Springer

KSME

Journal of Mechanical Science and Technology 31 (5) (2017) 2393~2398
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-017-0436-2

Design and optimization of prosthetic foot by using polylactic acid 3D printing †

Zhen Tao, Hyoung-Jong Ahn, Chenglong Lian, Kwang-Hee Lee and Chul-Hee Lee*
Department of Mechanical Engineering, Inha University, 100 Inha-ro, Nam-gu, Incheon, Korea

(Manuscript Received July 9, 2016; Revised December 21, 2016; Accepted January 4, 2017)

Abstract

This paper describes the complete design process of a passive prosthetic foot manufactured of Polylactic acid (PLA). It focuses on the reduction in the weight of prosthetic feet. Most of the prosthetic feet are designed with more weight and material than required. The structure of this passive prosthetic foot is designed and optimized as light as possible by using topology optimization. The topology-optimized model is printed from a Three-dimensional (3D) printer directly rather than interpreting the model using a Computer-aided design (CAD) software. The finite element analysis and the experiments are conducted to validate the structure. The test equipment is designed and installed for simulating the boundary conditions of the Heel strike (HS) and Toe off (TO). Since the weight of the prosthetic directly affects the mobility of patients, the weight of the proposed model is reduced 62 % when compared initial model to the final model.

Keywords: Passive prosthetic foot; Topology optimization; Polylactic acid (PLA); Three-dimensional (3D) printing

1. Introduction

Several designs of prosthetic feet with a variety of materials, shapes, and functions are available today. In recent years, artificial limbs, especially, the prosthetic feet have attracted the attention of developers. There has never been a standard ideal design because of the inability of any design to single-handedly perform all the several functions of sound limbs. Hence, a prosthetic foot can be suitable only for specific functions and reasons [1, 2]. Prosthetic feet can be classified into three categories: passive feet, Energy storage and return (ESR) feet, and bionic feet [3]. In the bionic feet, which is a contemporary state of the art in the powered ankle–foot prosthetic, the generated power and torques serve for the propulsion of the amputee. It is further categorized based on the actuation principle, i.e., pneumatic or electric [4]. The passive energy storing devices (ESR feet) are energetically efficient but do not provide the extra power needed for propulsion during walking [5].

In the passive prosthetic feet, the remaining musculature of a patient has to compensate for the absence of the propulsive ankle torques. It is well known that the passive feet, as well as other two types of the prosthesis feet, have not shown enhanced performance properties. However, the passive feet are superior with respect to weight. The low weight of a prosthetic foot is crucial for reducing the burden on the remaining musculature of a patient. There are two methods to achieve a low weight of the prosthetic feet: structural optimization and selection of lightweight materials. Several materials are used in the manufacture of prosthetic feet including the metal, carbon fiber, and plastic [6-9]. The performance of prosthetic feet differs with material properties such as density and elastic modulus. Polylactic acid (PLA), used for Three-dimensional (3D) printers, is also helpful for weight reduction. Even though there are some prosthetic feet made of PLA [10], they did not focus on the weight reduction.

In this study, a new design optimization process has been proposed and applied. The optimized model is printed by using 3D printer. Analysis and experiments are introduced to validate the safety of the prosthetic foot structure. The design process which is proposed in this paper can prevent the excessive design of the foot. It is proved that the design cycle and expense can be reduced by applying the process of this research. This study has a significant role in the small-scale customized production of the prosthetic foot.

2. Design optimization process

In this paper, the entire design process is divided into several parts as shown in Fig. 1. The design of the prosthetic feet and the results of the analysis and experiments are then described. The plan for the project and the main guidelines are laid out in detail. The initial geometry model is created on the basis of information extracted with the survey results. For determining the best design concept that meets the design requirements, topology optimization and Finite element analy-

*Corresponding author. Tel.: +82 32 860 7311, Fax.: +82 32 873 7311
E-mail address: Chulhee@inha.ac.kr
† Recommended by Associate Editor Yoon Hyuk Kim

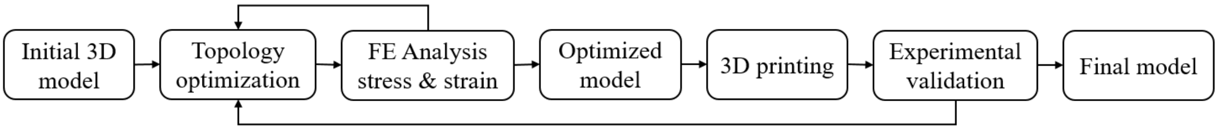

Fig. 1. Design optimization and manufacturing process for 3D printed prosthetic foot.

