Development of Artificial Foot of Active Transfemoral Prosthesis System using Topology Optimization

K.-H. Lee, J. H. Chung and C.-H. Lee

***Abstract*— This paper presents the design and optimization of the artificial foot of the active transfemoral prosthesis system. As the prosthesis leg should work according to the intention of the user, the artificial foot is used as a sensor to measure gait cycle.In order to estimate the gait cycle, strain gauges have been located heel and toe of the artificial foot to measure the loads on each part, separately. The locations of strain gauges have been determined by the result of finite element analysis. As the weight of the artificial foot is one of the important factors for users, the topology optimization is conducted to draw an optimized model that can stand the weight of the user with minimum volume. After the optimization, the finite element analysis has been conducted to verify the stability. Finally, the signals from artificial foot have been acquired by the experimental method to verify the gait cycle. Furthermore, the analysis result and experimental result have been compared to verify the reliability of analysis using the acquired signals.**

***Index Terms*— Active Transfemoral Prosthesis System, Topology Optimization, Finite Element Analysis, Artificial Foot**

I. Introduction

THE number of disabled people in South Korea has been increased continuously, which is expected to increase from 2.5 million in 2012 to 500 million in 2050. In addition, 53 percent of the disabled people, about 1.3 million, are the physically disabled people [1]. Also, about half of the physically disabled people are suffering from the disability of the lower body. Furthermore, almost of the lower body disabled people are leg amputee due to vehicle or industrial accidents. Also, some diabetic patients may cut some part of their body. Especially, patients who cut their leg from the upper part of the knee, about 7 million people around the world, are the most important amputees [2].

According to previous studies, the knee joint, such as more than half of the walking importance to provide a dominant effect on the human walking. Therefore, compared to the lower leg amputee, the transfemoral amputee will be subject to significant constraints on walking. Thus, the transfemoral prosthesis which can support the amputees to walk similar as human is needed to be developed. Therefore, various types of prosthesis – Passive, Semi-Active and Active - to help the patients walk have been developed. However, passive and semi-active prosthesis cannot make a perfect motion that the amputees want. As a results, active prosthesis leg has been studied to replace the passive and semi-active prosthesis leg. The most advanced kind of active prosthesis leg is a robotic leg that contains fully active actuators, sensors and micro control unit, which is possible to determine walking mode by sensing states of the prosthesis legs itself. The first step of the developing active prosthesis leg is knee joint development for the prosthesis. Because the knee joint motion is an important factor of the human gait cycle [3]. Flowers et al. researched preliminary types of active knee prosthesis legs [4-8]. An electronically controlled hydraulic actuator to operate these early prototype active prosthesis knees has been adopted. Moreover, they have a three-linkage structure that has the electrohydraulic actuator as a variable link. The electrohydraulic actuator is specified to generate a linear motion and the structure of electrohydraulic used mechanism is inspired by following studies on active prosthesis leg using an electric motor. A number of earlier studies on the active prosthesis that use an electric motor as its own power source has a ball screw which roles of electrohydraulic actuator [9-10].

Carl et al.'s study [9] is the most fundamental study of the active transfemoral prosthesis. However, the weight of the system, which makes the users more comfortable due to less tiredness, and the knee joint torque to increase the stability of the system are major factors of prosthesis leg system. Thus, the three-linkage type active transfemoral prosthesis system using various actuators has been developed in many former researches. However, the three-linkage type has limitations of performance and weight due to the dimension. Thus, the mechanism of prosthesis needed to change to increase the performances and the weight reduction. Also, the torque applied to the real human knee joint during walk shows different values and it depends on the gait cycle [11]. In addition, prior to walking, the load applied to the heel acts differently for every cycle [12]. By measuring the values in real time from the artificial foot, the active transfemoral prosthesis can determine the gait cycle by itself. In this study, the artificial foot for the active transfemoral prosthesis system has been developed to estimate the gait cycle using strain gauges.

