DEVELOPMENTS, MECHANICAL PROPERTY MEASUREMENTS AND STRENGTH EVALUATIONS OF THE WRIST BRACES FOR THE WRIST FRACTURE PATIENTS

Article *in* Journal of Mechanics in Medicine and Biology · April 2019

DOI: 10.1142/S0219519419400219

Jing-Jing Fang
National Cheng Kung University

Journal of Mechanics in Medicine and Biology
Vol. 19, No. 2 (2019) 1940021 (11 pages)

DOI: 10.1142/S0219519419400219

World Scientific
www.worldscientific.com

DEVELOPMENTS, MECHANICAL PROPERTY MEASUREMENTS AND STRENGTH EVALUATIONS OF THE WRIST BRACES FOR THE WRIST FRACTURE PATIENTS

CHUNG-DE CHEN*, CHING-HSIANG CHEN*, CHENG-LI LIN†,
CHIEN-KUNG LIN‡, CHI-TSANG WANG‡,§, RUEY-MO LIN§
and JING-JING FANG*,¶

*Department of Mechanical Engineering
National Cheng Kung University
Tainan City 70101, Taiwan

†College of Medicine, National Cheng Kung University
Tainan City 70101, Taiwan

‡Department of Chemical Engineering
National Cheng Kung University
Tainan City 70101, Taiwan

§Tainan Municipal An-Nan Hospital
Tainan City 70965, Taiwan
¶fangjj@mail.ncku.edu.tw

Received 26 December 2018
Revised 9 January 2019
Accepted 16 January 2019
Published 4 April 2019

In this paper, the wrist braces for the wrist fracture patients are developed. Geometry of the patient's wrist surface anatomy was digitalized and recorded by an optical 3D scanner. An expert software was developed to generate the brace model, on which several holes are distributed to increase the air permeability. Finally, the brace is fabricated by commercial FDM 3D printer. For ensuring the strength of the wrist brace, the tensile test and impact test were conducted to measure the elastic modulus, yielding strength and fracture strength. A finite element model was established to investigate the stresses and deformations when the wrist brace is subjected to a static load. The mechanical properties measured in the tensile tests are as input parameters in the model. The static analysis showed that, for four considered movements of the wrist, the maximum von-Mises stress is less than the yielding strength. An impact analysis was also conducted to simulate brace impacted by a moving rigid ball with a mass of 0.3768 kg. The results showed that the deformation at the impact point remains in the elastic range when the impact speed is 3 m/s. The finite element calculations give us rules to design the number of holes and the thickness of the brace.

Keywords: Wrist brace; 3D printing; finite element modeling.

¶Corresponding author.

1. Introduction

Wrist fractures are one of the most common types of fractures, accounting for around 25% of fractures in the pediatric population and up to 18% of all fractures in the elderly age group.[1] After the surgical intervention, the patient usually needs to put his wrist into the splint or cast for protection. The traditional wrist splint or cast is made from plaster casts, which can fit the profile of the patient's wrist. However, there are some disadvantages of wearing such plaster cast including hot and humid sensation, difficulty in cleaning and removing, uncomfortable contact and even skin allergy, etc. An alternative in orthopedic treatment after surgery is the use of customer-made splints. The traditional customer-made wrist immobilization splints are made of thermoplastic sheets by handmade.[2] The customized shapes of the splints are formed by cutting, molding and adjusting. The limitations such as the time consuming process, discomfort and poor aesthetics result in a reduced willingness to wear the splints.

