BIOMECHANICS: APPLICATIONS IN REHABILITATION

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Contents

Summary

This article shows the use of some mechanical principles to solve problems in lower-limb prosthetics, which serves as an example of applying biomechanics in the field of rehabilitation. Compensatory walking patterns, structural failure of the prosthesis and residual limb pain are commonly seen in people using prostheses. In an attempt to solve these problems, computational finite element modeling, theories of optimizing mechanical designs, structural tests, and gait analysis were used to evaluate and optimize the design of a prosthesis.

1. Introduction

There are at least 3 million amputees globally (Murdoch, 1990). Most amputations involve the lower limb at the trans-tibial level. The use of prostheses is one of the most important rehabilitation programs for those who lose their limbs. A high-quality lower-limb prosthesis can restore the locomotive function of the lost limb, and can boost functional status, physical appearance, as well as general health. However, it is not uncommon that residual limb pain, gait deviation and prosthetic structural failure occur when using a lower-limb prosthesis.

A good understanding of biomechanics is required to address these problems. High mechanical stress applied to the residual limb from the prosthetic socket is a major cause of residual limb pain. A lack of prosthetic ankle motion results in gait deviation. While some flexibility and ankle motions could improve gait, high loading can result in structural failure. There is a need for improved mechanical design of a prosthesis to enable lower-limb amputees to walk more efficiently, safely and comfortably.

Biomechanics has been widely used for different purposes in rehabilitation engineering. As an example, this chapter introduces the use of state-of-the-art biomechanical technologies in mechanical design and assessment of a prosthesis and covers gait, the relationship between pain and mechanical stress, as well as prosthetic socket-residual limb interface stresses (Zhang and Lee, 2006; Lee and Zhang, 2005, 2006,2007, Lee et al, 2004a&b, 2005, 2006). The following approaches are used:

- *Structural test*

ISO 10328 documents the test specifications for all components of trans-tibial and trans-femoral prostheses. A single test load is applied to the test prostheses, representing the desired combined loads which provide antero-posterior, medio-lateral bending moments, as well as torsional moments. The direction, magnitude and point of applications of loads, loading rate, as well as alignment of the prosthesis are specified in the standard.

There are two different test loading conditions: condition I is related to the instant of maximum loading occurring early in the stance phase of walking (heel strike), and condition II is related to the instant of maximum loading occurring late in the stance phase (toe off). Different load magnitudes are available, taking into account the amputees' physical parameters, such as body weight and locomotion characteristics.

The test comprises of *static* and *cyclic* tests. The static test relates to the highest anticipated loads generated in any activity. The load can be over three times of the body weight. The cyclic test relates to normal walking activities where loads occur regularly with each step. A prosthesis fails to comply with the ISO standard in static or cyclic test if it structurally fails or is permanently deformed at specified loading conditions.

- *Computational finite element modeling*

Commercially-available software packages enable users to build three-dimensional model in a computer environment, and compute the mechanical stress upon application of loads using finite element (FE) analysis. FE analysis reduces large and complex structure into small elements of simple shapes. Equations (using classic mechanics) are used to describe force and displacement of each element. The entire structural behavior can then be calculated by solving various equations.

FE analysis has advantages over experimental test in that stress/strain can be analyzed over the entire structure and parametric analysis can be performed efficiently. The accuracy of model computations depends on the geometrical representation, assignment of mechanical properties and loads, as well as the simulation techniques for the contact between the two structures.

FE analysis can compute the stress and strain within the model. The study of the prosthetic socket-residual limb interface stress allows design improvement of the socket. Together with the use of some failure criterion theory, in addition, mechanical failures of a prosthesis can be predicted. There are different failure criterion theories for various types of materials. For example, distortion strain energy theory is used to predict failure of ductile materials in which material failure occurs if the computed von Mises stress is above the yield stress of the material.

- *Design optimization*

Different design parameters exist in lower-limb prostheses. For example, the choice of material, material thickness and shank dimensions are related to the structural strength of a prosthesis. There are a number of methods to determine the optimum prosthetic design configuration. "Vary-one-factor-at-a-time" is popularly used in which the effect of one factor, for example the thickness of the material, is assessed by varying only that factor while keeping the other factors fixed at a specific condition. However, this method can sometimes lead to wrong results as the effect of the factor can be changed if other factors are substituted with different conditions (Phadke, 1989; Park, 1996). Another approach is to explore every possible combination of values of each factor. The drawback is that total number of experiments or simulations will be very high. A statistical approach developed by Taguchi utilizes an orthogonal array, which is a form of fractional factorial design containing a well-chosen subset of all possible combination of test conditions (Phadke, 1989; Park, 1996). Using Taguchi method, a balanced comparison of levels of any factor and significant reduction in the total number of required simulations can both be achieved.

