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Shape Optimization of Running Specific Prosthesis Based on Force-Displacement Characteristics †

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† Presented at the 13th Conference of the International Sports Engineering Association, Online, 22–26 June 2020.

Published: 15 June 2020

Abstract: Usage of carbon fiber reinforced plastics (CFRPs) in running-specific prostheses increases day by day. The tailorable properties of CFRP blades bring many discussions about design and performance. In this study, the effect of shape on performance is investigated through force-displacement characteristics of the prosthesis. For this purpose, the geometry of prosthesis is defined by using B-splines with an initially given thickness. The prosthesis is exposed to vertical tip load at the mounting point, and contact is defined between the prosthesis and ground without friction. The aim of the simulation is to observe the contact behavior of athletes at different positions during the contact phase of a prosthesis. While the prosthesis is in contact with the ground, two different behaviors are observed: compression occurs at a larger contact zone, whereas release occurs at a smaller contact region (almost only the tip of the prosthesis). Different force-displacement characteristics, such as linear and second order, are obtained and the geometry of the prosthesis is optimized to adjust the behavior in the first region. The releasing phase of a prosthesis is related to the contact angle (angle of attack) and stiffness of the prosthesis. The two phases of contact are combined into a non-linear spring-mass system. Ground reaction forces are estimated through the non-linear mass-spring system. Finally, the importance of contacting area, length of moment arm during contact, and effect of each type of force-displacement characteristics on performance is discussed.

Keywords: running-specific prosthesis; finite element method; spring-mass model; optimization

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have played an important role in reshaping running-specific prosthesis thanks to adjustable mechanical properties via lay-up design, ply, orientation, etc. [1]. It appears that the performance of an athlete who wears running-specific prostheses can be developed by the adjustment of shape and stiffness distribution [2]. The selection and design of running-specific prostheses influence sprinting performance [3]. Therefore, optimization of the shape and stiffness of the running prostheses becomes very important in order to design better products for amputee runners.

Mass-spring model, multibody dynamic models, and finite element models (FEM) are the most commonly used methods to understand how a prosthesis affects behavior and performance. The height of prostheses has considerable effects on the symmetry of the motion, contacting behavior, and leg stiffness according to the spring-mass model [4]. The efficiency of running-specific prostheses is investigated through the combination of finite element analyses and motion capture systems; additionally, the relation between stiffness of the prostheses and energy storage-return characteristics is examined [5]. The shape, stiffness, and adjustments of running-specific prosthesis affect force-displacement characteristics and comfort [6].

In this study, the aim was to establish a methodology to design the shape of a prosthesis in regard to force-displacement characteristics, to estimate ground reaction forces based on force-displacement characteristics, and to give a broad perspective of design aspects of the running-specific prosthesis.

2. Methods

For optimizing the shape of a prosthesis, several steps are followed in order to create shape, to create a finite element model, to adjust thickness, and to formulate the optimization problem. First, the shape of prosthesis is created by using B-splines with four points, as shown in Figure 1. The positions of two of the points—on top, point P_1 and on the bottom, point P_4—are fixed, and the positions of the remaining two points, P_2 and P_3, are considered design variables. Then, equidistant points are created on the B-spline to model nodes and elements of the finite element model. The material of the prosthesis is assumed to be isotropic with a density of 1500 kg/m^3, an elastic modulus of 120 GPa, and a Poisson's ratio of 0.3. Sectional properties of the prosthesis are assumed to be the same for all elements. While the width is constant, the thickness changes through the thickness adaptation process. The upper tip of the prosthesis, point P_1, is allowed to move in the vertical direction, whereas the other directions are fixed. Ground contact is modeled as frictionless in order to understand the behavior of the prosthesis through different contact zones by allowing sliding to easily occur.

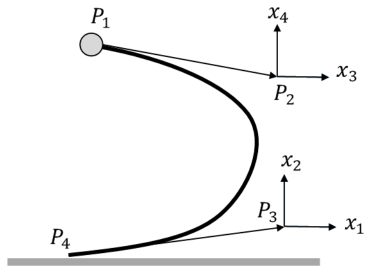


Figure 1. Points P_1, P_2, P_3, and P_4 are control points of the B-spline. While the positions of P_1 and P_4 are fixed, the positions of P_2 and P_3 change to optimize the force-displacement characteristics of the prosthesis.

Desired displacement and force levels are determined and a thickness adaptation rule is created to achieve this goal, as shown in Figure 2. Thickness is initially assigned as a sectional property and adapted to obtain the desired displacement at the desired force. When thickness is determined, the error between the desired curve and the obtained curve is calculated as an area between curves.