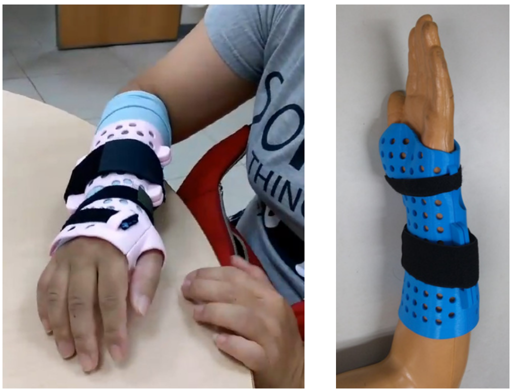
The 3D printing technologies have become significant in variety applications due to their rapid prototyping and customized abilities. The 3D printing is also applicable in orthopedic treatment, such as custom foot orthoses (FO),[3] ankle-foot orthoses (AF)[4] and prosthetic sockets.[5] In these medical applications, the personal needs have been considered in the orthoses design by 3D printing. A similar solution has been applicable to the wrist brace in a wrist fracture patient. Palousek *et al.* proposed a wrist orthosis using fused deposition modeling (FDM).[6] They showed that the 3D printing technologies reflect the patient's requirements. They also found that, comparing to the Aquaplast (material commonly used in traditional methods), the mechanical properties of the material used in FDM are sufficient for use in this particular application. Paterson *et al.* investigated various 3D printing technologies for customized wrist splints.[2] They evaluated four different 3D printing processes: stereolithography (SLA), laser sintering (LS), FDM and polyjet material jetting. They found that FDM was considered the least suitable AM process for upper extremity splinting. Kim and Jeong proposed a customized wrist brace using a hybrid design of tradition injection molding and 3D printing.[7] Their prototype includes outer cover and inner frame. The outer cover is fabricated by injection molding, a traditional process in mass production. The inner frame is fabricated by 3D printing so that it can fit the profile of the wrist skin surface. The inner frame has less material and can be quickly printed by a 3D printer. This hybrid design could be a balanced solution that can simultaneously meet personal needs, rapid fabrication and low cost. Faria proposed a design and fabrication process of a custom-fit orthosis for the upper limb.[8] The prototypes were fabricated by SL and FDM. He concluded that the surface quality of orthosis printed by the SL is better than that by the FDM. He also found that the SL can print an object with more complex geometry.

In this paper, the developments and strength evaluations of the wrist braces for the wrist fracture patients is presented. Although in SLA and SL have been recommended in printing the upper-limb orthosis according to the literature survey,[2,8] the FDM was used in this study due to their low cost of printing device. The material used in this study is polylactic acid (PLA), which is also available in low cost. The mechanical properties of the PLA were measured by experiments. The finite element model was established to investigate the stresses of the wrist brace under static and dynamic loads.

2. Design and Fabrication of the Wrist Brace

In this study, the wrist brace was made by 3D printing. First the geometry of the wrist surface anatomy was digitalized and recorded by an optical 3D scanner, Creaform Go!Scan50™. The digital brace model was generated associated to a personal wrist by an expert software developed by NCKU ME VR laboratory.[9] Firstly, we smoothed and removed noises from the original digital scan of the human wrist. Based on the pre-processing digital wrist, we offset the non-uniform allowances between inner layers of the brace from pressure sensor testing.[9] The parameters of allowance and their positions are based on the statistical analysis of comparison tests and the questionnaires of 20 subjects with NCKUH IRB approval number B-ER-103-201. The patient feels uncomfortable if a small allowance was applied. In the contrast to small tolerance, large allowance can improve the comfortability of wearing but lose functions of fixation treatment to the fracture wrist. The customized brace model was generated by increasing a certain thickness from the scan model. Finally, several ventilation holes were uniformly distributed on the brace model to increase the air permeability.

The well designed digital model of the brace was then exported to the FDM 3D printer for fabrication. Materials of colorful PLA (polylactic acid) are used to fabricate the brace, in which the raw material has been proven to be bio-compatible.



(a) (b)

Fig. 1. The wrist braces wearing on (a) human wrist and (b) training arm manikin.

Figure 1(a) shows the prototype of the brace wearing on the patient's wrist for protection and fracture fixation. The customized brace composes of two parts connected by fabricated latch. Patients can put the two pieces of the brace on wrist by themselves and fasten two parts into one by the Velcro.