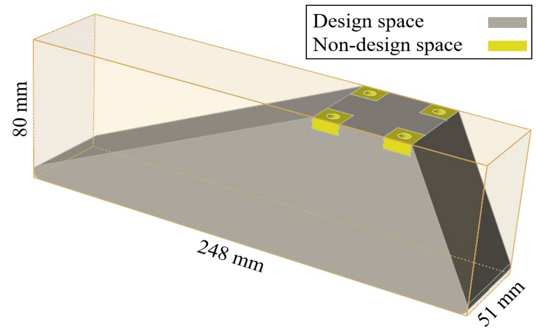

Fig. 2. Initial model of the prosthetic foot.

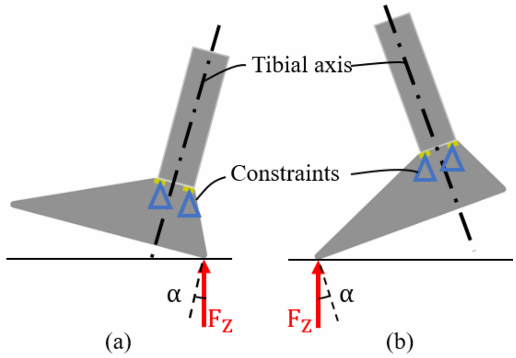

Fig. 3. Schematic of equivalent boundary condition: (a) Heel strike; (b) toe off.

sis (FEA) are conducted. Meanwhile, stress and strain distributions are obtained. To validate the prosthetic foot, printed the topology-optimized model by using a 3D printer and experiments are conducted. Agreement between the numerical and the experimental model is assessed by comparison of the FE analysis and the strain gauge analysis results.

For helping a patient to get used to the prosthetic in a better and more comfortable way, the prosthetic foot should be able to mimic the natural limb as much as possible. In the passive feet, the remaining musculature of a patient needs to compensate for the propulsive ankle torque. A lightweight prosthetic foot can reduce the burden on the remaining musculature of a patient. Thus, a lightweight prosthetic foot is designed. The design has the least number of movable parts, a majority of passive parts, and minimal external energy consumption.

According to the result of lower limb measurements, the mean foot length was 264.6 mm with a standard deviation of 14 mm for males. This is obtained from a survey conducted on 240 subjects (120 males and 120 females). The subjects were between 25 and 30 years of age [11]. The ankle height of approximately 80 mm is considered. With reference to the size of a male pyramid adapter, the width of the prosthetic foot is set at 51 mm. The design space including the shape of the foot is developed by using Siemens NX. Considering the property of PLA material and the shape of the human foot, the distance between the equivalent ankle center and the equivalent heel is set at 65 mm, and fillet processing is handled at an equivalent heel and toe position. It resulted in a reduction in the length of the foot from the initial 265 mm to 248 mm. The initial model of the prosthetic foot is illustrated in Fig. 2.

Human walking is a cyclic pattern of bodily movement. As generally defined, one gait cycle starts with the Heel strike (HS) and ends with the next HS of the same foot [12]. Each gait cycle can be divided into two main phases: Stance phase and swing phase. The stance phase starts with the HS and ends with the Toe off (TO). The swing phase starts with the TO and ends with the next HS. During the stance phase, there are five typical instants: HS, Foot flat (FF), Mid stance (MS), Heel off (HO), and TO. The HS represents the moment when the heel initially contacts the ground. The FF represents the moment when the toe initially contacts the ground. The MS represents the moment when the shank rotates from plantar flexion to the vertical position. The HO represents the moment when the heel loses contact with the ground, and the TO represents the moment when the toe loses contact with the ground [13]. However, because the ankle is fixed, the passive prosthetic foot has no instances of FF and HO. The prosthetics-structural testing of lower limb prostheses-requirements and test methods (ISO 10328) is the basis of the experimental procedure. It is followed to obtain the proper load application angles for the heel and toe, loading speed, and maximum loading force. Accordingly, a multicycle compression test is conducted to load the foot up to 1600 N and stop [14]. The forces are applied to the heel at an angle of 15° and the toe at an angle of 20° with respect to the axis of the tibia [14, 15]. The loading of the passive foot is divided into two phases: HS and TO. The schematic of the equivalent boundary condition is shown in Fig. 3.

