Mechanical stiffness of running-specific prostheses in consideration of clamped position

Yasuhiro NISHIKAWA* and Hiroaki HOBARA**
*Tokyo Metropolitan Industrial Technology Research Institute
Tama Techno Plaza, 3-6-1, Azuma-cho, Akishima-shi, Tokyo 196-0033 Japan
E-mail: nishikawa.yasuhiro@iri-tokyo.jp
**National Institute of Advanced Industrial Science and Technology
Waterfront 3F, 2-3-26, Aomi, Koto-ku, Tokyo 135-0064 Japan

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Abstract
Athletes with lower extremity amputations need to clearly understand the mechanical stiffness of running-specific prostheses to select the most suitable one. However, manufacturers do not show the detailed stiffness data, and currently, there is no standardized testing method available. In this study, load-deflection behavior and mechanical stiffness of carbon fiber composite prosthesis were evaluated under a static compressive load. Fifteen testing conditions were employed by changing the position and length of adapter jig. The results of compression tests showed all load-deflection relations to be non-linear. The mechanical stiffness increased with increasing the applied load and decreasing the adapter jig length. Immediately after loading, the backward lateral force was applied to the prosthesis shank, and then, the forward lateral force was generated in continuing loading. By interaction of the adapter jig position and length, fifteen load-deflection diagrams were classified into seven tendencies. From the observation results of deformation behavior, the product of the adapter jig position and length was defined as the positional parameter, which quantitatively indicated the clamped condition. Consequently, the evaluation method of mechanical stiffness correlated with the applied load and the positional parameter was proposed.

Keywords: Stiffness, Prostheses, Running, Amputation, Athlete, Compression, Load-deflection

1. Introduction

Running-specific prostheses (RSPs) are used by athletes with lower extremity amputations in athletic competitions such as sprinting and long jump events. RSPs of various designs are developed and improved by manufacturers of each country; however, the function of RSPs is basically the same. During the gait cycle, RSPs store the elastic strain energy with the bending deformation of the prostheses under the bodyweight induced ground impact load of the user and then release this energy. Therefore, leaf springs made from carbon fiber composites are used as RSPs to effectively store and release the accumulated energy per unit weight.

The recent topics about RSPs are whether they provide advantages or disadvantages for athletes with lower extremity amputations as compared with able-bodied athletes (Hobara et al., 2013). Previous studies (Weyand et al., 2009, Brüggemann et al., 2008) have reported that stride frequency, swing time, contact length, and vertical ground reaction force are correlated with the top running speed. Furthermore, leg stiffness strongly impacts running performance (Chelly and Denis, 2001, Brughelli and Cronin, 2008). McGown et al. (2012) have reported that leg stiffness for legs without amputations is constant or increases with speed, whereas leg stiffness for legs with RSPs of unilateral and bilateral transtibial amputees decreases with speed. Thus, identifying these biomechanical factors is important for determining advantages or disadvantages of using RSPs.

The leg stiffness of athletes with lower extremity amputations strongly depends on mechanical (spring) stiffness of RSPs because RSPs are inherently springs. Each RSP has a range of different mechanical stiffness values which are recommended based on the user’s bodyweight (Nolan, 2008). Manufacturers determine the mechanical stiffness using a
universal material testing machine but do not show the detailed stiffness data for RSPs. In addition, a standardized testing method for RSPs does not exist currently, although the static and dynamic structural testing method of conventional lower-limb prostheses is determined as JIS T 0111 (1997) or ISO 10328 (2016).

Only a few studies have evaluated mechanical stiffness of RSPs. Dyer et al. (2013, 2014) investigated the mechanical stiffness of two prostheses under three boundary conditions at the distal end. Consequently, the most easily repeatable method was the evaluation of mechanical stiffness by fixing the distal end. However, the alignment conditions also strongly influence the mechanical stiffness of RSPs. Thus, a more practical evaluation is required to clearly understand the mechanical stiffness of RSPs and select the most suitable one for athletes with lower extremity amputations.

This study investigates the mechanical stiffness of RSPs under different clamped conditions. The evaluation method in consideration of the clamped condition of RSPs is discussed by clarifying the relations among mechanical stiffness, applied load, and clamped position.