One of the aims of this study is to investigate the strength of the wrist brace under impact. For a long term scope, a training arm manikin wearing a brace will be put on the shock tester to measure the strength of the brace after the impact. Therefore, the brace analyzed in this study is scanned from the wrist of the training arm manikin, as shown in Fig. 1(b).

3. Mechanical Property Measurements

The elastic modulus of PLA was measured following ASTM D638. The dimension of the specimen is shown in Fig. 2(a). The specimen was fabricated by the same 3D printer that printed the wrist brace. The layer orientation (θ), which is defined as the angle between the loading direction of the specimen and the out-of-plane normal of the layer, could be a factor that affects the mechanical properties. Three layer orientations of the specimen, $\theta = 0°$, $\theta = 45°$ and $\theta = 90°$, were fabricated, as illustrated in Fig. 2(b). The specimens are shown in Fig. 2(c). The experiments were performed by a tensile testing machine (INSTRON 5565).

The experimental stress–strain curves are shown in Fig. 3. The numbers of the specimens for $\theta = 0°$, $\theta = 45°$ and $\theta = 90°$ are 12, 11 and 9, respectively. It is seen that for the case of $\theta = 90°$, the specimen exhibits a ductile stress–strain curve. For $\theta = 0°$, the specimen is brittle. The average Young's modulus for the specimens with $\theta = 0°$, $\theta = 45°$ and $\theta = 90°$ are 1.181, 1.109 and 1.044 GPa, respectively, as listed in

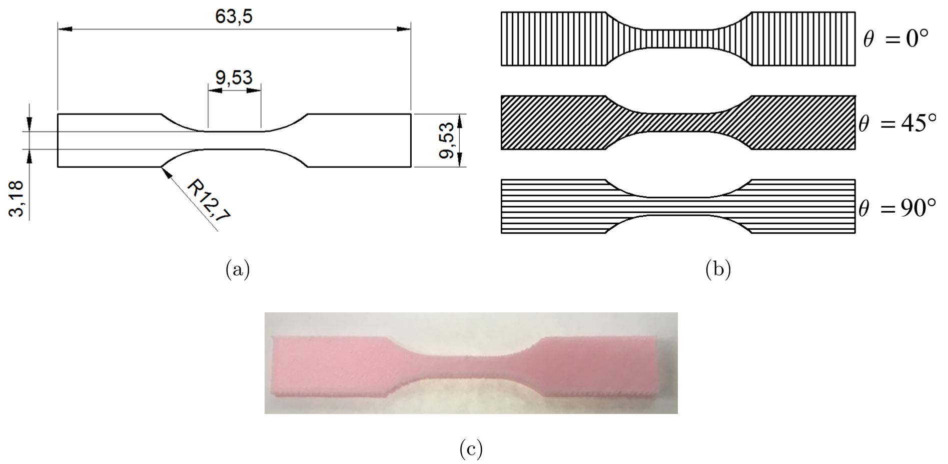


Fig. 2. The specimen for measurement of elastic modulus: (a) the dimensions of the specimen; (b) the illustrations of the printing layer orientation; (c) the photo of the specimens.

