (3D System, South Carolina, United State) was used to capture the hand of the subject.
Following that, the scanned image was transferred into 3Matic software (Materialise Technologies,
Leuven, Belgium) for the development of a customized 3D hand cast model. Three different designs
were created (figure 1) for three different subjects. The designs consist of the same thickness and same
length, which were 0.5 cm and 15 cm, respectively (Figure 1). Design 1 was made in half full circular
hole pattern, while Design 2 in full circular hole and Design 3 in full honeycomb hole pattern.

These 3D model casts were subsequently printed out into a physical form for the assessments. Ender
3D printer (Creality 3D Technology Co., Shenzen, China) was used in this step with polylactic acid
(PLA) filament as the material. The PLA is a bioplastic material that can be used for fused deposition
modeling (FDM) printers. Moreover, the PLA is environmentally friendly which it is biodegradable
compared to other bioplastic materials such as polypropylene and ABS [14].
Figure 1. Three designs of 3D hand cast (a) Design 1 (b) Design 2 and (c) Design 3 with standardize thickness and length.

2.2. Finite element analysis
To test the stability and strength of the developed 3D hand casts, biomechanical evaluations were made on each model through the finite element method. For that, the first step was the meshing process. All models were meshed using first-order tetrahedral elements [15] in 3-Matic software (Materialise Technologies, Leuven, Belgium) and exported to Marc Mentat (MSC. Software, Santa Ana, CA) for the computational analyses. As in the physically printed cast, PLA filament was used. Hence, the same material properties were applied in the FEA with Young’s modulus of 3500 MPa and Poisson’s ratio of 0.36 [16]. The models were assumed as isotropic, homogenous, and linearly elastic materials [17]. In this study, a three-point bending test or so-called flexure test was conducted on the developed 3D hand cast models. The function of the bending test is to evaluate the flexural strength of a material [18]. Hence, fixed supports were applied at both ends and loaded by a point load of 9.81N at the center of interest area, representing 1kg of external force that might hit the cast during its application. The boundary condition applied was illustrated as in Figure 2.

Figure 2. Boundary condition used in the FEA.

2.3. Comfortability and clinical effectiveness assessment
The assessment of comfortability and clinical effectiveness were performed and evaluated by the three subjects via questionnaire. The subjects were needed to wear and assess all three designs of the fabricated 3D cast (Figure 3). The questionnaire includes the subject’s comfort, compliance and preferences, cast odour and smell, and lastly skin itchiness while wearing the 3D printed hand cast [12]. To fetch the result and determining which of the three designs gives
excellent comfortability, the total mean score will be calculated among the result and lastly, the result for the most comfortable design will be obtained.

**Figure 3.** 3D printed hand casts were worn by volunteers for evaluation.

### 3. Result and discussion

Fabrication is a process of manufacture, inventing, and building something whether inventing a new product or improving an existing one. Following the fabrication process, biomedical evaluations were often conducted to make sure that the designs created are suitable and safe for use. One of the most well accepted fabrication processes in these days is the 3D printing technique. It is undeniable that the popularity of 3D printing technology in medical field especially the hand and wrist rehabilitation is increasing [13]. Hence this project is focusing on the fabrication of three designs of 3D printed hand cast specifically for scaphoid fracture. Three different tests were carried out on the printed hand cast in validating its functionality and safety to be used as broken bone treatment. The tests and analyses were the FEA, comfortability and clinical effectiveness assessment.

**Figure 4.** Stress distribution on the 3D hand cast models (a) Design 1, (b) Design 2 and (c) Design 3.

For the current study, it was seen that the external load had caused high stress at the point of load application. Different stress distributions were also found between the three designs (Figure 4). For FEA, specifically in Subject A, the maximum value of stress was found to be the highest in Design 3,
followed by Design 1 and finally Design 2 with 1.27MPa, 0.85MPa, and 0.81MPa, respectively. In general, all designs had produced a relatively low stress on average, in which, lower stress is always necessary for preventing product's failure. Nevertheless, all models had shown small stress values, below the yield strength of PLA which is 26 MPa [19]. It indicated that all designs were safe for use as the risk of cast failure was lowered.