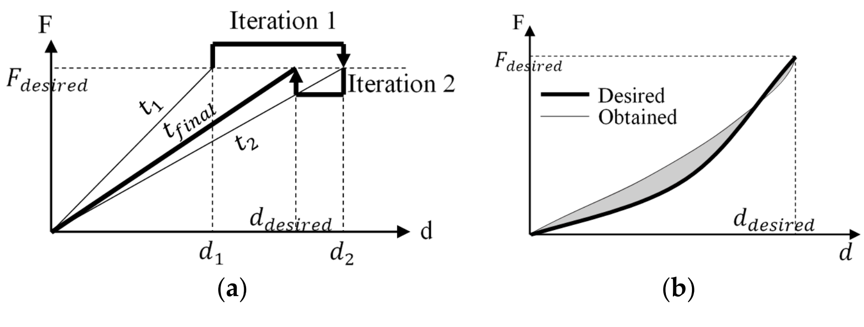


Figure 2. (**a**) Process of thickness adaptation through thickness adaptation on the force-displacement curve. (**b**) Desired and obtained force-displacement curve. The hatched area shows error.

Three different types of force-displacement curves are created; linear, hardening, and stepy. Optimization procedures are conducted to obtain shapes that provide desired force-displacement characteristics, as shown in Equation (1). A general overview of the method is shown in Figure 3.

$$\min \int_0^{disp_{desired}} \left(f(x) - f_{desired}(x)\right)^2 \, dx$$
$$\begin{gathered} subject\ to: \\ 0 \le x_1 \le 400 \\ 0 \le x_2 \le 75 \\ 0 \le x_3 \le 400 \\ 225 \le x_4 \le 300 \end{gathered} \tag{1}$$

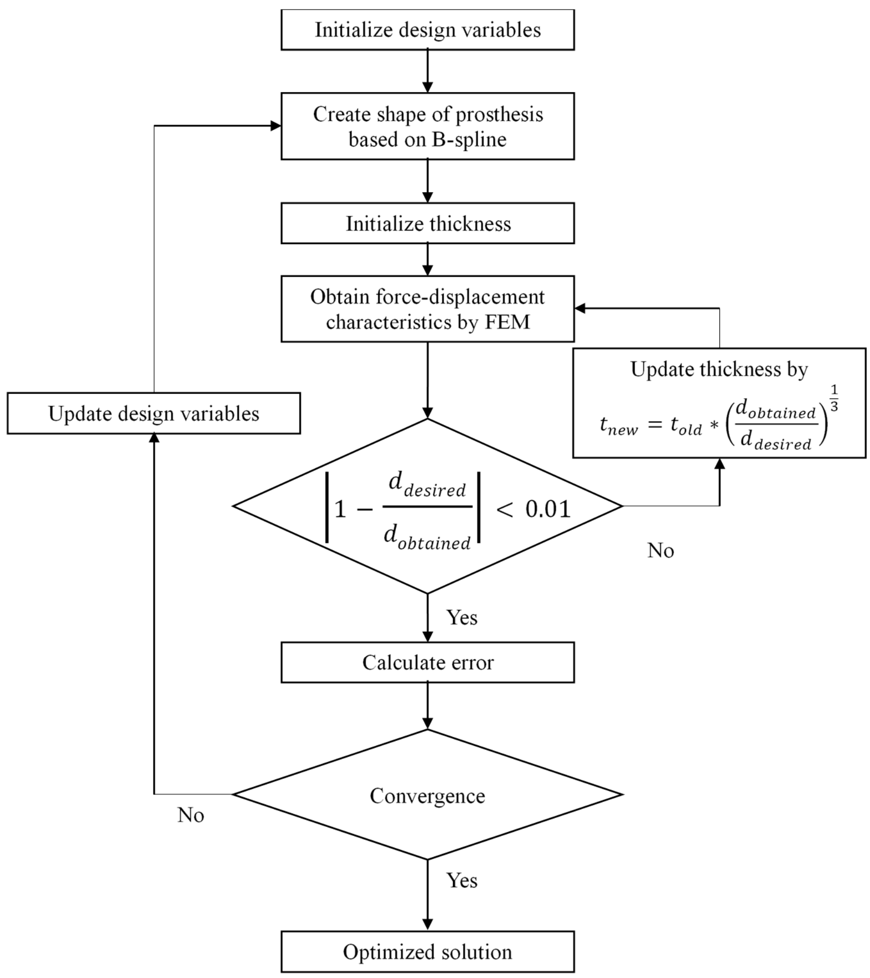


Figure 3. The overall procedure of shape optimization of prosthesis based on force-displacement characteristics.