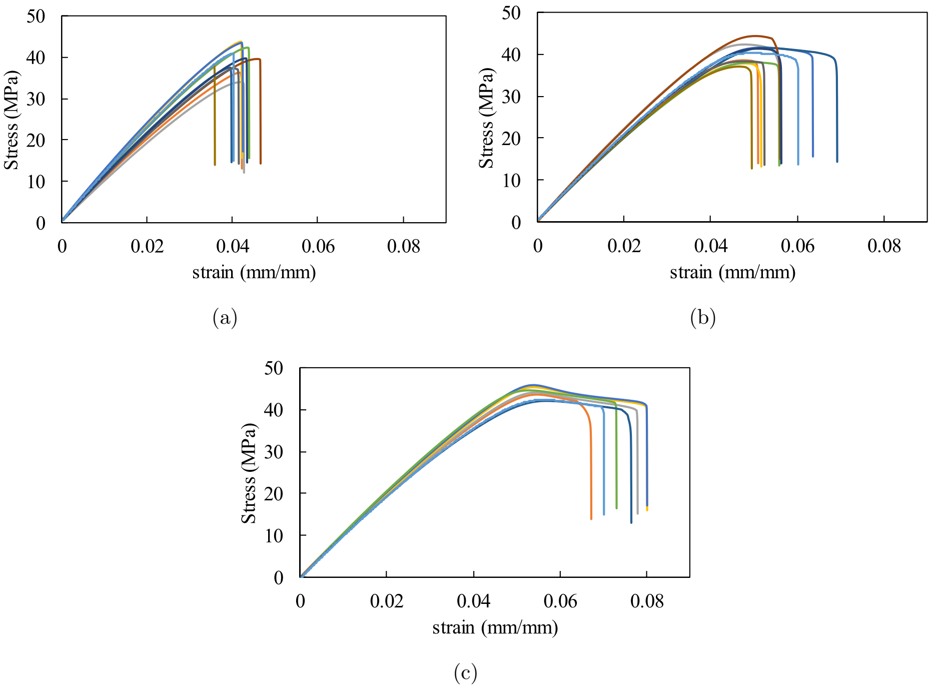


Fig. 3. The measured stress–strain curves for (a) $\theta = 0°$; (b) $\theta = 45°$; (c) $\theta = 90°$.

Table 1. The average in elastic modulus for all specimens is 1.123 GPa. A variation of the elastic moduli is found between these three types of specimen. This variation is insignificant, therefore, the 3D printing specimens can be considered approximately as isotropic in the elastic range.

The Izod impact test (ISO 180) was also conducted in order to measure the impact resistance of the PLA. Figure 4 shows the specimen used in the Izod test. Similar to the elastic modulus measurement, three layer orientations of the specimen, $\theta = 0°$, $\theta = 45°$ and $\theta = 90°$, were conducted for the test. For each layer orientation, 10 specimens were prepared for the test. The test results are listed in Table 2, indicating that the required impact energy to fracture for the specimen with $\theta = 90°$ is significantly larger than that with $\theta = 0°$ or $\theta = 45°$.

Table 1. The measured elastic moduli of the specimens (unit: GPa).

Specimen type	Average	Standard deviation
$\theta = 0°$ (9 specimens)	1.18	0.0763
$\theta = 45°$ (11 specimens)	1.11	0.0371
$\theta = 90°$ (12 specimens)	1.06	0.0311

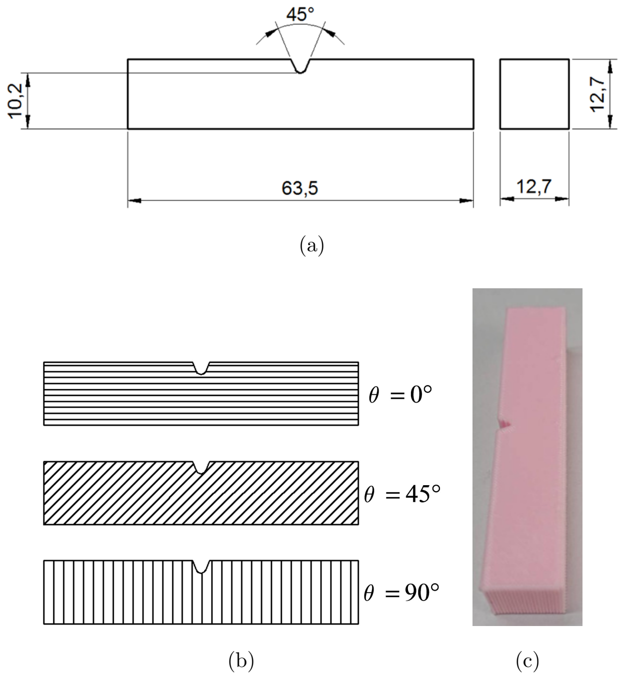


Fig. 4. The specimen used in the Izod impact test: (a) the dimensions; (b) the layer orientation; (c) the photo of the specimen.