This research was supported by the MSIP(Ministry of Science, ICT and Future Planning), Korea, under the C-ITRC(Convergence Information Technology Research Center)support program(IITP-2015-H8601-15-1003) supervised by the IITP(Institute for Information & Communications Technology Promotion)

K.-H. Lee is with the Department of Mechanical Engineering, Inha University, Incheon, 402751, South Korea

J. H. Chung was with Inha University. He is now with R&D Team, LG Electronics, Changwon, 642713, South Korea

C.-H. Lee is with Department of Mechanical Engineering, Inha University, Incheon, 402751, South Korea. (e-mail: chulhee@inha.ac.kr).

II. THREE-LINKAGE TYPE ACTIVE TRANSFEMORAL PROSTHESIS SYSTEM

In this study, the three-linkage type prosthesis system with one DOF model that has been developed in the previous study [13] has been used. As shown in the Fig. 1, the system has three main parts - knee joint, main frame and actuator housing. The weight of the prototype is 1,946.0g, and the minimum length of the system is 450 mm, and a range of length adjustment is maximum 26 mm. In addition, the absolute encoder to measure the absolute angle of the knee joint, the ball screw to change from the rotational motion of the BLDC motor to the a linear motion, for load cell to measure the load and the torque applied to the knee have been attached. When the motor runs, the prosthesis can rotate from 0 degree to 90 degrees shown in Fig. 2. The current prosthesis system used Load cell to measure the torque applied to the knee. Then it has been used to determine the gait cycle.

III. RESULT OF DESIGN AND ANALYZE OF ARTIFICIAL FOOT

As shown in Fig. 3, the walking algorithm of active transfemoral prosthesis consists of 5 steps. The artificial foot of this study has been developed to determine the phase of the gait cycle. To determine the phase, the load applied to each part, front and rear of the artificial foot measured in real-time.

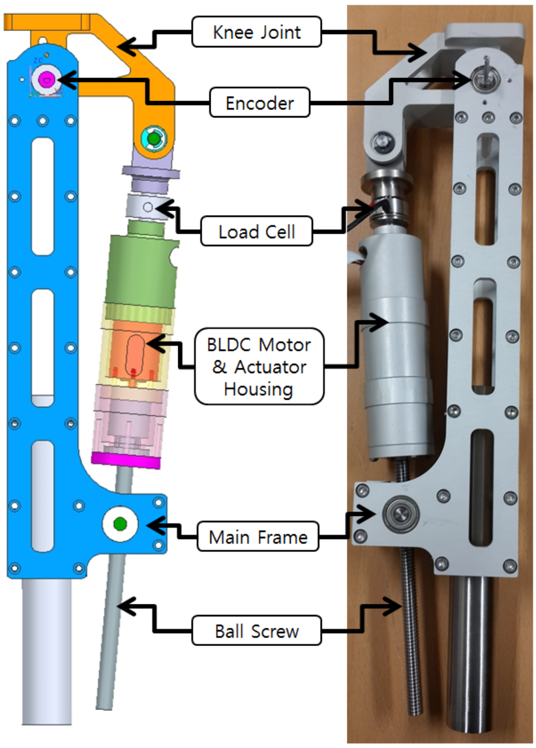

Fig. 1. Three-linkage type active transfemoral prosthesis system

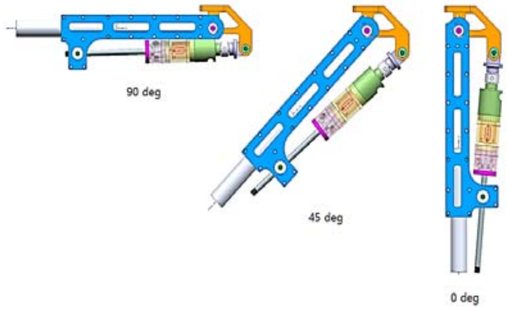

Fig. 2. Operating angle of three-linkage type active transfemoral prosthesis system