2. Experimental
2.1 Test prosthesis

IE90 SPR-2 (Sprinter; Ottobock) was used as a typical example of RSPs in this study. It is a carbon fiber composite prosthesis designed to undertake various activity including short distance sprinting by a user with a mass of about 60 kg. Figure 1 shows the geometry and dimensions of this prosthesis, evaluated using a three-dimensional coordinate measuring machine (Crysta Apex C9106; Mitutoyo co.). The geometry of the prosthesis was broadly divided into the shank side and toe side at the top of the calf part. The thickness of the shank side was approximately 10 mm. From the top of the calf part, the thickness was gradually tapered down to approximately 5.4 mm at the toe. The width of the prosthesis was approximately 72 mm.

2.2 Testing jigs

The prosthesis was mounted to two sets of steel jigs, which could change the clamped condition of the prosthesis. Figures 2 (a) and 2 (b) show the composition of the testing jigs. The fixed socket jig was completely fixed to the testing machine, while the sliding socket jig could only slide forward. The joint jig was combined with the socket jig by a shaft. The prosthesis was mounted on the adapter jig. The angle between the adapter jig and prosthesis shank was 90 °. These jigs were extremely rigid as compared with the prosthesis; therefore, the deformation of the jigs themselves was neglected in comparison with the test results.

Fifteen testing conditions were employed in this study. As shown in Fig. 2, the length $L_1$ from the top of the calf part to the adapter jig position was set at 205, 255, and 305 mm. These are the same lengths as those from the shank edge to the adapter jig positions of 100, 50, and 0 mm, respectively. The adapter jig length $L_2$ from the prosthesis to the joint jig was set at 75, 100, 125, 150, and 175 mm. Hereafter, the clamped condition is written as $L_1$-$L_2$ (for example, in the case of $L_1 = 205$ mm and $L_2 = 75$ mm, the clamped condition is denoted as 205-75).

$L_1$ and $L_2$ are determined optionally based on the physical characteristic and running-performance of the prosthetic user; therefore, both the parameters do not have a standard length. In this study, the range of $L_1$ was assumed to be the longest possible (from 205 mm to 305 mm) in the test prosthesis. In addition, the range of $L_2$ was set from 75 mm to 175 mm to clarify the influence of $L_2$ on mechanical stiffness in practical use.

2.3 Static compression test

Images of experimental setup examples are shown in Figures 3 (a) and 3 (b). All tests were conducted under laboratory conditions ($23 \pm 2 ^\circ \mathrm{C}$ and $50 \pm 5 \%$ relative humidity). The prosthesis was vertically compressed using a universal material testing machine (AutoGraph AG-100KNX; Shimadzu co.). The crosshead speed was 100 mm/min. The prosthesis shank was aligned at a 90 ° angle from the horizontal table of the testing machine. The prosthesis toe contacted the supporting block with a fluorine resin sheet. Immediately after loading, the prosthesis toe separated from this block; therefore, the supporting block and the fluorine resin sheet did not influence the test results. The prosthesis bottom surface contacted a steel plate in a line. The surface of the steel plate without surface treatment was smooth.

Figures 4 (a) and 4 (b) show the situations after the compression tests. The prosthesis was loaded in compression for
Fig. 1 Geometry and dimensions of prosthesis.

(a) Fixed socket jig type

(b) Sliding socket jig type

Fig. 2 Composition of testing jigs.

(a) Fixed socket jig type

(b) Sliding socket jig type

Fig. 3 Images of experimental setup examples.
three separate times up to a maximum load of 2,500 N; this value was chosen as this was approximately four times the bodyweight of the intended user for the prostheses specification. Under the compressive load of 2,500 N, the prosthesis bottom surface contacted the steel plate in a line as shown in Fig. 4 (a). However, the compression test stopped when the prosthesis slipped backward or slid forward, as shown in Fig. 4 (b).

3. Results and Discussion

3.1 Load-deflection relation

Figures 5 (a)-(c) show the typical load-deflection diagrams in the case of using the fixed socket jig. All load and deflection relations were non-linear; this tendency has also been witnessed in other studies (Dyer et al., 2013, 2014). This may be due to a combination of the tapered thickness of the toe region and the change in prosthesis length with the movement of the contact line. The mechanical stiffness of the prosthesis is defined as load divided by deflection. In consideration of this definition, as the applied load increased, mechanical stiffness increased independently of the clamped condition. In comparison, at the same load, the stiffness increased with decreasing adapter jig length. Unlike the previous studies (Dyer et al., 2013, 2014), the testing jigs in the present study applied both vertical load and moment to the prosthesis. Therefore, the moment and deflection decreased with decreasing adapter jig length, leading to higher mechanical stiffness under the same load.