3. 3D printing of optimized model

The ability to easily design and manufacture prosthetic feet with novel design characteristics has a great potential to improve the amputee rehabilitation and care [16]. This study presents a design process using topology optimization methods to develop a new prosthetic foot. Topology optimization is a mathematical approach that optimizes material layout within the given design space for a given set of loads and boundary

Table 1. Results of PLA specimen tensile test.

Specimens	Maximum load (N)	Tensile stress at maximum load (MPa)	Tensile stress at yield (Offset 0.2 %) (MPa)	Young's modulus (MPa)
1	2280.85	57.02	39.31	3867.57
2	2243.33	56.08	38.48	3858.17
3	2249.50	56.24	32.34	4316.84
Average value	2257.89	56.45	36.71	4014.20

Table 2. Properties of PLA material.

Properties	Values
Density (g/mm^3)	1.24e-03
Poisson ratio	0.36
Young's modulus (MPa)	4014.20
Yield strength (MPa)	36.71

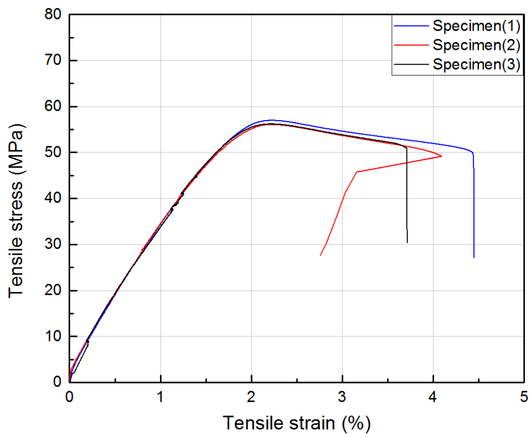

Fig. 4. Tensile stress–strain curve of PLA specimens.

conditions such that the resulting layout meets a prescribed set of performance targets [17]. With the use of topology optimization, it is easy to determine the best design concept that not only meets the design requirements but also reduces the design development time and overall cost while improving the design performance. In some cases, proposals obtained using topology optimization, although optimal, may be expensive or difficult to manufacture. Additive manufacturing (AM) is often used to develop complex optimized shapes. 3D printing employs an AM process whereby products are developed on a layer-by-layer basis using a series of cross-sectional slices. All 3D printers use a 3D software that measures the cross-sections of each product at thousands of instances to determine exactly how each layer is to be constructed. 3D printing is most widely used in applications with low production volumes, small part sizes, and intricate designs. The advantages of 3D printing in comparison to other technologies include the ability to build custom products economically in limited production runs, the capacity to share designs and outsource manufacturing, and the speed and ease of designing and modifying a product [18]. The materials used for 3D printing differ with the 3D printing method. PLA typically used in Fused deposition modeling (FDM) is a biodegradable, thermoplastic, aliphatic polyester derived from renewable resources such as cornstarch or sugarcanes. It has several benefits including low weight, easy machining, and environmental protection. The PLA material tensile test was conducted to obtain the yield strength of the PLA material according to ISO 527, Plastics-determination of tensile properties. There are three PLA specimens prepared for the tensile test. The parameters and results are shown in Fig. 4 and Table 1, respectively. Tensile stress–strain curve of PLA specimens shows the specimens have no apparent yield point. Thus, offset yield stress is considered as the actual use of the limit of the PLA material. Mechanical properties of the PLA specimens were measured and recorded by a Universal testing machine (UTM), and the average values were calculated. The material properties used in topology optimization and the experiments are listed in Table 2 [19].