- *Gait analysis*

Force platforms measure the ground reaction forces during walking, which reflect the efficiency and stability of walking. A force platform is usually synchronized with a motion analysis system using reflective markers and cameras. A motion analysis system allows accurate measurement of movement of body segments. The cameras of the motion analysis system obtains the coordinates of the markers by detecting the reflection of the infra red light from the markers.

Normal gait is characterized by a high degree of symmetry between both legs in terms of temporal, kinetic and kinematics parameters, which allow an energy efficient mode of gait (Hirokawsa, 1989; Isakov et al, 1996). Trans-tibial amputee patients using a prosthesis, however, usually demonstrate asymmetries between the sound and prosthetic limbs. Specifically, the prosthetic limb has a shorter stance phase time, longer step length and swing time, lower range of knee flexion and vertical peak forces than the sound limb (Isakov et al, 1996; Isakov et al, 1997, 2000; Bateni and Olney, 2002). Lower-limb amputees walk with lower speeds and higher energy cost than non-amputees (Gailey et al, 1994; Molen, 1973).

Previous research (Michael, 1992; Gard and Konz, 2003; Coleman et al, 2001) suggests that amputees generally prefer more flexible prostheses with dynamic elastic response and shock absorption properties to conventional ones with a Solid-Ankle-Cushioned Heel (SACH) foot that is rigidly connected to the prosthetic socket through a metal pylon. However, objective gait assessments could not generally reach a conclusion whether or not more flexible prosthesis significantly outperformed conventional ones.

2. Structural Test and Design Optimization

A trans-tibial prosthesis consists of a prosthetic socket, a shank portion, and a prosthetic foot. The prosthetic socket is rigidly attached to the prosthetic foot by means of a metal pylon and some adaptors (Figure 1). Lack of ankle motions are believed to be the major cause of gait deviation (Winter, 1983; Bowker and Kazim, 1989; Brandell, 1977).

Another approach is to fabricate the socket together with the shank out of one piece of high-temperature thermoplastic material (Figure 1). The prosthesis is named ‘monolimb’, denoting the use of one piece of material. Reducing the material thickness and the cross-sectional area of the shank is postulated to increase shank flexibility and could therefore potentially compensate for the loss of ankle motions. However, high flexibility can compromise structural strength. Structural failures of prostheses can lead to serious consequences, such as fall and injuries. This section demonstrates the applications of structural tests, using both computational and experimental approaches and a statistical-based optimization method for improved monolimb design. Attempt is made to develop some guidelines for the shank design, striking the balance between flexibility and strength.

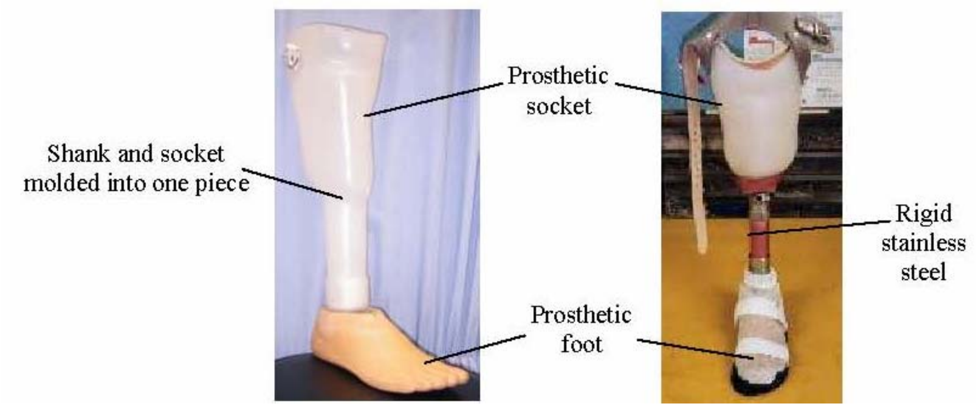

Figure 1. (left) monolimb and (right) conventional trans-tibial prosthesis.

2.1 Static Test Using Computational Modeling

Four design factors of the monolimb were chosen, namely the thickness (T) of the thermoplastic material, depth of posterior seam line (S), anteroposterior (AP) and medial-lateral (ML) dimensions of the shank (Figure 2). Using a commercial CAD software, different monolimb shank geometries were created, as shown in Table 1. Foot block, socket filler, extension rod were added (Figure 2) so that the load applied was offset from the prosthesis as instructed in ISO10328.