Then find the pre-landing and pre-swing phases which are the factor to classify stance phase and swing phase. By this real-time measurement, the active prosthesis system can walk by determining the current gait cycle. Also, the basic structure of the artificial foot is similar to the bones of the human foot [14]. For the basic model of an artificial foot, bone structure of the actual human foot, and has a structure of the artificial leg which has been produced by considering the design from Vanderbilt University as a reference. The foot consists of three parts, toe, heel, and ankle. To replicate the space under the foot, the parts have been inclined about 9 degrees for the toe part, 5 degrees for the heel part. The 3D design of basic model is shown in Fig. 4. For the basic model of artificial foot, there are some holes at the toe and heel parts to reduce weight because the topology optimization was not carried out. Therefore, only finite element analysis has been conducted to verify the reliability. The analysis conditions are shown in Fig. 5. The constraints have been added to the front and rear part where the contact between the artificial foot and the land exists. Moreover, the loads have been applied to three directions, Fig. 5(a) presents the load of pre-swing, Fig 5(b) presents the load of stance, and the Fig. 5(c) presents the load of pre-landing. The analysis has been conducted under these conditions.

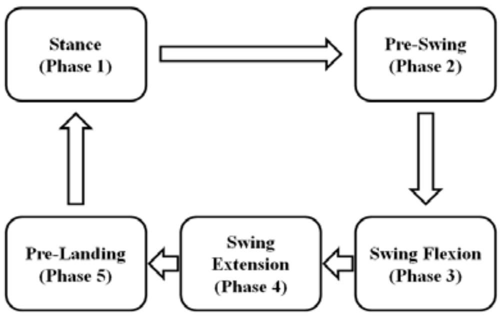

Fig. 3. Walking algorithm of active transfemoral prosthesis system

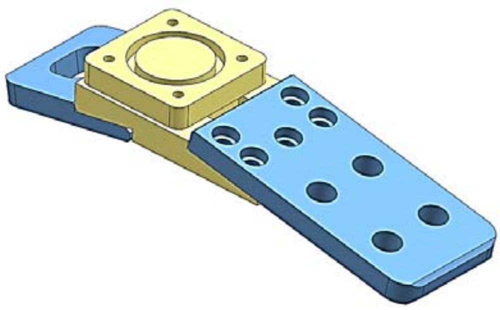

Fig. 4. 3D design of basic model of artificial foot

Fig. 6 and Fig. 7 show the results of the analysis. According to Fig. 9, the FEA results show that the front side of ankle part shows the most amount of stress, 85.3MPa, which is lower than the tensile strength of the material AL6061-T6, 276MPa.

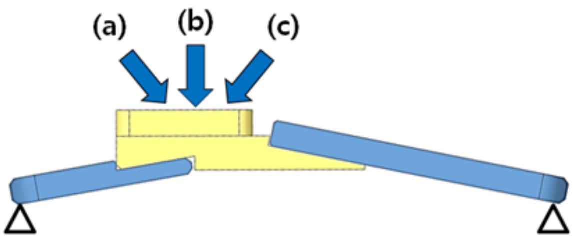

Fig. 5. Analysis conditions of basic model of artificial foot

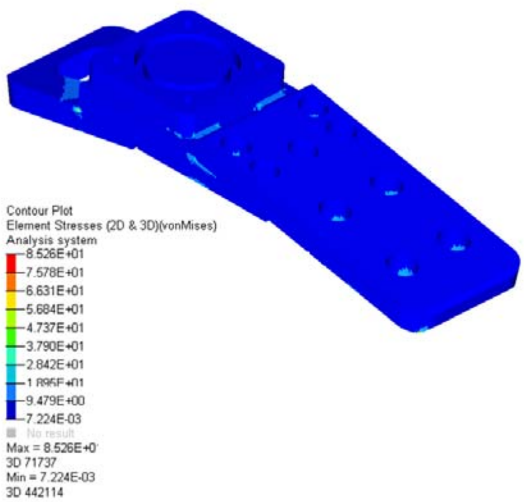

Fig. 6. Finite element analysis result of basic model of artificial foot – Element stresses

