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Principles of obstacle avoidance with a transfemoral prosthetic limb

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ABSTRACT

In this study, conditions that enable a prosthetic knee flexion strategy in transfemoral amputee subjects during obstacle avoidance were investigated. This study explored the hip torque principle and the static ground principle as object avoidance strategies. A prosthetic limb simulator device was used to study the influence of applied hip torques and static ground friction on the prosthetic foot trajectory. Inverse dynamics were used to calculate the energy produced by the hip joint. A two-dimensional forward dynamics model was used to investigate the relation between obstacle–foot distance and the necessary hip torques utilized during obstacle avoidance. The study showed that a prosthetic knee flexion strategy was facilitated by the use of ground friction and by larger active hip torques. This strategy required more energy produced by the hip compared to a knee extension strategy. We conclude that when an amputee maintains enough distance between the distal tip of the foot and the obstacle during stance, he or she produces sufficiently high, yet feasible, hip torques and uses static ground friction, the amputee satisfies the conditions for enable stepping over an obstacle using a knee flexion strategy.

1. Introduction

Stepping safely over obstacles is a common daily living activity [1]. During obstacle avoidance, the stance limb must establish a base of support that appropriately maintains stability to avoid slipping or falling. The swing limb must clear the obstacle successfully to avoid tripping [2,3]. The applied joint moments of the swing limb and the obstacle–foot distance during stance determine the clearance achieved during obstacle avoidance [4]. Flexion of the knee in the swing leg is the most important motor strategy used by able-bodied (AB) subjects for foot clearance. This knee flexion is achieved by an increase in the force of the knee flexors [5–9] and through kinetic coupling by the hip flexors. The amputation of a lower limb results in a deficiency in sensory input and an absence of muscles and joint(s). A person with a lower limb prosthesis must adapt to a mechanical device to become functionally independent again [10]. Transtibial (TT) amputee subjects increase swing hip elevation and hip and knee flexion as a function of obstacle height during obstacle avoidance. An increase of the knee flexion on the prosthesis side is achieved by modulating the work performed at the hip, not at the knee, as seen on the amputee's non-affected side [11,12]. In addition, the stance limb hip flexion, knee flexion and (on the non-affected side) ankle plantarflexion increase slightly with increased obstacle height, but the stance limb hip elevation does not. Hill et al. [11] concluded that modulations of the stance limb served to position the pelvis further back from the obstacle as the height of the obstacle increased.

Transfemoral (TF) amputee subjects make use of adjustment strategies to compensate for the loss of muscles and sensory input in their prosthetic limb during obstacle avoidance, and they learn to cope with bilaterally delayed and decreased obstacle avoidance responses in both limbs [13]. Vrieling et al. [14,15] found that the prosthetic knee flexion during obstacle avoidance of transfemoral amputee subjects was reduced in comparison with unimpeded walking and compared to TT amputees and able-bodied subjects. The lack of knee strategy in TF amputee subjects is compensated for by circumduction at the hip on the prosthesis side and by plantar flexion on the non-affected side [14]. These results suggest that TF amputee subjects use an extension strategy: their knee is fixed in extension, which is combined with hip abduction and exorotation. This strategy has an advantage over the knee flexion strategy. The extended prosthetic knee eases the transition from swing to stance. However, the extension strategy also has disadvantages. Not only does it reveal the use of a prosthetic limb, but also changes in the gait cycles are necessary when accelerating and decelerating the prosthetic limb in a lateral direction. Therefore, more degrees of freedom must be controlled. Additional free space is necessary for the clearance as the foot moves farther outward. Possible reasons for choosing the extension strategy over the flexion strategy are (1) a reduced gait velocity of the TF amputee subjects, which impedes the initiation of the pendulum motion of the prosthetic limb or (2) not being able to produce a sufficient flexion moment at the hip joint. To reduce the number of falls of amputees, Vrieling et al.

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suggested that it is important to train amputees in complex motor tasks, such as stepping over an obstacle, during the rehabilitation period. This training should be aimed at improving knee flexion or the execution of adjustment strategies. Although TF amputee gait and obstacle avoidance include many out of plane actions, including trunk sway [16–18] and the previously reported circumduction strategy [14,15], we believe it is of interest to study the possibility of crossing an obstacle with a knee flexion strategy as this strategy reduces the changes in gait cycles and masks the use of a prosthetic limb. In theory, crossing an obstacle with an upper leg prosthesis, which is confined to the sagittal plane, can be executed in four ways, where the prosthetic limb is either leading or trailing with the artificial knee joint either in flexion (flexion strategy) or fixed in extension and combined with hip abduction and exorotation (extension strategy).