4. Results and discussion

For the stable installation of the male pyramid adapter, the initial model is divided into a design space and a non-design space. By discretizing the domain into a finite element mesh, the optimization algorithm in OptiStruct calculates the material properties for each element. The optimization algorithm in OptiStruct alters the material distribution to optimize the objective under the given constraints. Each element of the model is assigned a legend color, indicating the density of each element for the selected iteration. Regions that need reinforcement tend towards a density of 1. Regions that do not need reinforcement tend towards a density of 0 [20]. Removing the regions that do not need reinforcement to obtain the final model. The topology optimization process of the designed prosthetic foot is illustrated in Fig. 5. The topology-optimized model has a smooth outer surface and a rough inner surface. The smooth outer surface not only satisfies the applicability but also ensures the aesthetics. Meanwhile, the rough inner surface has no effect on use. Although the topology-optimized model is too difficult to be interpreted precisely using a Computer-aided design (CAD) software, but it is easy to be manufactured accurately by FDM 3D printer directly.

The FE analysis is a useful tool for the determination of the stress and strain behavior in the lower limb prosthetic [21]. The FE model of the geometrical model is constructed by

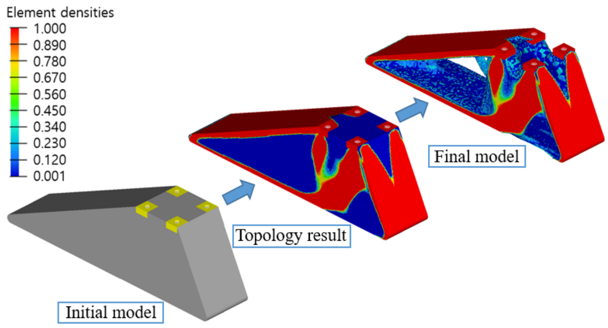

Fig. 5. Topology optimization process of designed prosthetic foot.

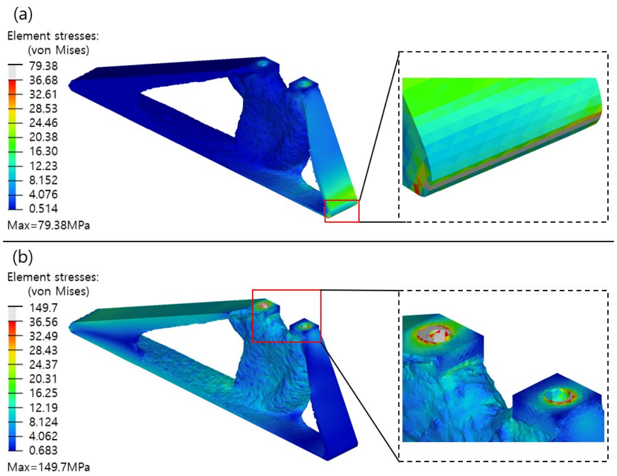

Fig. 6. Sectional view of the von Mises stress of the prosthetic foot at (a) heel strike; (b) toe off.

using HyperMesh automesh features. Then, OptiStruct 13.0 is used for structural FE analysis. Fig. 6 shows the sectional view of the von Mises stress of the prosthetic foot with the peak stress area enlarged. Because the ground reaction forces and the constraints were applied on the geometrical model directly. The elements located at boundary conditions are affected significantly by the concentration of stress. The value of the peak stress is higher than the yield strength of the PLA material obtained using a tensile test. In the HS state, the maximum stress appeared at the heel, which is simplified as a rigid component. In the TO state, the maximum stress appeared at the bolt holes, which are simplified as rigid elements. The node of a rigid element is regarded as the point of application, and the stress at that point is negligible based on Saint-Venant's principle.

Table 3 shows the comparison between the initial model and the topology-optimized model with respect to the peak von Mises stress and the peak displacement at loading conditions. From the Table 3, it can be observed that the value of the von Mises stress and peak displacement increase after topology optimization. However, the weight of the prosthetic foot decreases from 0.79 kg to 0.30 kg. 62 percent of the weight reduction is important to reduce the burden of a patient and improve the performance of walking.

