Dynamic Analysis of Hip and Knee Joints of Lower Limb with Trans-Femoral Prosthesis

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Abstract: The gait cycle forces and moments acting on the hip and knee joints of a lower limb with a trans-femoral prosthesis were investigated. The kinematics parameters of a lower limb with a prosthesis were determined from motion-captured system data. The reaction force was measured with a force sensor in the footplate. A 3D model of the residual limb was created using CAD software and based on MRI data. All parts of the prosthesis were measured and a full-size 3D model was created. The 3D model of the prosthesis was exported to Matlab Simmechanics to calculate the forces and moments acting on the joints. The results of this study could be used to calculate the load transferred from the socket to the residual limb. They could also be used to design the structure of a prosthesis and optimize the dynamic characteristics of such a prosthesis.

Key Words: Trans-femoral, Reaction force, Reaction moment, Lower limb prosthesis, Hip joint, Knee joint

1. Introduction

There are many people who have had to have a limb amputated, or who were born with limb different. This is especially prevalent in the developing countries and those that have been at war. In Japan, the incidence of amputation is 3 per every 100,000 people [(1)].

A lower limb prosthesis is designed to replace the functions of the missing lower limb. An understanding of the structure's dynamic properties and the load transfer between the socket of the prosthesis and the residual limb is important to the evaluation of the quality of a prosthesis.

In some previous studies, models were created to calculate the force and moment acting on the hip and knee joints. Examples include Xiaohong Jia et al. [(2)]. However, these models were of a trans-tibial prosthesis with one degree of freedom, and the reaction force was assumed to act on a fixed point on the foot, so that the position of the center of gravity (CG) of each segment was not accurate. The model of the socket and residual limb was a pseudo model created in software.

In this study, the authors modeled the residual limb and prosthesis as a coupled pendulum with two links. Each part of the prosthesis was modeled in full size. The input kinematic parameters were derived from data acquired with a motion capture system, a footplate force sensor, and mechanical equations. Thus, the error in the estimation could be reduced. These results show the forces and moments acting on the hip and knee joints in the dynamic state. This method offers greater flexibility and the calculation requires less time.

2. Method

The subject in this study was a man with a right-side trans-femoral amputation. He was aged 47, 167 cm in height, and weighed 61 kg without his prosthesis. His prosthesis incorporated a UCLA socket, a Nabco prosthesis, and an Ottobock foot.

The kinematic data for the lower-limb and prosthesis, as well as the reaction forces applied to the prosthesis foot while walking were measured using a Mac3D system (Motion Analysis Corporation) and a force plate platform (Kisler Corporation). Two plates were placed such that both of the subject's feet struck them during a gait cycle. Data was recorded at a sampling rate of 200 Hz while the subject was walking. The model was considered on the sagittal plane and the socket of the prosthesis and the residual limb were assumed as one block.

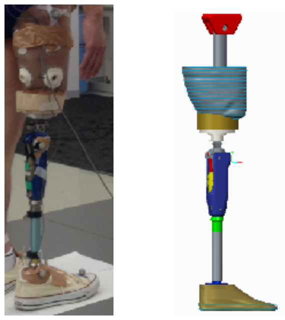

Fig. 1 Real and 3D model of lower limb with prosthesis

2.1. Established model

Fig. 1 shows the actual lower limb with the prosthesis, as well as the 3D model. The first joint is the hip joint to which the first link, including the residual limb and part of the prosthesis above the knee joint is connected to the fixed part by a revolute joint. A 3D model of the residual limb and socket prosthesis were created using MRI data consisting of 17 layers, each separated by 10 mm. The density of the residual limb was obtained by averaging the density of the bone, muscle, fat, and skin. The second joint is the knee joint where the second link below the knee joint of the prosthesis is connected to the first link by a revolute joint. The dimensions of the parts were taken from the actual prosthesis. The material density of each part was calculated from $d = m/V$ (m: mass of a part, V: volume of a part). The 3D model was designed using Creo parametric 2.0 (PTC Inc.).

2.2. Kinematics parameters

The positions to which markers were attached to the lower limb prosthesis are shown in Fig. 2. The angular rotations at the hip (θ_1) and knee (θ_2) joints were defined as shown in the diagram. Matlab (Mathworks Inc.) was used to calculate the angle, angular velocity, and angular acceleration at the hip and knee joints based on the time difference between the markers' coordinates.

The reaction force acts on the foot of the prosthesis at the center of pressure (COP). The position of the COP in the first force plate coordinate system is shown in Fig. 3.