Table 2. The impact energy from the Izod impact test (unit: J/m^2).

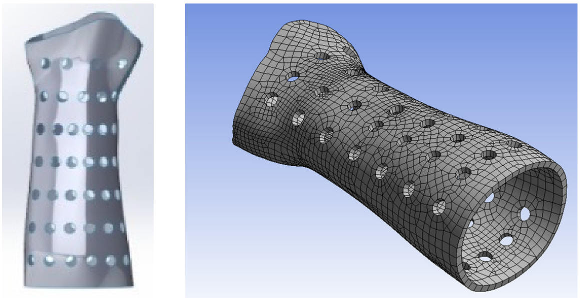
Specimen type	Average	Standard deviation
$\theta = 0°$ (10 specimens)	2691	267
$\theta = 45°$ (10 specimens)	1723	262
$\theta = 90°$ (10 specimens)	1742	113

4. Finite Element Analysis

In this paper, the static analysis and dynamic impact analysis of the brace are investigated by the finite element software ANSYS. The geometry of the finite element model was generated from a training arm manikin, as shown in Fig. 1(b). In both the static and dynamic analyses, the 8-node shell element SHELL281 is used to mesh the model as the geometry of the brace can be considered as a shell structure, as shown in Fig. 5. Detail information of the model and the analysis results and discussions will be given in this section.

4.1. *Static analysis*

In the finite element analysis, the stresses and displacements are investigated under four wrist movements: flexion, extension, radial deviation and ulnar deviation, as



(a) (b)

Fig. 5. Brace model and the finite element mesh.

shown in Fig. 6. The elastic modulus used in the analysis is 1.123 GPa. Faria *et al.* measured the maximum wrist forces under the four movements, as listed in Table 3.[8] According to the four movements, the boundary conditions in the finite element model are shown in Fig. 7.

Three main parameters are considered in the model: thickness of the brace, diameter of the hole and center-to-center distance between two adjacent holes. Each parameter has two design values so that there are totally 8 cases, as listed in Table 4. Among all the possible combination of design parameters, the maximum von-Mises stress is 7.08 MPa, which is less than the yielding strength. The results

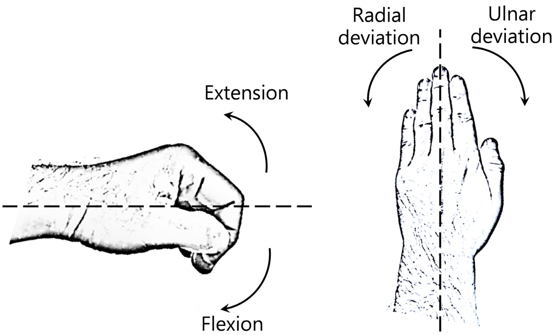
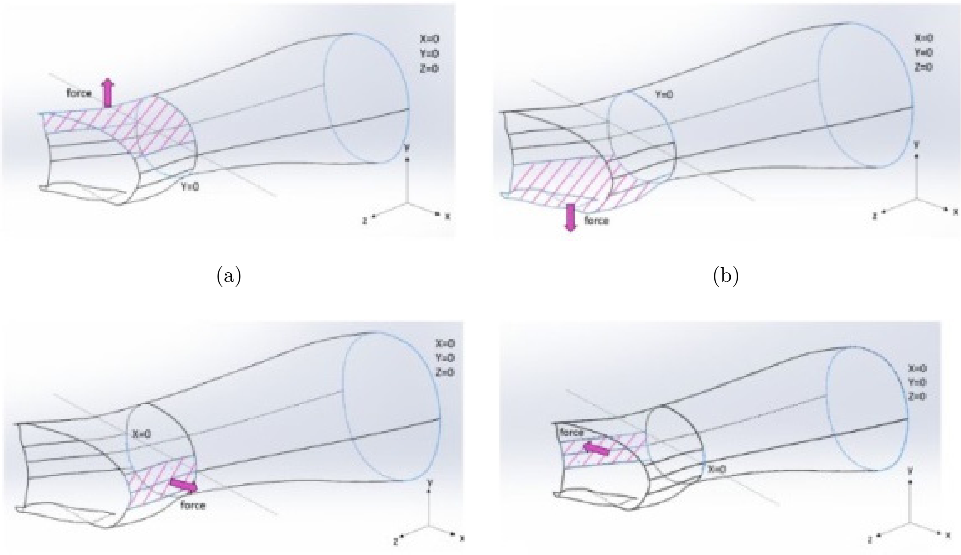