A commercially-available FE software was used to compute the mechanical response when specific loadings were applied to the prosthesis. 3D tetrahedral elements were used to mesh the parts. The mesh densities of the monolimbs were chosen such that convergence of the maximum principle stress was within 3% of that of the previous coarser mesh. The Young’s modulus and Poisson’s ratio of the monolimb were assigned, based on the polypropylene homopolyer material properties. Foot block, adaptor, screw and extension rod were assumed to be rigid. Loadings were added as specified in ISO10328, simulating heel off during normal walking.

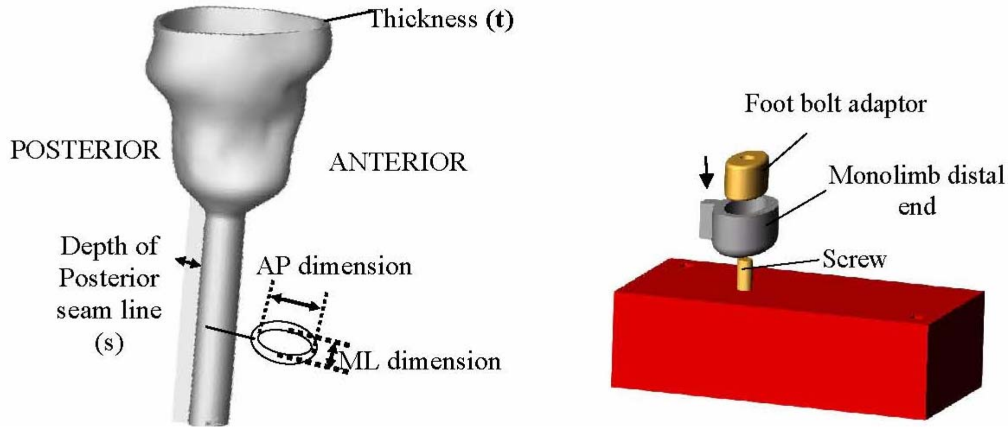

Figure 2. (left) The four design factors considered in the design of monolimbs; (right) The foot bolt adaptor and the screw fix the monolimb onto a foot block.

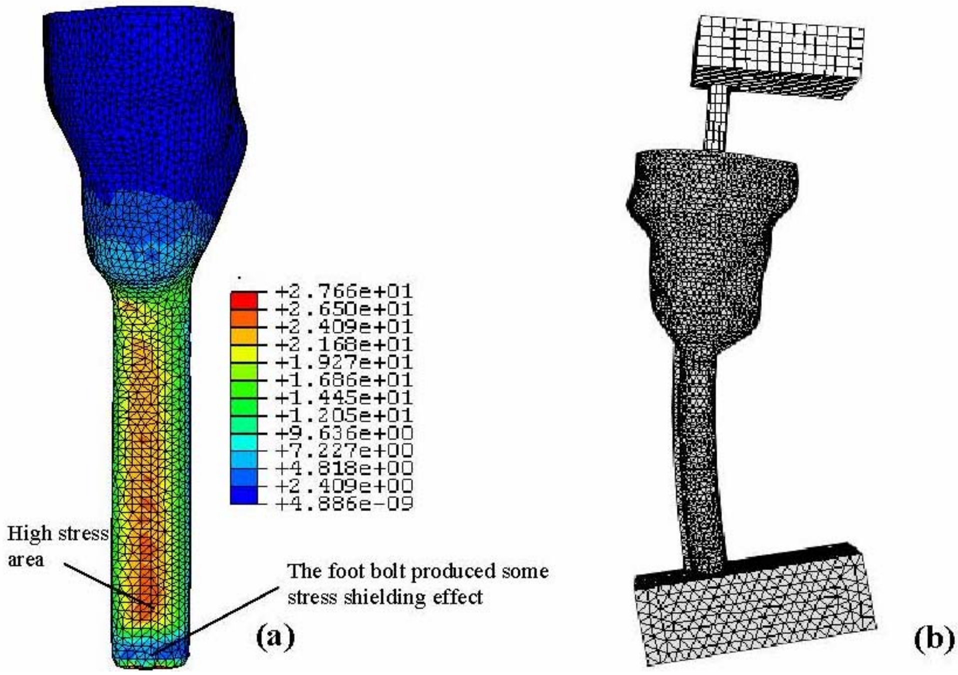

Figure 3. (a) Von Mises stress distribution and (b) deformation at the monolimb.

