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Stabilizing moments of force on a prosthetic knee during stance in the first steps after gait initiation

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ABSTRACT

In this study, the occurrences of stabilizing and destabilizing external moments of force on a prosthetic knee during stance, in the first steps after gait initiation, in inexperienced users were investigated. Primary aim was to identify the differences in the external moments during gait initiation with the sound leg leading and the prosthetic leg leading. A prosthetic leg simulator device, with a flexible knee, was used to test able-bodied subject, with no walking aid experience. Inverse dynamics calculations were preformed to calculate the external moments. The subjects learned to control the prosthetic leg within 100 steps, without walking aids, evoking similar patterns of external moments of force during the steps after the gait initiation, either with their sound leg loading or prosthetic leg leading. Critical phases in which a sudden flexion of the knee can occur were found just after heelstrike and just before toe off, in which the external moment of force was close to the internal moment produced by a knee extension aiding spring in the opposite direction.

1. Introduction

Amputee subjects who learn to walk with a prosthetic leg with an artificial knee, perform poorly during the initial gait training, hence the use of parallel bars, supported by therapists and other safety measures. In the weeks that follow, subjects develop adjustment strategies to improve obstacle crossing, gait initiation and gait termination [17]. It is suggested that the most significant gait adaptations occurred following receipt of a functional prosthesis. Research does not show a clear benefit in gait patterns at discharge following use of generic prosthetic devices (early walking aids with limited functionality) during the initial rehabilitation process [1]. Therefore, it is of value to study the gait initiation strategies, with fully functional prosthetic legs, in inexperienced prosthetic leg users in the early phase of motor learning. In the current study we investigated the stabilizing external extension moments on the prosthetic knee in the first steps after gait initiation with the sound leg or prosthetic leg leading in inexperienced prosthetic leg users.

The preference of experienced transfemoral (TF) amputee subjects to initiate gate with their prosthetic leg leading, indicates that they have implicit knowledge of the active control possibilities in their sound ankle, which they use to gain forward velocity [15,18]. Because of these active control possibilities it seems advisable to initiate gait with the prosthetic leg leading. When considering the first step after gait initiation, in which the leading prosthetic leg becomes the stance leg, the leading leg has to be placed in such a manner that sufficient knee stability is reached when loading the leg. The ground reaction force (GRF) under the prosthetic foot results from the angle at which the leg is placed, the internal moment of force around the hip joint and gravitational forces on the body segments. When this GRF generates an external moment of force around the knee joint that remains within the limits of the knees stability, the knee will not buckle and stable stance will be achieved.

In contrast to experienced prosthetic leg users, inexperienced patients are taught to initiate gait with their sound leg leading in the initial stage of therapy in our rehabilitation facility. This strategy ensures a stabilizing external extension moment on the prosthetic stance leg during gait initiation and minimizes the risk of falling during the first step, as the sound leg, with more control possibilities, becomes the stance leg. Consequently, in the second step the prosthetic leg becomes the stance leg again, with the same need to stabilize the knee.

Based on differences in step length and velocity of the prosthetic leg in the steps after the gait initiation with either the prosthetic leg or the sound leg leading, we expect different ground reaction forces under the prosthetic foot. These forces generate external flexion or extension knee moments which may stabilize or destabilize the prosthetic knee. During the swing phase knee flexion is necessary for ground clearance. At the end of the swing phase, an internal hip extension moment can be applied to extend the prosthetic knee, using the inertial properties of the lower part of the prosthetic

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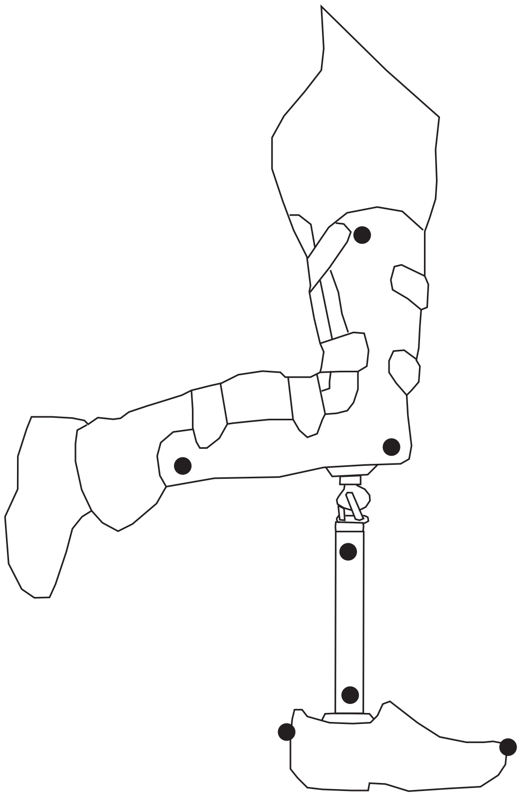

Fig. 1. Kneewalker prosthetic leg for able-bodied subjects. The black dots indicate the optical marker positions.

leg. This internal hip extension moment also contributes to ground reaction forces, which contribute to the stabilization of the knee during stance.