Fig. 6. Four movements of the wrist.

Table 3. The wrist force measurements of the wrist movements.[8]

Movement	Maximum force (N)
Flexion	30
Extension	25
Radial deviation	30
Ulnar deviation	30



(a) (b) (c) (d)

Fig. 7. Boundary conditions and loading conditions of the finite element model: (a) Extension; (b) Flexion; (c) Ulnar deviation; (d) Radial deviation.

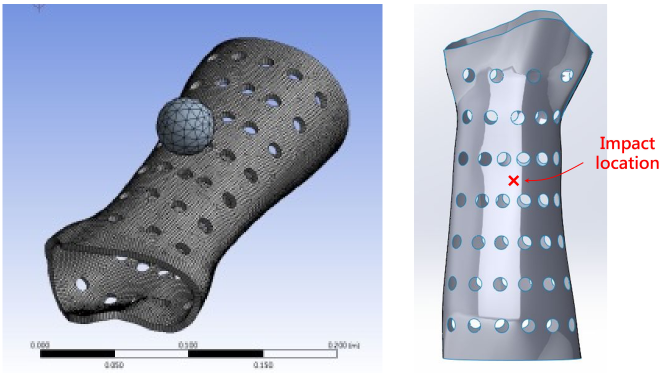
Table 4. The maximum von-Mises stress in the finite element analysis for various design models and wrist movements.

				Maximum von-Mises stress (MPa)			
Model	Thickness (mm)	Hole diameter (mm)	Distance between holes (mm)	Flexion	Extension	Radial deviation	Ulnar deviation
1	5	15	15	3.0442	2.3880	2.0994	1.5377
2	5	15	8	3.0438	2.4369	2.1362	1.8415
3	5	10	15	2.4526	2.0669	1.9631	1.7342
4	5	10	8	2.8189	2.2504	1.9935	1.5264
5	3	15	15	7.0764	5.1177	4.9063	3.5188
6	3	15	8	7.2384	5.2539	4.9931	4.1902
7	3	10	15	6.7375	4.0486	4.6153	3.2997
8	3	10	8	6.9152	4.7114	4.6551	3.6526

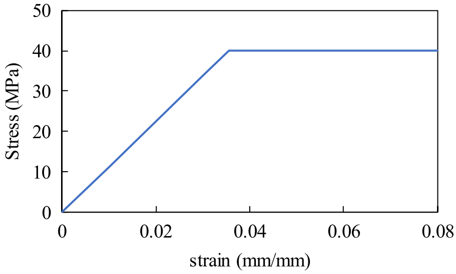
also show that, under the static loading, the most important parameter is the thickness. The maximum von-Mises stress for the brace with 3 mm thickness is roughly twice than that with 5 mm thickness. In contrast to the thickness, the other two parameters, hole diameter and hole distance, have minor effects on the static stresses. It suggests that the current design with 5 mm thickness can be accepted in the normal use.