Table 3. Comparison of FEA results between initial and topology-optimized model.

Result type	Model	HS	TO
Von Mises stress (MPa)	Initial model	51.85	138.01
	Topology-optimized model	79.38	149.70
Displacement (mm)	Initial model	0.29	2.07
	Topology-optimized model	0.54	3.39

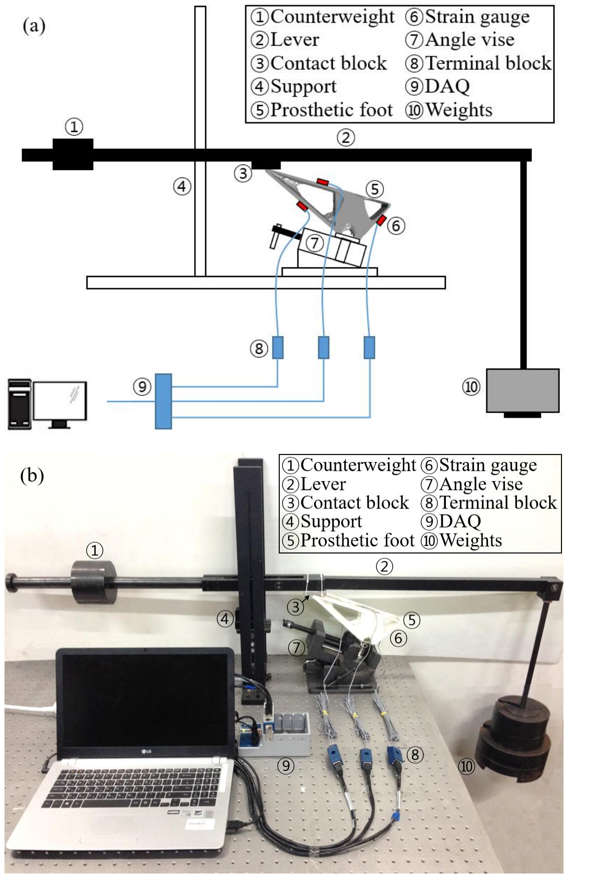

Fig. 7. Prosthetic foot test equipment: (a) Schematic diagram; (b) actual photograph.

To test and verify the topology-optimized model, the test equipment shown in Fig. 7 is designed and installed. The equipment main consisted of a lever, strain gauges, angle vise and data acquisition (DAQ) system. The DAQ system consists of strain gauges (N32-FA-5-120-11-VS3), a DAQ measurement hardware (NI 9237), and a computer with a programmable software (LabVIEW). The principle of leverage is utilized for the tests. The equipment applies a force by using a lever in which the ratio of the length of the power arm to that of the resistance arm is five. By adding 32 kg weights to achieve a force of approximately 1600 N. The experimental trials consisted of the HS test (HS angle of 15°) and TO test (TO angle of 20°). The prosthetic foot is fixed and changed the inclination by adjusting the angle vise. Through the synergism between lever and angle vise, imitated the boundary conditions

Table 4. Comparison between stress obtained from FE analysis and that measured using strain gauge.

Load condition	HS	TO	
Position of strain gauge	A	B	C
Stress (FE analysis) (MPa)	7.99	9.59	10.91
Stress (Strain gauge measurement) (MPa)	8.43	9.83	11.50

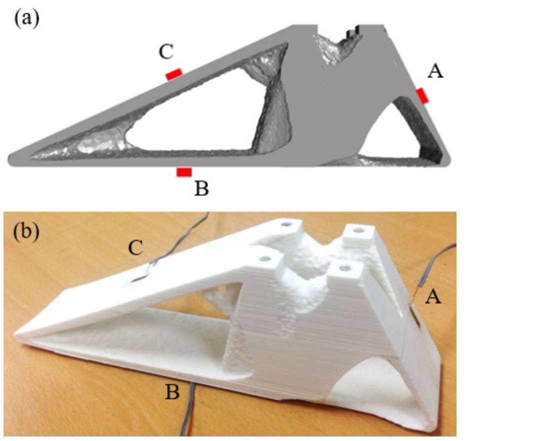

Fig. 8. Positions of strain gauge: (a) Schematic diagram; (b) actual photograph.