Figure 3 shows one typical von Mises stress distribution and the deformation of the monolimb. High von Mises stresses were predicted in the anterior region of the shank. Because of the stress shielding effect resulting from the much higher stiffness of the foot bolt relative to the thermoplastic material, stress values were low in the foot bolt region. The mechanical responses, including peak von Mises stresses, displacement of the top load application point, dorsiflexion and inversion angles of the 16 different monolimb configurations were computed.

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Bibliography

Murdoch G. (1990). CAD/CAM and the developing world. Report of ISPO Workshop on CAD/CAM in Prostehtics and Orthotics, 94-96. [A report showing the prevalence of people receiving different levels of amputations]

Zhang M., Lee W.C.C. (2006). Quantifying regional load bearing ability of trans-tibial stumps. *Prosthetics and Orthotics International* 30,25-34. [Providing supplementary information to section 5- Residual Limb Pain and Mechanical Stress]

Lee W.C.C., Zhang M. (2007). Using computational simulation to aid in the prediction of socket fit: A preliminary study. *Medical Engineering & Physics* 29,923-929. [Providing supplementary information to section 4- Prosthetic Socket-Residual Limb Interface Stress]

Lee W.C.C., Zhang M, Chan P.P.Y., Boone D.A. (2006). Gait analysis of low-cost flexible-shank trans-tibial prostheses. *IEEE Transactions on Neural Systems and Rehabilitation Eng* 14,370-377. [Providing supplementary information to section 3- Gait Analysis]

Lee W.C.C., Zhang M. (2006). Fatigue test of low-cost flexible-shank trans-tibial prostheses. *Prosthetics and Orthotics International* 30,305-15. [Providing supplementary information to section 2.3- Fatigue Testing Of the Optimized Prosthesis]

Lee W.C.C., Zhang M. (2005). Design of Monolimb Using Finite Element Modeling and Statistics-Based Taguchi Method. *Clinical Biomechanics* 20,759-766. [Providing supplementary information to section 2.1-Static Test Using Computational Modeling and 2.2-Taguchi Method and Design Optimization]

Lee W.C.C., Zhang M., Mak A.F.T. (2005). Regional differences in pain threshold and tolerance of trans-tibial residual limb: including the effects of age and interface material. *Archives of Physical Medicine and Rehabilitation* 86,641-649. [Providing supplementary information to section 5- Residual Limb Pain and Mechanical Stress]

Lee W.C.C., Zhang M., Boone D.A. (2004a). Finite element analysis to determine the effect of monolimb flexibility on structural strength and interaction between residual limb and prosthetic socket, *Journal of Rehabilitation Research and Development* 41,775-786. [Providing supplementary information to section 4- Prosthetic Socket-Residual Limb Interface Stress]

Lee W.C.C., Zhang M., Cheung J.T.M. (2004b). Finite element modeling of contact interface between trans-tibial residual limb and prosthetic socket. *Medical Engineering & Physics* 26,655-662. [Providing supplementary information to section 4- Prosthetic Socket-Residual Limb Interface Stress]

ISO10328. Prosthetics- structural testing of lower limb prostheses – Geneva: International Organization for Standardization, 1996. [Official document for ISO10328]

Phadke M.S. (1989). Quality engineering using robust design. Englewood Cliffs, N.J.: Pretice Hall. [Explaining the Taguchi Method in details]

Park S.H. (1996). Robust design and analysis for quality engineering. London; New York: Chapman & Hall. [Explaining the Taguchi Method in details]

Hirokawsa (1989). Normal gait characteristics under temporal and distance constrains. *Journal of Biomedical Engineering* 11,449-456. [Describing the characteristics of normal gait]

Isakov E., Burger H., Krajnik J., Gregoric M., Marincek C. (1996). Influence of speed on gait parameters and on symmetry in trans-tibial amputees. *Prosthetics and Orthotics International* 20,153-158. [Describing the characteristics of the gait of trans-tibial amputees]

Isakov E., Burger H., Krajnik J., Gregoric M., Marincek C. (1997). Double-limb support and step-length asymmetry in below-knee amputees. *Scand J Rehab Med* 29,75-79. [Describing the characteristics of the gait of trans-tibial amputees]

Isakov E., Keren O., Benjuya N. (2000). Trans-tibial amputee gait: time distance parameters and EMG activity. *Prosthetics and Orthotics International* 24,216-220. [Describing the characteristics of the gait of trans-tibial amputees]

Bateni H., Olney SJ. (2002). Kinematic and kinetic variations of below-knee amputee gait. *Journal of Prosthetics and Orthotics* 14,2-10. [Describing the characteristics of the gait of trans-tibial amputees]