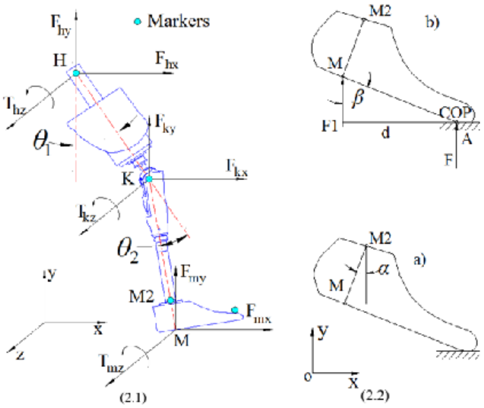

Fig. 2 Position of markers and angles on lower limb and foot

The reaction force was moved to point M, shown in Fig. 2, with two components. The first component is the force (F1) that has same magnitude and direction as reaction force F. The second is a moment with a magnitude defined as T = F•d. The direction of moment T depends on the positions of A (COP) and M.

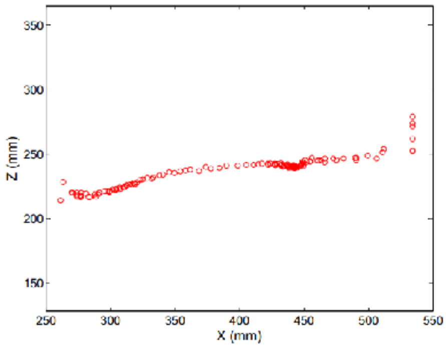

Fig. 3 Position of COP on force plate

The coordinates of M (M_x, M_y) were calculated using equations (1) and (2), below. Here, (M_{2x}, M_{2y}) and d_2 denote the coordinates of M2 and the distance between M and M2, respectively.

$$M_x = M_{2x} - d_2 \bullet \cos\alpha \qquad (1)$$

$$M_y = M_{2y} - d_2 \bullet \sin\alpha \qquad (2)$$

2.3. Simulation with Simmechanics

The data determined with Creo, including the material density, inertia moment, geometry data, and constraints were exported to Simmechanics (MathWorks). The initial simulation parameters consisted of the angle, angular velocity, and the angular acceleration at the hip and knee joints. The reaction force and moments at the foot were calculated from the measured data.

3. Results and discussion

The forces and moments at the hip and knee joints as determined using Simmechanics are shown in Figs. 4, 5, and 6. In Figs. 4 and 5, the graphs of the reaction force at the hip and knee joints are almost the same as the ground reaction force. Especially, the magnitude of the reaction force at the knee joint is almost the same as that at the ground. The direction of the moment at point M and at the hip and knee joints are reversed in Fig. 6. This means that, in these two cases, the reaction force vector passes the opposite side. The maximum and minimum moment of the hip joint appear in the heel contact and toe off periods, respectively.

4. Conclusion

In this study, the forces and moments acting on the hip and knee joints were calculated for one gait cycle. From these results, we can calculate the forces and moments applied to the hip and knee joints, and the load transfer between the socket and the residual limb. These results could be used to analyze the socket, and enable the quantitative evaluation and optimization of prosthesis.

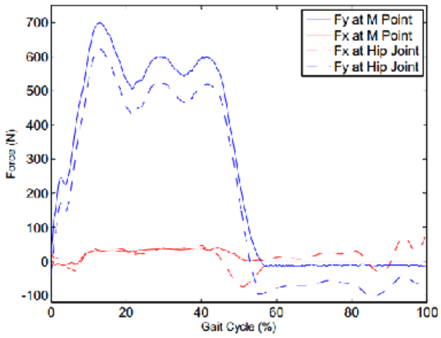

Fig. 4 Reaction force at point M and hip joints

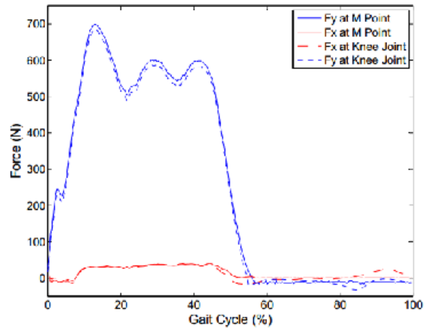

Fig. 5 Reaction force at point M and knee joints

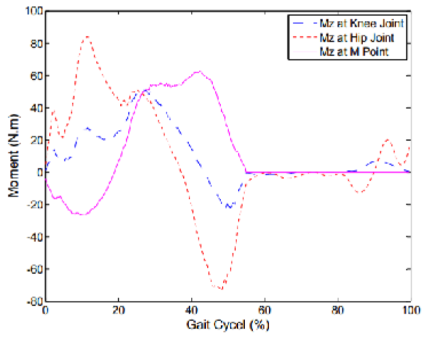

Fig. 6 Moment at point M, hip, and knee joints

References

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