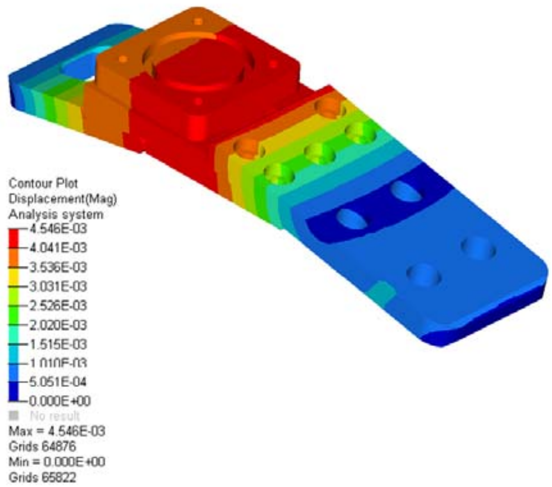

Fig. 7. Finite element analysis result of basic model of artificial foot – Displacement

Also, the maximum displacement is 0.005mm, as shown in Fig. 7. To use the results of FEA, the location of strain gauges to measure the load applied to the foot have been selected. For the toe part, the area of 0.001 mm deformed has been selected. And the area of 0.004mm deformed has been selected for the heel part. The locations of strain gauge have been selected at the parts which have different amount of deformation to see the signals separately. The prototype of basic model of artificial foot is shown in Fig. 8. Using the prototype shown in Fig 8, the signal from the strain gauges on the artificial foot has been acquired to determine the load applied to each part, front and rear of the artificial foot measured in real-time. Then find the pre-landing and pre-swing phases which are the factor to classify stance phase and swing phase.

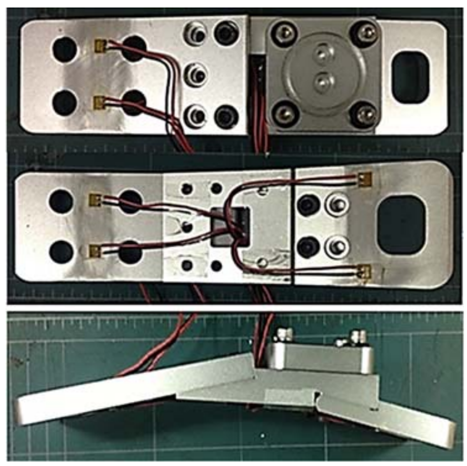

Fig. 8. Prototype of basic model of artificial foot

ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

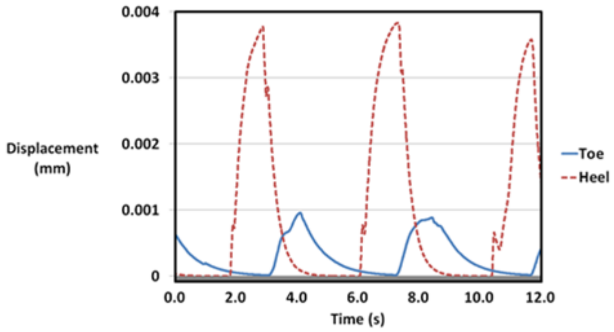

Fig. 9. Acquired signals of strain gauges on basic model of artificial foot during the gait cycle

As shown in Fig. 9, the gait cycle has been determined by three steps using displacements. The pre-landing has been shown from 2.0 to 3.0 seconds. And the stance has been shown from 3.0 to 4.0 seconds. And the pre-swing has been shown from 4.0 to 5.0 seconds. To use these three steps, the active transfemoral prosthesis system could control the knee joint angle similar with the human's gait cycle. By this real-time measurement, the active prosthesis system can walk variously by determine the current gait cycle. Furthermore, the displacement generated from the signal shown in Fig. 9 has been compared with the analysis result shown in Fig. 7. According to the comparison, the actual displacement of toe part is 0.0009 mm, which is 10% smaller than the displacement from the analysis result, 0.001 mm. Furthermore, the actual displacement of heel part is 0.0038 mm, which is 5% smaller than the displacement from the analysis result, 0.004 mm. The difference between the load condition of analysis, 150 kg and the weight of the person who gives a demonstration, 80 kg could be the reason of the difference between actual and analysis results.