In the present study, we asked how the hip torques and static ground friction [19] contributed to a flexion strategy in obstacle avoidance and what the costs are of this strategy. We hypothesized that to move a prosthetic foot using a knee exion strategy over an obstacle that is close by, it is preferable to use ground friction and large hip torques. This combination helps to achieve height with less forward motion compared to a combination of small hip torques and without the use of static ground friction. To achieve sufficient obstacle–foot clearance during the knee flexion strategy, the TF amputee subject must overcome the extension spring force that keeps the prosthetic knee in extension. The applied hip torque and the static ground friction on the prosthetic foot can help overcome the extension spring force. Consequently, the following knee flexion lowers the moment of inertia of the prosthetic limb by bringing the foot and the lower leg shaft closer to the hip joint. These changes may be useful when stepping over an obstacle. In the current study, we limited the modeling to the sagittal plane, as crossing an obstacle with a flexed upper leg prosthesis is confined to the sagittal plane.

In the first part of this study, we experimentally investigated the relationship among the static ground friction on a prosthetic foot, a wide range of hip torques and the trajectory of the prosthetic foot. The temporal (duration) and spatial (forward motion) data, the inverse dynamics (energy produced by the hip, the hip torques and the mean angular velocities of the upper leg) and the statistical relationships among fast or slow hip flexion to move the foot 0.1 m upward, with and without static ground friction conditions, were investigated. In the second part of this study, we used a two-dimensional forward dynamics model to investigate obstacle avoidance for which we focused on (a) the influence of a constant hip torque on the first part of the prosthetic foot trajectory, with and without the use of static ground friction and (b) the relation between the obstacle–foot distance and the associated necessary time varying hip torques in the sagittal plane while stepping over an obstacle. Testing for these discrete parameters in human subjects, without the interference of compensation strategies, was not feasible; therefore, it was decided to approach this problem in a theoretical way. The outcome and insights we gained from this study can be used to understand why TF amputee subjects prefer to use the knee extension strategy during obstacle avoidance and to provide insights into what we should take into account when teaching a knee flexion strategy during obstacle avoidance to TF amputee subjects who have a prosthetic limb.

2. Methods and results

Informed consent was obtained from all subjects before testing.

2.1. Part I – Measurements

In first part of this study, we investigated the relationships among static ground friction, hip torques and the trajectory of the prosthetic foot.

2.1.1. Hip torques

A wide range of hip torques driving a prosthetic limb was produced by four naive AB male subjects (mean 30 y (SD 7); mean 80 kg (SD 7.3); mean 1.87 m (SD 0.08)), with no previous experience using a prosthetic limb. A kneewalker transfemoral prosthetic simulator was used [20,21]. To obtain a high degree of equivalence for the comparison, we used a kneewalker prosthetic limb that was relatively short compared to the length of the non-affected leg, with the same properties, alignment settings and segments length for all four subjects. To make contact with the ground, the leg length difference between the non-affected leg and the prosthetic leg was compensated for by flexing the non-affected stance limb. The kneewalker prosthetic limb consisted 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 was equipped with an extension spring. The spring served two main functions. First, the spring supported the forward motion of the foot and the shaft at the end of the swing phase. Second, the spring enabled the prosthetic limb user to raise the prosthetic limb forward against gravity without flexion of the knee, assuming that the motion is not performed at a high acceleration. This second feature provided a prosthetic limb user control over the passive knee when positioning the prosthetic foot for the stance phase. When using the extension spring, the prosthetic knee remains locked in full extension. The spring generates a moment between 45 and 0 degrees of flexion. The amount of moment is inversely related to the amount of flexion, which decreases to 0 Nm at a 45 degree flexion. Hyperextension of the prosthetic knee is prevented by a mechanical stop, i.e., a very high stiffness. The spring produces a maximal 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 prosthetic leg is relatively stiff. The upper leg socket of the kneewalker prosthetic limb is

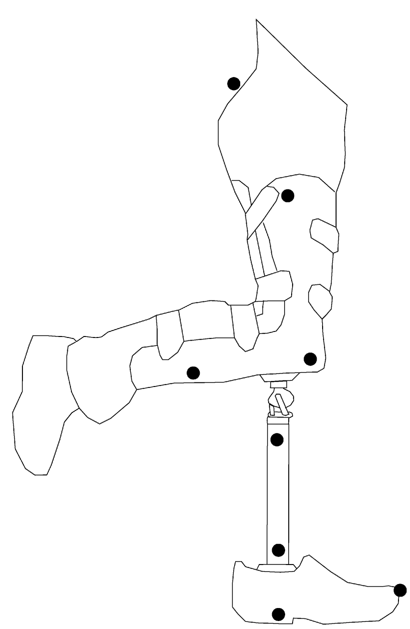

Fig. 1. Kneewalker prosthesis for able-bodied subjects. The black dots indicate the position of the retroreflective markers.