of HS and TO. The strain gauge measured the strain and converted the physical phenomenon into a measurable electrical signal that can be obtained by using a DAQ device [22]. The schematic diagram and the actual image of the positions of the strain gauge are shown in Figs. 8(a) and (b), respectively. Positions A, B and C are selected and the strain gauges connected to a quarter bridge are attached to the three positions. Table 4 shows the comparison between the stress determined using the FE analysis and that measured using a strain gauge. The strain gauge located at position A measur-es the stress in the HS test. Similarly, the strain gauges located at positions B and C measure the stress in the TO test. In spite of some discrepancies, the numerical and experimental results show a good agreement; thus, the results are suitable for stress evaluation.

Throughout the process, referring to prosthetics-structural testing of lower limb prostheses-requirements and test methods (ISO 10328), two boundary conditions have served for optimizing and validating the structure. 3D printers provide a great convenience for the manufacture of the prosthetic foot. But there are limitations in the choice of materials which could be available in 3D printers. PLA materials are chosen in herein. The prosthetic foot designed and manufactured in this study shows its superiorities comparing to the previously designed prosthetic feet made of PLA (Full scale prototype V2), such as in terms of decreasing weight and improving safety. The prosthetic foot is weighted 0.30 kg which is 0.034 kg lighter than the Full scale prototype V2 previously tested [10]. Benefit from the use of topology optimization, its own weight is drastically reduced while the structure is maintained at a high strength. Furthermore, compared with the prosthetic foot designed with topology optimization method previously [16], the boundary conditions in this study are set to heel strike and toe off instead of toe off and foot flat. At the same time, the limit of load is also increased significantly. It greatly enhances the stability and safety of the prosthetic foot during use.

5. Conclusions

In this study, a design optimization and manufacturing process have been proposed and applied. Through this process, a prosthetic foot made of PLA manufactured using an FDM 3D printer is designed and tested. Considering the customization needs, the initial model is optimized by using topology optimization methods and the optimized model is printed directly using an FDM 3D printer for reducing the weight of the prosthetic feet. The safety of the structure is validated by using the FE analysis, which is then verified by using a strain gauge test. The FDM 3D printer, a common desktop printer, is often owned by individuals and laboratories. It means that patients can print the prosthetic feet by themselves. Meanwhile, the PLA material, a type of the FDM material, has low weight, low cost, and environment-friendly features. Finally, it reduces the weight of the prosthetic foot from 0.79 kg to 0.30 kg. 62 percent of the weight reduction plays an important role in attaining patient satisfaction. Even though this is not a perfect design, it should be emphasized that this design process is a good method to achieve prosthetic weight reduction and shorten the design and manufacturing cycle.

Acknowledgment

This research was supported by Inha University.

References

[1] B. Meikle, C. Boulias, T. Pauley and M. Devlin, Does increased prosthetic weight affect gait speed and patient preference in dysvascular transfemoral amputees?, *Archives of Physical Medicine and Rehabilitation*, 84 (11) (2003) 1657-1661.

[2] D. Rihs and I. Polizzi, *Prosthetic Foot Design*, Rehab Tech-Monash Rehabilitation Technology Research Unit (1996).

[3] R. Versluys, P. Beyl, M. Van Damme, A. Desomer, R. Van Ham and D. Lefeber, Prosthetic feet: State-of-the-art review and the importance of mimicking human ankle–foot biomechanics, *Disability and Rehabilitation: Assistive Technology*, 4 (2) (2009) 65-75.

[4] P. Cherelle, V. Grosu, A. Matthys, B. Vanderborght and D. Lefeber, Design and validation of the ankle mimicking prosthetic (AMP-) foot 2.0, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 22 (1) (2014) 138-148.

[5] B. Brackx, M. Van Damme, A. Matthys, B. Vanderborght and D. Lefeber, Passive ankle-foot prosthesis prototype with extended push-off, *Int. J. Adv. Robot. Syst.* (2013).