IV. CONCLUSION

In this study, an artificial foot has been developed. The pre-landing, stance and pre-swing status have been determined. By using the status, the knee joint of active transfemoral prosthesis could be controlled related to gait cycle. Furthermore, the displacement generated from the signal has been compared with the analysis result. According to the comparison of basic model, the actual displacement of toe part is 0.0009 mm, which is about 10% smaller than the displacement from the analysis result of original model, 0.001 mm. Furthermore, the actual displacement of heel part is 0.0038 mm, which is about 5% smaller than the displacement from the analysis result of the original model, 0.004 mm. Moreover, the mass of artificial foot should similar with human's foot for carrying out activities more comfortably. The design of artificial food need to optimize for keep the similar mass with human's foot in the further work.

REFERENCES

[1] Ministry of Employment and Labor of Korea, "2012 Statistics of Disabled", pp. 26-49, 2012
[2] F. Sup, H. A. Varol, J. Mitchell, T. J. Withrow and M. Goldfarb, "Preliminary Evaluations of a Self-Contained Anthropomorphic Transfemoral Prosthesis", *IEEE, transl. on mech*., vol. 14, no. 6, pp. 667-676, 2009.
[3] J. Lin, Y. Wu and T. S. Huang, "Modeling Constraints of Human Hand Motion", *Workshop on Human Motion*, pp.121-126, 2000.
[4] W. C. Flowers, "A Man-Interactive Simulator System for Above-Knee Prosthetics Studies", Ph.D. thesis, *MIT*, 1972.
[5] J. L. Stein, "Design Issues in the Stance Phase Control of Above-Knee Prosthesis", Ph.D. thesis, *MIT*, 1983.
[6] M. Donath, "Proportional EMG Control for Above Knee prostheses", MS thesis, *MIT*, 1974.
[7] J. L. Stein and W. C. Flowers, "Stance Phase Control of Above-Knee Prostheses: Knee Control Versus Sach Foot Design", *Journal of Bio Mech.*, vol. 20, no. 1, pp. 19-28, 1987.
[8] D. L. Grimes, "An Active Multi-Mode Above-Kee prosthesis Controller", Ph. D thesis, *MIT*, 1979.
[9] C. D. Hoover, G. D. Fulk and K. B. Fite, "The design and initial experimental validataion of an active myoelectric transfemoral prosthesis", *J. Med. Devices*, vol. 6, no. 1, pp. 1-12, 2012.
[10] K. Fite, J. Mitchell, F. Sup and M. Goldfarb, "Design and control of an electrically powered knee prosthesis", *IEEE 10th Int. Conf.*, Noordwijk, 2007, pp. 902-905.
[11] D. A. Winter, "Biomechanics and motor control of human movement", *John Wiley& Sons, Inc*., 4th ed., pp. 346-349. 2009.
[12] C. H. Kim, S. H. Lee, S. Y. Shin and J. W. Lee, "Design of an 1 DOF Assistive Knee Joint for a Gait Rehabilitation Robot", *J. Korea Rob. Soc*., vol. 8, no. 1, pp. 8-19, 2013.
[13] K. H. Lee, J. H. Chung and C. –H. Lee, "Design and Optimization Study of Active Transfemoral Prosthesis Leg", *RESKO*, vol. 7, no. 2, pp.41-46, 2013.
[14] Foot Education, "Bones of the Foot and Ankle", http://www.footeducation.com/bones-of-foot-and-ankle