Foot Clearance during Free Swing of a Transfemoral Prosthetic Leg: Four-Bar Knee vs. Ankle Dorsiflexion

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Abstract
Polycentric knees are frequently used in transfemoral prostheses because they provide added stability in stance phase and relative ankle dorsiflexion in swing phase. Despite this relative ankle dorsiflexion, patients still complain of inadequate toe clearance even with polycentric knees. We hypothesize that active ankle dorsiflexion via a knee-ankle coupling provides more toe clearance than provided by polycentric knees during midswing - the most critical phase of toe clearance. This hypothesis was evaluated by examining toe clearance of kinematic knee models processed on data from existing able-bodied data. A knee with active ankle dorsiflexion achieved larger toe clearance (3.01 cm) than the polycentric knee (3.89 cm) during midswing. Knee designs with active ankle dorsiflexion should be reconsidered for improved toe clearance in the gait of amputees.

1 Introduction

There are over 34,000 persons with a verified lower-limb amputation in Thailand, and it is estimated that there are more than 50,000 amputees [1]. The main causes of amputation are traffic accidents, trap mine explosions, diabetes, and congenital deformity [2]. Amputation occurs in all sectors of Thai society: anyone in Thailand may receive an amputation. Therefore, lower-limb prostheses are very important for Thailand. Lower-limp prostheses should be simple, adjustable, comfortable, and durable [3]. They should provide stability during stance and clearance during swing. The transition between stance and swing should be easily decided by the user and provide perception to the user. These properties are lacking. However, in many existing prostheses. Passive prostheses may be improved by emulating processes found in the human body.

Polycentric knees are frequently used in transfemoral prostheses because they provide added stability in stance phase and relative ankle dorsiflexion in swing phase [4]. Despite this relative ankle dorsiflexion, patients still complain of inadequate foot clearance even with polycentric knees. To provide more foot clearance than required for normal human gait to accommodate socket sag during swing. We hypothesize that ankle dorsiflexion provides more foot clearance than inclusion of a four-bar linkage mechanisms. This hypothesis will be evaluated by examining foot clearance of kinematics model including ankle dorsiflexion and four-bar linkage mechanism over the range of hip-knee-ankle data encountered in normal human gait. For understanding if the ankle dorsiflexion caused by polycentric knees occur at a useful phase of gait to increase more foot clearance. The achievement of these will provide a better understanding of some of the ideal properties of gait.

2 Methods

For evaluating our hypothesis that ankle dorsiflexion provides more foot clearance than inclusion of a four-bar linkage mechanism. We will be examined the kinematics model of foot clearance that includes ankle dorsiflexion and four-bar knee over the range of hip-knee-ankle data from able-bodied gait.

The gait data are from Steven A. Gard's laboratory in Northwestern University. They collected the data based on the basic Helen Hayes maker set. We used MATLAB R2010a program to implement the kinematics model based on mathematics knowledge ex. trigonometry, homogeneous transformation (translation and rotation matrix), statistics, and, etc.

$$Translation\ matrix = \begin{bmatrix} 1 & 0 & X \\ 0 & 1 & Y \\ 0 & 0 & 1 \end{bmatrix}$$

$$Rotation\ matrix = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}$$

We simulated the model of able-bodied gait for better understanding in some properties of gait [5]. Then we focused the thigh motion data (position and orientation) in gait model and used them for mimicking walking in an amputee gait model.

For preliminary polycentric knees model, we simulated a knee model based on Otto Bock 3R60 at first [6]. It is a four-bar knee design that is worldwide in lower-limb prosthesis. We focused on the four-bar mechanism motion. This mechanism has the property to provide some foot clearance. We created and recorded its motion for mimicking walking in amputee gait model.