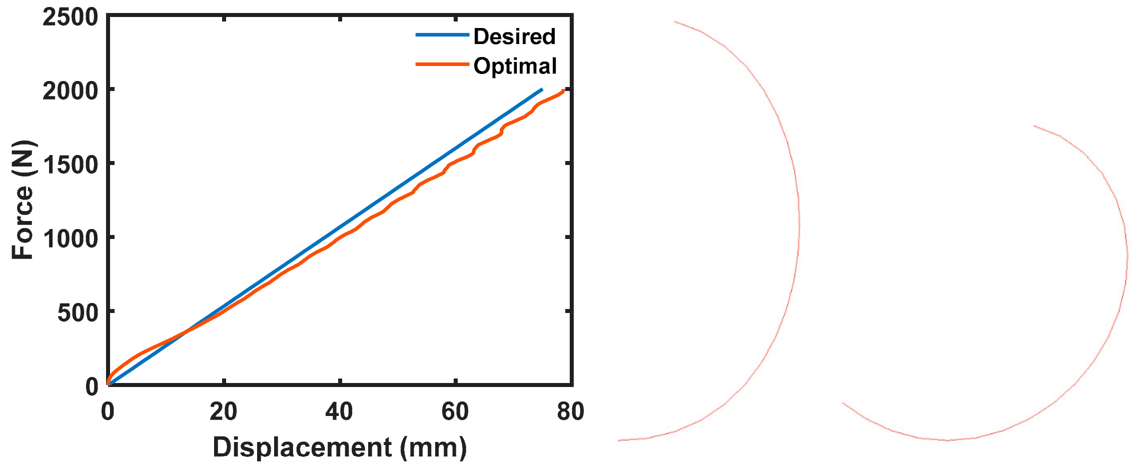
3. Results

3.1. Force-Displacement Characteristics

First, desired force and displacement levels are determined as 2000 N and 75 mm, respectively. Then, three different force-displacement characteristics are created as linear, hardening, and stepy characteristics.

3.1.1. Linear Force-Displacement Characteristics

Symmetrical behavior in ground reaction forces is expected if force and displacement changes linearly. Therefore, a prosthesis that has linear force-displacement characteristics is obtained, as shown in Figure 4. The circular shape of the contacting area causes a smooth response of the force-displacement curve. Since the length of moment arm does not vary, linear force-displacement relation is established.

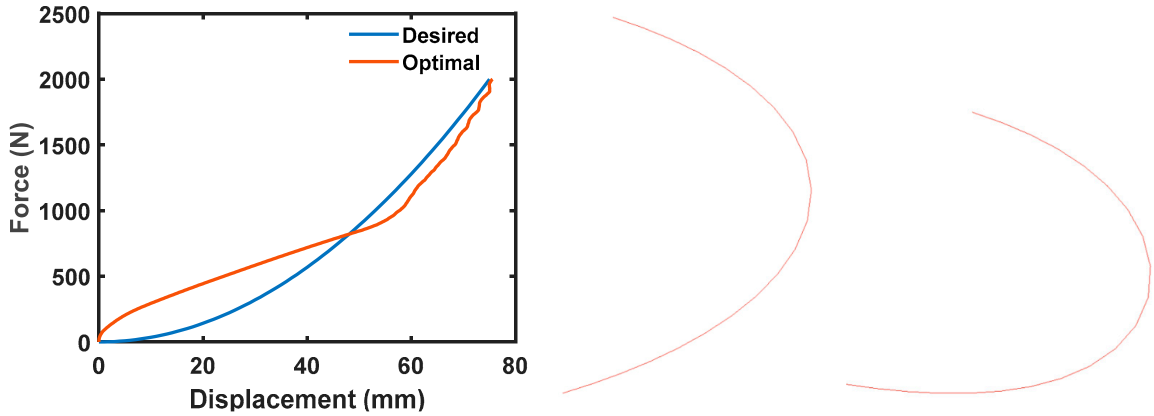


(**a**) (**b**) (**c**)

Figure 4. (**a**) Force-displacement characteristics of the prosthesis with linear characteristics. (**b**) Initial shape of the optimized prosthesis with linear characteristics. (**c**) Deformed shape of the optimized prosthesis with linear characteristics under force 2000 N.

3.1.2. Hardening Force-Displacement Characteristics

Hardening force-displacement characteristics allow a prosthesis to have initially stiffer and gradually decreasing stiffness behavior during the loading phase of the prosthesis. Therefore, the vertical ground reaction force increases suddenly and the loading rate decreases during contact. Due to the sudden changes of shape in the contact region, the length of moment arm decreases after some level of force is applied, as shown in Figure 5.