It should be noticed that loads will cause the bodies to deform and, as a result, points in a body will undergo displacements or changes in the position [18]. As the results had shown, the deformities of the 3D hand cast could be seen clearly. In Figure 5, the pink shadow represented the original cast shape while the grey and blue colour showed the deformation of the cast. Design 3 produced the highest deformities while the lowest deformities or displacement was found in Design 2. High deformation may cause a loose fit of the cast, leading to failure of the fracture bone correction [11]. Therefore, Design 2 was able to hold the bone better, ensuring a proper alignment.

![Figure 5. Deformation of the 3D models for Subject A, with the blue and grey representing the deformed shape, and pink shadow as the original shape.](image)

Next, for the comfortability test, Table 1 showed the results. Different subjects had different preferences, in which Design 3 for subject A and C, and Design 1 for subject B. The results for the comfortability test presented that the highest total mean score is 2.72 for Design 3, followed by Design 1 with 2.59, and Design 2 with 2.46. This had made Design 3 the most comfortable design. The evaluation included the patient satisfaction while wearing the 3D printed hand cast, such as patient comfort, patient compliance, patient preference, cast odour, and skin itchiness.

| Table 1. Total mean score for comfortability test. |
|-----------------------------------------------|
| Subject A | Subject B | Subject C | Total mean score |
| Design 1   | 0.73       | 1.00       | 0.86       | 2.59       |
| Design 2   | 0.73       | 0.93       | 0.80       | 2.46       |
| Design 3   | 0.86       | 0.93       | 0.93       | 2.72       |

According to the clinical effectiveness test, the highest total mean score is on Design number 2 of 2.73, followed by Design 3 of 2.49, and Design 1 of 2.34. Both subjects A and B chose Design 2 for higher efficacy, while subject C rated equally high for both Design 1 and 2. Table 2 summarize the clinical effectiveness test results. The evaluation included the test of the stability of immobilization, blood circulation, wear pressure-related pain, and pressure sore.

| Table 2. Total mean score for clinical effectiveness test. |
|-----------------------------------------------|
| Subject A | Subject B | Subject C | Total mean score |
| Design 1   | 0.60       | 0.83       | 0.91       | 2.34       |
| Design 2   | 0.91       | 0.91       | 0.91       | 2.73       |
| Design 3   | 0.83       | 0.83       | 0.83       | 2.49       |
The comfortability and clinical effectiveness tests proved that Design 3 was more preferred for its comfort, while Design 2 provided better clinical effectiveness. It had higher total mean score compared to the other designs for the respective test. The percentage different on the total mean score between designs was higher in clinical effectiveness test than in comfortability test (9.2% difference between Design 2 and 3, and 15.4% difference between Design 2 and 1 for clinical effectiveness test, while 4.9% difference between Design 3 and 1 and 10% difference between Design 3 and 2 for comfortability test). Despite its lower comfort score, the smaller percentage difference implied that Design 2 could provide comparable comfortability as in Design 1 and 3.

As seen, Design 3 was made with hexagonal holes forming honeycomb pattern while Design 1 with half-fill circular holes and Design 2 in full circular holes pattern. Besides able to retain the rigidity of the cast and reduce its weight, the honeycomb pattern which was in a semi-enclosed cast design allows airflow to increase ventilation and reduce skin infection risk, as well as allows access to the skin if there is irritation occur [10, 14]. Contrarily, traditional hand cast which fully covers the broken bone often develop several skin diseases and potential bone and joint injuries due to heavy structure and poor ventilation [11]. It also fits improperly while also causing discomfort [14]. For that, a patient-specific feature of casting is needed as it ensures the matching surface geometry between the cast and arm and thus disperses pressure while maintaining the alignment and avoid loss of closed reduction [14].