Gailey R.S., Wenger M.A., Raya M., Kirk N., Erbs K., Spyropoulos P., Nash M.S. (1994). Energy expenditure of trans-tibial amputees during ambulation at self-selected pace. *Prosthetics and Orthotics International* 18,84-91. [Describing the characteristics of the gait of trans-tibial amputees]

Molen N.H. (1973). Energy/speed relation of below-knee amputees walking on a motor-driven treadmill. *Int Z angew Physioil* 31,173-185. [Describing the characteristics of the gait of trans-tibial amputees]

Michael J.W. (1992). Below-knee amputee gait with dynamic elastic response prosthetic feet: a pilot study. *Journal Rehabilitation Research and Development* 29,10. [Describing the effects of the use of prosthetic feet with dynamic elastic responses on the gait of trans-tibial amputees]

Gard S.A. and Konz R.J. (2003). The effect of a shock-sbsorbing pylon on the gait of persons with unilateral transtibial amputation. *Journal Rehabilitation Research and Development* 40,109-124. [Describing the effects of the addition of shock-absorbing capabilities on the gait of trans-tibial amputees]

Coleman K.L., Boone D.A., Smith D.G., Czerniecki J.M. (2001). Effect of trans-tibial prosthesis pylon flexibility on ground reaction forces during gait. *Prosthetics and Orthotics International* 25,195-201. [Describing the effects of the increased flexibility at the prosthesis on the gait of trans-tibial amputees]

Winter D.A. (1983). Energy generation and absorption at the ankle and knee during fast, natural and slow cadences. *Clinical Orthopedics and related research,* 147-54. [Explaining the important functions of ankle plantarflexion and dorsiflexion during walking]

Bowker J.H., Kazim M. (1989). Biomechanics of ambulation. In: Moore WS, Malone JM, eds. Lower Extremity Amputation. Philadelphia, Pa: WB Saunders Co, 261-273. [Explaining in details about the biomechanics of walking]

Brandell B.R. (1977). Functional roles of the calf and vastus muscles in locomotion. *American Journal of Physical Medicine* 56:59. [Explaining more in details about the biomechanics of walking]

Barr A.E., Siegel K.L., Danoff J.V,. Mcgarvey C.L., Tomasko A., Sable I., Stanhope S.J. (1992). Biomechanical comparison of the energy-storing capabilities of SACH and Carbon Copy II prosthetic feet during the stance phase of gait in a person with below-knee amputation. *Physical Therapy* 72:44-54.. [Describing the effects of use of prosthetic feet with energy storing properties on the gait of trans-tibial amputees]

Lehmann J.F., Price R., Boswellbessette S., Dralle A., Questad K., Delateur B.J. (1993). Comprehensive analysis of energy storing prosthetic feet: Flex-Foot and Seattle Foot versus standard SACH foot. *Archives of Physical Medicine and Rehabilitation* 74, 1225-31. [Describing the effects of use of prosthetic feet with energy storing properties on the gait of trans-tibial amputees]

Zhang M., Lord M., Turner-Smith A.R., Roberts V.C. (1995). Development of a non-linear finite element modeling of the below-knee prosthetic socket interface. *Medical Engineering & Physics* 17,559–566. [The material properties of the model described in this chapter were based on this referenced article]

Perry J. (1992). Gait analysis – normal and pathological function. USA: Thorofare, NJ. [Explaining the basics of gait]

Radcliff C.W., Foort J. (1961). The patellar-tendon-bearing below-knee prosthesis. Berkeley, CA: Biomechanics laboratory, University of California. [Describing the trans-tibial prosthetic socket rectification scheme]

Kingdon R.T., Stanley J.K., Kizior R.J.(1998), Pain management. W. B. Saunders Company, USA, 105-106. [Providing useful information explaining the increase of pain threshold after walking with a prosthesis]

Koseoglu E., Akboyraz A., Soyuer A., Ersoy A.O. (2003). Aerobic exercise and plasma beta endorphin levels in patient with migrainous headache without aura. *Cephalalgia* 23,972-976. [The findings may help explain the increase of pain threshold after walking with a prosthesis]

Biographical Sketches

Winson Lee obtained his bachelor degree in The Hong Kong Polytechnic University (PolyU) in 2001, and PhD degree in Biomedical Engineering in the same university in 2006. In 2005-2007 he worked as a Postdoctoral Fellow (academic level A) in Queensland University of Technology in Australia and was promoted to Research Fellow (academic level B) in mid-2007. He joined National Yang-Ming University in Taiwan in early 2008 as an Assistant Professor. He returned to PolyU in mid 2009 as an Assistant Professor. Dr. Lee has been conducting research in optimizing the mechanical design of prostheses, orthoses, implants and rehabilitation protocols.

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