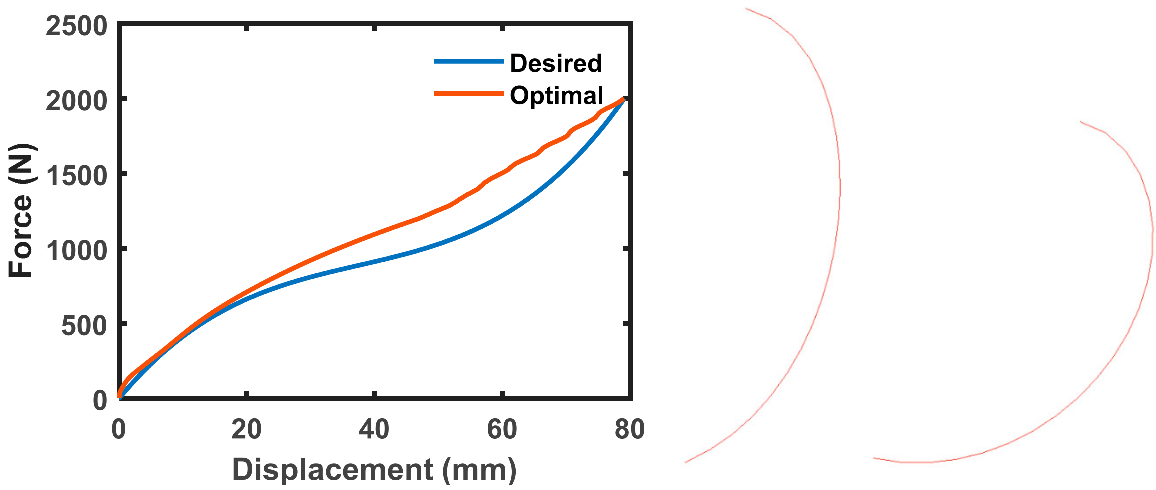


(**a**) (**b**) (**c**)

Figure 5. (**a**) Force-displacement characteristics of the prosthesis with hardening characteristics. (**b**) Initial shape of the optimized prosthesis with hardening characteristics. (**c**) Deformed shape of the optimized prosthesis with hardening characteristics under force 2000 N.

3.1.3. Stepy Force-Displacement Characteristics

The term 'stepy' is used to describe variant-stiffness characteristics. The force-displacement curve can be composed into three regions: stiffer, less stiff, and stiffer. Such a characteristic leads to having a higher loading rate initially, gradually decreasing stiffness, and higher stiffness during the releasing phase of contact. Force-displacement characteristics and initial/deformed shapes are shown in Figure 6. These characteristics are achieved due to the slender shape of the prosthesis. Contact starts at the tip and continues; therefore, the length of moment arm increases and stiffness decreases. After a certain level of loading, the contact area moves backwards and the length of moment arm decreases and stiffness increases again.

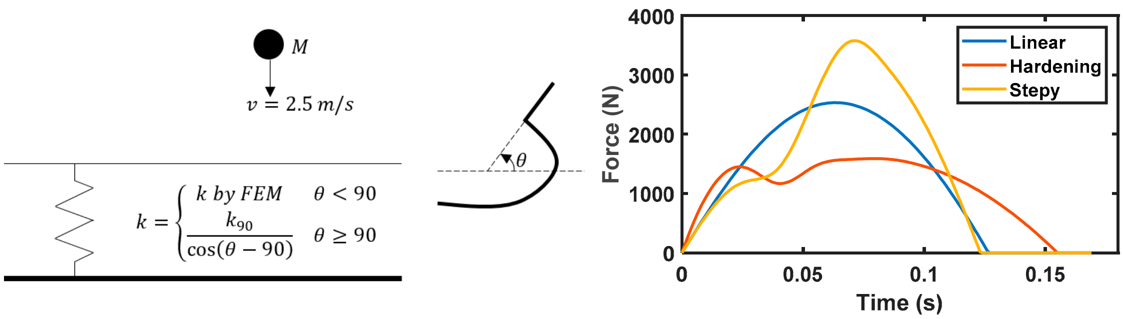


(**a**) (**b**) (**c**)

Figure 6. (**a**) Force-displacement characteristics of the prosthesis with stepy characteristics. (**b**) Initial shape of the optimized prosthesis with stepy characteristics. (**c**) Deformed shape of the optimized prosthesis with stepy characteristics under force 2000 N.