Nevertheless, there is still a limitation with 3D printed hand cast for example in emergency cases, 3D printed hand cast cannot be performed immediately. It involves several tedious procedures but, in the future, as the technology grows, the production time can be minimized. Yet, those who seek comfortability in the rehabilitation process, 3D printed hand cast can be one way out. It can hold the fractured bone as well as providing comfort and clinical effectiveness along with its usage.

Some assumptions and limitations have been considered in this study. First, the use of isotropic, homogeneous, and linear material properties of the 3D model in finite element analysis. Apart from that, the model was modelled with tetrahedral elements [15, 20, 21]. For more complex models, it is recommended that complex model can be considered in the future study by modelling the 3D hand cast with hexahedral elements. In the other point of view, the model could be verified and validated with experimental results [22, 23]. In terms of thermal imaging analysis, it could be done in the future study to determine the heat transfer from the skin to the air. From here, more new insight information will be obtained for clinicians to justify the choices of hand cast application in treating fracture bone.

4. Conclusion
The usage of 3D printing in fabricating almost everything is undeniable. It makes the fabrication process simpler and in a shorter period especially in a customized design. On that account, the application of 3D printing in biomedical engineering is also growing and promising to be practiced in the near future. This project has proven that customizable hand cast by using 3D printing technique is reliable and provides comfort to the patients. It could help in restoring the broken bone. Besides, it was also found that different designs of hand casts gave out different mechanical stability, comforts, and clinical effectiveness. Design 2 which is in full circular holes pattern generally possessed better functionality, as it could produce lower stress and deformation, while giving out better clinical effectiveness than the other two designs, though it lacks on the comfortability. The results and feedback obtained throughout this study shall be guidance for future research.