Figures 6 (a)-(c) show the typical load-deflection diagrams in the case of using the sliding socket jig. The prosthesis was slid forward at the maximum load. Figure 7 shows the relations between the applied load and lateral force, which was measured at the sliding socket jig in the case of \( L_1 = 205 \) mm. Immediately after loading, the backward lateral force (acting in the direction opposite to that of RSP) was applied to the prosthesis shank. After the backward lateral force reached the peak, the forward lateral force (propulsive force) was generated. When the backward lateral force decreased and only the forward lateral force was applied to the shank, the prosthesis was pushed out forward. This means that the minimum necessary vertical load to effectively propel the RSP exists.

3.2 Effect of clamped condition on mechanical stiffness

Figure 8 shows fifteen load-deflection diagrams under all clamped conditions using the fixed socket jig (as shown in Figures 5 (a)-(c)). Each load-deflection behavior corresponded under the certain clamped conditions (for example, 205-125, 255-100, and 305-75). According to the interaction of the adapter jig position and length, fifteen load-deflection diagrams were classified into seven tendencies.

The deformation behavior of the prosthesis was observed to discuss the effect of the adapter jig position \( L_1 \) and adapter jig length \( L_2 \) on the load-deflection relations. Figures 9 (a)-(c) show the observation results of the prosthesis in the case of clamped condition 205-125. The deformation behavior differed at the shank and tow sides. The thick shank
side bent forward, whereas the toe side became flat.

Figure 10 shows the relations between the deflection and inclined angle of the shank obtained from the observation results of the deformation behavior. Except for the clamped condition 205-75, the inclined angle was quite proportional to the deflection in all cases. Therefore, the inclined angle can become the key factor influencing the load-deflection behavior. In the case of clamped condition 205-75, an increment in the inclined angle decreased with an increment in deflection because the vertical load as compared with the moment was strongly applied to the prosthesis.

The prosthesis shank side is assumed to be a simple truss structure, as shown in Fig. 11. In this model, the inclined angle was calculated using the product of $L_1$ and $L_2$, which is defined as a positional parameter (indicating the clamped condition quantitatively). Figure 12 shows the relations among $L_1$, $L_2$, and the positional parameter. Each positional parameter value corresponded under the certain clamped conditions (for example, 205-125, 255-100, and 305-75). The seven classified tendencies of the positional parameter were same as those shown in the load-deflection diagrams.
Fig. 7 Relations between applied load and lateral force ($L_1 = 205$ mm).

Fig. 8 Fifteen load-deflection diagrams classified into seven tendencies (using fixed socket jig).

Fig. 9 Observation results of deformation behavior (clamped condition: 205-125).
Figure 13 shows the relations among mechanical stiffness, applied load, and the positional parameter. The mechanical stiffness was calculated as the average load divided by average deflection in the load range of ± 25 N. The minimum necessary vertical load to propel the RSP is also shown in Fig. 13. As for these relations, it can guide the athletes with lower extremity amputations in selecting the RSPs with the most suitable mechanical stiffness in consideration of their clamped condition. Consequently, the evaluation method of mechanical stiffness correlated with the applied load and positional parameter was proposed.

4. Conclusions

In this study, mechanical stiffness of RSP was evaluated under fifteen clamped conditions by changing the adapter jig position and length. The results are summarized as follows.

1) All load-deflection relations were non-linear. The mechanical stiffness increased with increasing applied load and decreasing adapter jig length.

2) Immediately after loading, the backward lateral force was applied to the prosthesis shank, and then, the forward lateral force was generated in continuing loading. We also confirmed that there was a minimum necessary vertical load to effectively propel the RSP.

3) According to the interaction of the adapter jig position and length, fifteen load-deflection diagrams were classified into seven tendencies. From the observation results of the deformation behavior, the product of the adapter jig
position and length was defined as positional parameter, which quantitatively indicated clamped condition.
Consequently, the evaluation method of mechanical stiffness correlated with the applied load and positional
parameter was proposed.

In future work, the correlation between our results and running-performance (leg stiffness, vertical ground reaction
force, and running speed) of athletes with lower extremity amputations will be investigated. In addition, mechanical
stiffness of RSP, including a viscoelastic property, was evaluated under a dynamic compressive load.

Fig. 13 Relations among mechanical stiffness, applied load, and positional parameter.

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