4.2. *Dynamic impact analysis*

The dynamic impact analysis of a wrist brace is also performed by ANSYS. The brace model used in the analysis has a thickness of 5 mm, a hole-diameter of 10 mm and a distance between holes of 15 mm, which is model 3 in Table 4. The analysis model simulates a steel ball with a diameter of 40 mm and a mass of 0.3768 kg impacts to the brace at a speed, as shown in Figs. 8(a) and 8(b). In the transient dynamic analysis, we also consider the elasto-plastic model of the material, as shown in Fig. 8(c), which is an approximation to the stress–strain curve measured by the tensile test. The yielding strength is 40 MPa. The simulation results are listed in Table 5, indicating that when the impact speed is 3 m/s, the deformation at impact point is in the elastic range. For the other two impact speeds, 4 m/s and 5 m/s, the plastic deformations occur at the impact point. According to Fig. 3(c), the fracture strains are approximately 0.07 and 0.04 for $\theta = 90^\circ$ and $\theta = 90^\circ$, respectively. Comparing to the measured data and the simulated strains listed in Table 5, it is concluded that fracture may occur at the impact point for the other two impact speeds, 4 m/s and 5 m/s.



(a) (b)



(c)

Fig. 8. The dynamic impact model: (a) mesh of brace and impact steel ball; (b) impact location; (c) elasto-plastic material model.

Table 5. The maximum principal strain and von-Mises stress at the impact point.

Impact velocity (m/s)	5	4	3
Maximum principal strain	0.0610	0.0516	0.0346
von-Mises stress (MPa)	40	40	34.3

5. Conclusions

In this paper, the development of the wrist brace for wrist fracture patient is presented. The brace was fabricated by FDM. The mechanical properties, including the elastic modulus and impact energy, were obtained by experiments. The results showed that the 3D printing material, PLA, can be approximately considered as isotropic material with an elastic modulus of 1.123 GPa. On the other hand, the impact test showed that the material exhibit anisotropic behavior. The finite element analysis was conducted to evaluate the strength of the brace subjected to static and dynamic loading. In the static analysis, design parameters such as thickness, hole-diameter and distance between holes are considered. The analysis results showed that the von-Mises stress is sensitive to the thickness of the brace. Among all the possible combination of design parameters, the maximum von-Mises stress is 7.08 MPa, which is less than the yielding strength. In the dynamic analysis, the simulation considered the transient responses after the brace is collided by a falling object with a mass of 5 kg. The results showed that the deformation at the impact point remains in the elastic range when the impact speed is 3 m/s. The finite element calculations give us rules to design the number of holes and the thickness of the brace.

Acknowledgments

The authors are grateful to the Ministry of Science and Technology, Taiwan for the financial support through grant MOST 106-3114-E-006-010.

References

1. Court-Brown CM, Caesar B, Epidemiology of adult fractures: a review, *Injury* **37**:691–697, 2006.
2. Paterson M, Campbell RI, Bingham G, Comparing additive manufacturing technologies for customised wrist splints, *Rapid Prototyping J* **21**:230–243, 2015.
3. Jin YA, Plott J, Chen R, Wensman J, Shih A, Additive manufacturing of custom orthoses and prostheses – A review, *Proc CIRP* **36**:199–204, 2015.
4. Pallari JHP, Dalgarno KW, Munguia J, Muraru L, Peeraer L, Telfer S, Woodburn J, Design and additive fabrication of foot and ankle-foot orthoses, *Proc. 21st Annual Int Solid Freeform Fabrication Symposium–An Additive Manufacturing Conf*, pp. 834–845, 2010.
5. Herbert N, Simpson D, Spence Spence WD, Ion W, A preliminary investigation into the development of 3-D printing of prosthetic sockets, *J Rehabil Res Dev* **42**:141–146, 2005.

6. Palousek D, Rosicky F, Koutny D, Stoklasek P, Navrat T, Pilot study of the wrist orthosis design process. *Rapid Prototyping J* **20**:27–32, 2014.
7. Kim H and Jeong S, Case study: Hybrid model for the customized wrist orthosis using 3D printing, *J Mech Sci Technol* **29**:5151–5156, 2015.
8. Faria ASTJ, Additive manufacturing of custom-fit orthoses for the upper limb. Master Thesis, University of Porto, 2017.
9. Tsai ZY, Pressure experiments and analysis for customized wrist brace, Master Thesis, National Cheng Kung University, 2016.