Acknowledgments
The work has been carried out with the support of research funding from Ministry of Higher Education Malaysia, under Fundamental Research Grant Scheme (FRGS) (Grant no.: 5F135 and FRGS/1/2019/TK05/UTM/02/3), Universiti Teknologi Malaysia (UTM) under Tier 2 (Grant no.: 15J84), Prototype Development Fund from Innovation and Commercialisation Centre (ICC) (Grant no.: 4J490), Matching Grant (Grant no.: 02M69) and Universiti Kuala Lumpur under Collaboration Research Grant Scheme (Grant no.: 4B618).
References
[1] Sabbagh MD, Morsy M and Moran SL 2019 Diagnosis and management of acute scaphoid fractures Hand Clinics 35 259-69.
[2] Dias JJ, Brealey SD, Fairhurst C, Amirfeyz R, Bhowal B, Blewitt N, Brewster M, Brown D, Choudhary S, Coapes C, Cook L, Costa M, Davis T, Di Mascio L, Giddins G, Hedley H, Hewitt C, Hinde S, Hobby J, Hodgson S, Jefferson L, Keding A, Leighton P, Logan A, Mason W, McAndrew A, McNab I, Muir L, Nicholl J, Northgraves M, Palmer J, Poulter R, Rahimtoola Z, Rangan A, Richards S, Richardson G, Stuart P, Taub N, Tavakkolizadeh A, Tew G, Thompson J, Torgerson D and Warwick D 2020 Surgery versus cast immobilisation for adults with a bicortical fracture of the scaphoid waist (swifft): A pragmatic, multicentre, open-label, randomised superiority trial The Lancet 396 390-401.
[3] Hughes TB 2020 Acute scaphoid waist fracture in the athlete Clinics in Sports Medicine 39 339-51.
[4] Rhemrev SJ, Ootes D, Beeres FJP, Meylaerts SAG and Schipper IB 2011 Current methods of diagnosis and treatment of scaphoid fractures International Journal of Emergency Medicine 4 4.
[5] Buijze GA, Goslings JC, Rhemrev SJ, Weening AA, Van Dijkman B, Doornberg JN and Ring D 2014 Cast immobilization with and without immobilization of the thumb for nondisplaced and minimally displaced scaphoid waist fractures: A multicenter, randomized, controlled trial The Journal of Hand Surgery 39 621-7.
[6] Kawanishi Y, Oka K, Tanaka H, Sugamoto K and Murase T 2017 In vivo scaphoid motion during thumb and forearm motion in casts for scaphoid fractures The Journal of Hand Surgery 42 475.e1-e7.
[7] Dias J and Kantharuban S 2017 Treatment of scaphoid fractures: European approaches Hand Clin 33 501-9.
[8] Elstrom J, Virkus W and Pankovich A 2005 Handbook of fracture (The McGraw-Hill Education / Medical)
[9] Boyd AS, Benjamin HJ and Asplund C 2009 Principles of casting and splinting Am Fam Physician 79 16-22.
[10] Fitzpatrick A and Mohammed M 2017 Design of a patient specific, 3d printed arm cast KnE Engineering 2 135.
[11] Lin H, Shi L and Wang D 2016 A rapid and intelligent designing technique for patient-specific and 3d-printed orthopedic cast 3D Printing in Medicine 2 4.
[12] Chen YJ, Lin H, Zhang X, Huang W, Shi L and Wang D 2017 Application of 3d–printed and patient-specific cast for the treatment of distal radius fractures: Initial experience 3D Printing in Medicine 3
[13] Keller M, Guebeli A, Thieringer F and Honigmann P 2021 In-hospital professional production of patient-specific 3d-printed devices for hand and wrist rehabilitation Hand Surgery and Rehabilitation 40 126-33.
[14] Ayirimis N 2018 Effect of layer thickness on surface properties of 3d printed materials produced from wood flour/pla filament Polymer Testing 71 163-6.
[15] Ramlee MH, Gan H, Daud S, Wahab A and Abdul Kadir M 2020 Stress distributions and micromovement of fragment bone of pilon fracture treated with external fixator: A finite element analysis The Journal of Foot and Ankle Surgery 59 664-72.
[16] Farah S, Anderson DG and Langer R 2016 Physical and mechanical properties of pla, and their functions in widespread applications — a comprehensive review Advanced Drug Delivery Reviews 107 367-92.
[17] Abd AAU, Abdul Wahab AH, Abdul Rahim RA, Abdul Kadir MR and Ramlee MH 2020 A finite element study: Finding the best configuration between unilateral, hybrid, and ilizarov in terms of biomechanical point of view Injury 51 2474-8.
[18] Hibbeler RC 2014 *Mechanics of materials, 9th edition*. (Upper Saddle River, N.J: Pearson Education)

[19] Subramaniam SR, Samykano M, Selvamani SK, Ngui WK, Kadirkama K, Sudhakar K and Idris MS 2019 Preliminary investigations of polylactic acid (pla) properties *AIP Conference Proceedings* 2059 020038

[20] Ramlee MH, Kadir MRA and Harun H 2014 Three-dimensional modelling and finite element analysis of an ankle external fixator *Advanced Materials Research* 845 183-8.

[21] Abidin NAZ, Kadir MRA and Ramlee MH 2020 Biomechanical effects of different lengths of cross-pins in anterior cruciate ligament reconstruction: A finite element analysis *Journal of Mechanics in Medicine and Biology* 20 2050047.

[22] Abd AAU, Gan HS, Nasution AK, Kadir MRA and Ramlee MH 2019 Development and verification of three-dimensional model of femoral bone: Finite element analysis *Journal of Physics: Conference Series* 1372 012014.

[23] Abidin NAZ, Rafiq Abdul Kadir M and Ramlee MH 2019 Three dimensional finite element modelling and analysis of human knee joint-model verification *Journal of Physics: Conference Series* 1372 012068.