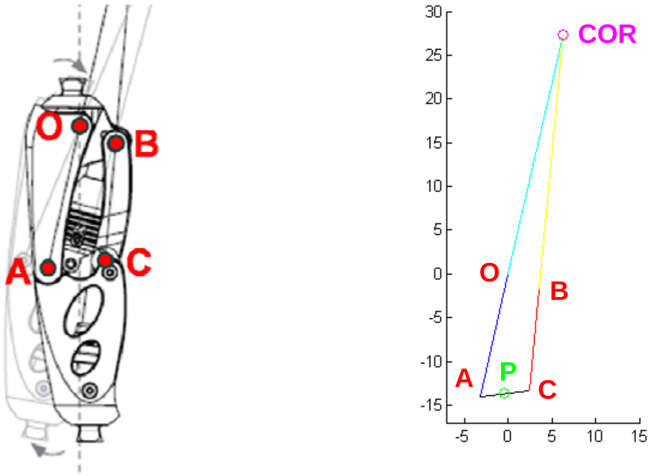

Figure 1: Show Otto Bock 3R60 design and the model of it. O, A, B, and C points are a joint in four-bar mechanism. COR is center of rotation. P is a joint to attach prosthetic leg.

We simulated amputee gait model base on thigh motion in able-bodied by using four-bar knee motion and single-axis knee motion with 0, 5, and 10 degree dorsiflexion. For evaluating amputee gait, we mimicked the angle rotation between thigh and shank by calculating the angle γ from able-bodied as shown in figure 2 and used the interpolation algorithm to calculate the position of prosthetic foot.

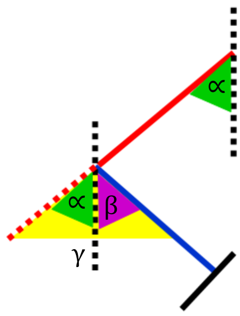

Figure 2: Show angle γ between thigh and shank in the leg model, $\gamma = \propto + \beta$

Then we calculated foot clearance during swing phase in each position of foot motion and collected them in a table. Therefore, we can analyze our results by comparing toe clearance between four-bar knee model and ankle dorsiflexion as shown in figure 3.

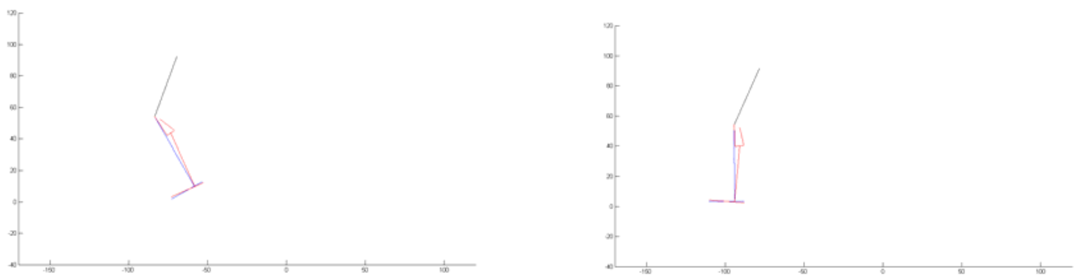

Figure 3: Plot the kinematics model during swing phase. First figure is in initial swing, and another is in midswing.

3 Results

The pilot results of vertical foot clearance are shown in figure 4.