3.2. Ground Reaction Force Estimation

The ground reaction forces generated by various prosthesis are estimated by using force-displacement curves. The motion of the prostheses is composed of two phases: the loading phase and the releasing phase. It is assumed that the loading phase takes place from the initial contact to the vertical alignment of the prosthesis—in other words until the contact angle is 90 degrees. The stiffness of the spring is estimated by using the finite element model for the loading phase. The stiffness of the releasing phase is shown in Figure 7. Ground reaction forces are estimated by assuming $v = 2.5$ m/s and $M = 55$ kg. Then, the forces generated during the contact phase of the prosthesis are calculated.



(**a**) (**b**)

Figure 7. (**a**) Non-linear mass-spring model used to estimate ground reaction forces. θ, k, v, and M represent contact angle, stiffness of spring, vertical velocity at mounting point of prosthesis, and mass of athlete, respectively. k_{90} is stiffness when $\theta = 0$;in other words, when $d = 0$ on the force-displacement curve. (**b**) Estimated vertical ground reaction forces for prostheses having linear, hardening, and stepy force-displacement characteristics.

4. Discussions

Three different prostheses with different characteristics have been obtained through the introduced methodology. Thickness adaptation and optimization aspects were separated to reduce design variables and computational time. The four-point B-spline has two free points to adjust the shape of the prosthesis. This limits the design space of the shape of the blades and allows for the minimization of error to a certain level. Therefore, the error between the desired and optimal curve is higher, but the desired characteristics are obtained. The error can be reduced by increasing the number of control points of the B-spline and by increasing the mesh density around the contact area in order to smoothen the force-displacement curve. Additionally, thickness is assumed to be constant along the blade. In addition to control points, a thickness function can be utilized in the optimization problem as a design variable in order to further reduce errors. It has been revealed that the contacting shape of the prosthesis and variations in the length of moment arm have considerable effects on the force-displacement characteristics of prostheses.

Force-displacement curves are used to estimate ground reaction forces. Stiffness variation and stiffness when the contact angle is 90 degrees are two important factors that shape ground reaction forces. Stiffness variation during the loading phase determines the shape of the curve. The initial loading rate and the stiffness of the prosthesis at initial contact are directly related, therefore the prosthesis with hardening force-displacement characteristics shows a higher slope. Also, the trend of the curve during the loading phase is determined by the change in stiffness. Another interesting finding is that peak vertical force is related to initial stiffness on the force-displacement curve.

5. Conclusions

A methodology to design the shape of prostheses is introduced and explained in this study. Due to simplicities in the shape modeling, the error is high, but the desired force-displacement characteristics are obtained. Design aspects of the running-specific prosthesis are considered in order to obtain different force-displacement characteristics. The estimation method of ground reaction forces was established by considering force-displacement characteristics. Although the estimation of the ground reaction force gives higher peak forces than estimated, it gives reasonable trends for ground reaction forces.

Future research will include thickness variations and detailed shape modelings in order to reduce error. Also, an investigation of the performance of each prosthesis will be conducted experimentally after prototyping.

Author Contributions: In this study, C.G. contributed to the development of model and method, also conducted calculations. K.S., H.H., S.S. helped to discussions and evaluation of results. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Scholz, M.-S.; Blanchfield, J.P.; Bloom, L.D.; Coburn, B.H.; Elkington, M.; Fuller, J.D.; Gilbert, M.E.; Muflahi, S.A.; Pernice, M.F.; Rae, S.I.; et al. The use of composite materials in modern orthopaedic medicine and prosthetic devices: A review. *Compos. Sci. Technol.* **2011**, *71*, 1791–1803.
2. Nolan, L. Carbon fibre prostheses and running in amputees: A review. *Foot Ankle Surg.* **2008**, *14*, 125–129.
3. Grobler, L. Characterisation of Running Specific Prostheses and Its Effect on Sprinting Performance. Ph.D. Thesis, Stellenbosch University, Stellenbosch, South Africa, 2015.
4. Wilson, J.R.; et al. A new methodology to measure the running biomechanics of amputees. *Prosthet. Orthot. Int.* **2009**, *33*, 218–229.
5. Rigney, S.M.; Simmons, A.; Kark, L. Mechanical characterization and comparison of energy storage and return prostheses. *Med. Eng. Phys.* **2017**, *41*, 90–96.
6. Beck, O.N.; Taboga, P.; Grabowski, A.M. Characterizing the mechanical properties of running-specific prostheses. *PLoS ONE* **2016**, *11*, e0168298.