[6] J. Geeroms, L. Flynn, R. Jimenez-Fabian, B. Vanderborght and D. Lefeber, Ankle-knee prosthesis with powered ankle and energy transfer for CYBERLEGs α-prototype, *Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on IEEE* (2013) 1-6.
[7] H. M. Herr and A. M. Grabowski, Bionic ankle–foot prosthesis normalizes walking gait for persons with leg amputation, *Proc. R. Soc. B, The Royal Society,* 279 (1728) (2012) 457-464.
[8] M. Sam, D. Childress, A. Hansen, M. Meier, S. Lambla, E. Grahn and J. Rolock, The 'shape & roll' prosthetic foot: I. Design and development of appropriate technology for low-income countries, *Medicine, Conflict & Survival*, 20 (4) (2004) 294-306.
[9] C. Y. Ko, S. B. Kim, J. K. Kim, Y. Chang, H. Cho, S. Kim and M. Mun, Biomechanical features of level walking by transtibial amputees wearing prosthetic feet with and without adaptive ankles, *Journal of Mechanical Science and Technology*, 30 (6) (2016) 2907-2914.
[10] J. Yap and G. Renda, *Low-cost 3D-printable Prosthetic Foot* (2015).
[11] A. A. Ahmed, Estimation of sex from the lower limb measurements of Sudanese adults, *Forensic Science International*, 229 (1-3) (2013) 169.e1-169.e7.
[12] V. T. Inman, H. J. Ralston and F. Todd, *Human Walking,* Williams & Wilkins (1981).
[13] J. Zhu, Q. Wang and L. Wang, On the design of a powered transtibial prosthesis with stiffness adaptable ankle and toe joints, *IEEE Transactions on Industrial Electronics*, 61 (9) (2014) 4797-4807.
[14] A. Schmitz, Stiffness analyses for the design development of a prosthetic foot, *Doctoral Dissertation*, University of Wisconsin-Madison (2007).
[15] M. S. El-Mohandes and M. E. H. Ibrahem, Stiffness analyses of modified niagara prosthetic feet using finite element modelling, *Biomedical Engineering Conference (CIBEC), 2014 Cairo International IEEE* (2014) 19-23.
[16] N. P. Fey, B. J. South, C. C. Seepersad and R. R. Neptune, Topology Optimization and Freeform Fabrication Framework for Developing Prosthetic Feet, *Solid Freeform Fabrication Symposium* (2009) 607-619.
[17] M. P. Bendsoe and O. Sigmund, *Topology Optimization: Theory, Methods, and Applications*, Springer Science & Business Media (2013).
[18] B. Berman, 3-D printing: The new industrial revolution, *Business Horizons*, 55 (2) (2012) 155-162.
[19] B. Bax and J. Müssig, Impact and tensile properties of PLA/Cordenka and PLA/flax composites, *Composites Science and Technology*, 68 (7) (2008) 1601-1607.
[20] S. Subramaniam, R. Bathina and P. K. Tripathi, Interpretation of 3D Optimization Results with Best Design Variants, *Altair Technology Conference*, India (2013).
[21] M. Omasta, D. Paloušek, T. Návrat and J. Rosický, Finite element analysis for the evaluation of the structural behaviour, of a prosthesis for trans-tibial amputees, *Medical Engineering & Physics*, 34 (1) (2012) 38-45.
[22] J. Park and S. Mackay, *Practical data acquisition for instrumentation and control systems*, Newnes (2003).

Zhen Tao received his Bachelor of Science degree in 2015 from Mechanical Engineering, Hannam University, Korea. He is a master student in the Department of Mechanical Engineering, Inha University, Korea. His research interests are in the areas of 3D printing, tribology (friction, adhesion and wear), structural FE analysis and optimization.

Chul-Hee Lee is a Professor in the School of Mechanical Engineering, Inha University, Korea. He received his Bachelor of Science degree in 1994 and Master of Science degree in 1996, both from Mechanical Engineering, Inha University, Korea, and his Doctor of philosophy degree in 2006 from Mechanical & Industrial Engineering, University of Illinois at Urbana-Champaign, USA. His research interests are in the areas of transportation-vehicle components design and controls, tribology (friction, adhesion, wear and lubrication), structural FE analysis and optimization, vehicle dynamic and vibration analysis, smart materials and mechanical control.