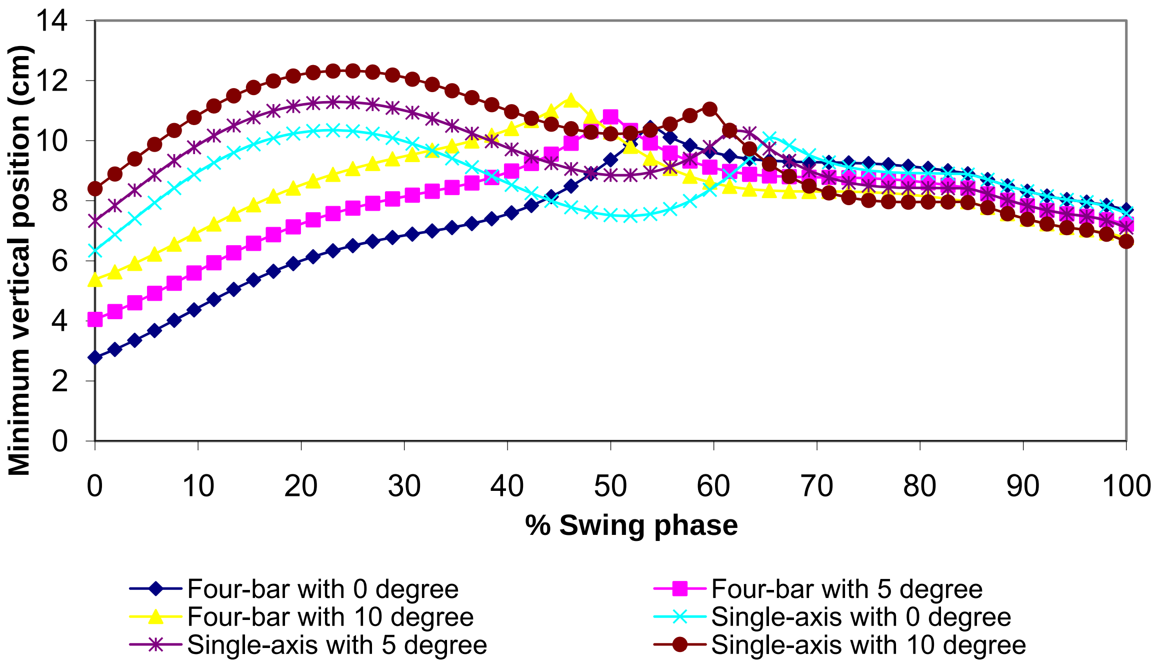

Figure 4: Plot showing minimal clearance of prosthetic foot in varied dorsiflexion during swing phase.

From a graph in figure 4, it shows the minimum vertical clearances of four-bar leg in each dorsiflexion tends to be lower than single-axis leg during initial swing. However foot clearances of four-bar leg in each dorsiflexion tend to be higher than single-axis leg during midswing. Then there are similarities in terminal swing. The foot clearances of single-axis leg with 5 degree dorsiflexion, there are lower than four-bar leg with no dorsiflexion. The foot clearances of single-axis leg with 10 degree dorsiflexion, there are little lower than four-bar leg with 5 degree dorsiflexion too.
From the study of Steven A. Gard's group, they showed the critical toe clearance in able-bodied gait usually occurred in midswing phase [7]. Then we focused on midswing phase for examining the minimal vertical clearance. From our results, the average of minimal foot clearance during midswing in four-bar leg is 3.01, 4.45, and 3.94 cm (with 0, 5, and 10 degree dorsiflexion, respectively), and single-axis leg is 1.17, 2.51, and 3.89 cm (with 0, 5, and 10 degree dorsiflexion, respectively).

4 Discussion

There is measured difference in foot clearance for subjects wearing single-axis and four-bar knee. Our modeling studies driven by patient kinematics data have demonstrated that if the user walks the same and if the knee has the same dynamics, four-bar knee does increase foot clearance. However, our modeling studies also show that four-bar knee also has substantially worse dynamics, reducing rotation of motion and introducing a phase lag. Both of these effects reduce the foot-clearance, providing less foot-clearance than single axis knee. It thus appears that user does compensate between knees, and that they actually raise their legs more when wearing 4-bar knee to compensate for the inferior foot-clearance.
From our results, four-bar knee mechanism is provided some foot clearance. However, if an ankle can flex in a critical period, it is provided more foot clearance for smooth swing. The achievement of this study will provide a better understanding of some of the ideal properties of prostheses gait. It could be useful for redesigning the passive mechanism to improve foot clearance in the prosthetic leg.

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