In this study, we investigated whether an inexperienced prosthetic leg user with only limited training (100 steps) is able to initiate gait and walk two steps without walking aids on a prosthetic leg with a flexible knee, without the occurrence of a sudden flexion of that knee during stance, either in a sound leg leading condition, in which the prosthetic leg is used in the second step, or in a prosthetic leg leading condition, in which the prosthetic leg is used in the first step. To ensure that our subjects had no experience with the use of a prosthetic leg, or related walking aids, and to control for learning period and comorbidity, we used able-bodied (AB) subjects. The AB subjects used a kneewalker prosthetic leg, on which AB subjects use the same compensation strategies as inexperienced prosthetic leg users, and that kinematic and kinetic analysis results are similar to gait analysis from people with TF amputations [8]. The flexible knee is equipped with an extension aiding spring, which can deliver an internal extension moment. We wondered if the evoked GRF delivers an external flexion moment that is close to the internal extension moment.

2. Methods

2.1. Subjects

Eleven inexperienced naive AB subjects (7:4 (m:f); 28 y (±3); 75.7 kg (±8.4); 1.85 m (±0.07)) wearing a kneewalker prosthetic leg (Fig. 1) with no impairments of walking volunteered to participate in the study. The healthy subjects were recruited via advertisement on a local university bulletin board. They had no known neurological or orthopedic complaints or diseases. Informed consent was obtained from all subjects before testing.

2.2. Apparatus

We used a PRIMAS 3D motion capture camera system, a Bertec force plate and a kneewalker prosthetic leg for AB subjects. The 3D motion capture camera system consists of six infrared cameras recording at 100 Hz. Seven retroreflective markers, positioned on the socket (3: upper leg, knee joint, lower leg), the shaft (2: proximal, distal) and the foot (2: heel, toe) (Fig. 1) were used to record the motion of the prosthetic leg. The GRF and center of pressure (CoP) under the prosthetic foot were recorded at 100 Hz with the Bertec force plate. The marker data and force plate data were rotated around the vertical (y) axis and projected in the sagittal plane through the artificial knee joint, enabling us to calculate the external flexion and extension moment on the knee. The motion and force data were filtered with a second order 5 Hz low pass zero time-lag Butterworth filter and processed in MATLAB with custom made software for the 2D inverse dynamics calculations. The outcome parameters were analyzed with SPSS. The kneewalker prosthetic leg is a prosthesis for AB subjects [8] which consists of an Otto Bock Habermann modular four bar linkage knee joint (3R36), an Otto Bock dynamic foot with toes (1D10, size 26) and a shoe (size 43/9, toe–heel length 0.30 m) (Fig. 1). The artificial knee is equipped with an extension aiding spring. This spring has two main functions. Firstly, the spring supports the forward motion of the foot and shaft at the end of the swing phase, reducing the swing time. Secondly, the spring enables a prosthetic leg user to raise the prosthetic leg forward against gravity without flexion of the knee, assumed that the motion is not performed with high accelerations. This second feature provides a prosthetic leg user control over the passive knee when positioning the prosthetic foot for the stance phase at low speed. By making use of the extension spring the prosthetic knee remains locked in full extension. The spring generates an internal moment between 45 and 0° flexion. The magnitude of the moment is inversely related to the amount of flexion, decreasing down to 0 Nm at 45° flexion. Hyperextension of the prosthetic knee is prevented by a mechanical stop, i.e. a very high stiffness. The spring produces a maximal internal extension moment of 12.4 Nm in full extension. The length of the shaft can be adjusted to match the contralateral leg length. The mass of the knee–shaft–socket system is 2.08 kg. The prosthetic ankle-foot system of the kneewalker prosthetic leg is relatively stiff. The leg socket of the kneewalker is constructed in such a way that the prosthetic leg is connected to the upper and lower leg, which is fixed in 90° flexion at the knee joint. Because of this construction, the AB subjects are able to put weight on the kneewalker via their knee and the socket/leg connection. In this way the prosthesis can be used in a comparable manner as a prosthesis for knee-exarticulation amputees. All subjects used the same shoe under the prosthetic foot. The heel-toe length was 0.3 m.

2.3. Procedure

Before the measurements the subjects were allowed to walk with the kneewalker prosthetic leg without walking aids. The subjects were not allowed to make more than 100 steps. No other instructions were given. All subjects were informed and they experienced that the kneewalker was equipped with a flexible knee that not only can flex during the swing phase, but also flexes in loaded condition when used inadequately.

Before gait initiation measurements started, the subjects had to balance on the kneewalker with little support from the contralateral foot for at least 3 s to determine a midstance position per subject, based on the angles of the joints and segments. After this measurement all subjects were tested in two conditions. In the first condition subjects initiated gait with their sound leg leading, placing their prosthetic leg on the force plate in the second step. In the second condition subjects initiated gait with their prosthetic