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The influence of a user-adaptive prosthetic knee across varying walking speeds: A randomized cross-over trial

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ABSTRACT

Previously conducted trials comparing the gait pattern of individuals with a transfemoral amputation using a user-adaptive and a non-microprocessor-controlled prosthetic knee (NMPK) found mixed and conflicting results. Few trials, however, have compared user-adaptive to non-adaptive prosthetic knees across different walking speeds. Because of the ability of variable damping, the effect of user-adaptive knees might be more pronounced at lower or higher walking speeds. Our aim was to compare the Rheo Knee II (a microprocessor-controlled prosthetic knee) with NMPKs across varying walking speeds. In addition, we studied compensatory mechanisms associated with non-optimal prosthetic knee kinematics, such as intact ankle vaulting and vertical acceleration of the pelvis. Nine persons with a transfemoral amputation or knee disarticulation were included and measured with their own NMPK and with the Rheo Knee II. Measurements were performed at three walking speeds: preferred walking speed, 70% preferred walking speed and 115% preferred walking speed. No differences on peak prosthetic knee flexion during swing were found between prosthetic knee conditions. In addition, prosthetic knee flexion increased significantly with walking speed for both prosthetic knee conditions. At 70% preferred walking speed we found that vaulting of the intact ankle was significantly decreased while walking with the Rheo Knee II compared to the NMPK condition ($P = 0.028$). We did not find differences in peak vertical acceleration of the pelvis during initial and mid-swing of the prosthetic leg. In conclusion, comparison of walking with the Rheo Knee II to walking with a NMPK across different walking speeds showed limited differences in gait parameters.

1. Introduction

Developments in prosthetic knee design have led to the introduction of microprocessor-controlled prosthetic knees (MPKs), such as the Rheo Knee or C-Leg. User-adaptive prosthetic knees should, in contrast to non-microprocessor-controlled prosthetic knees (NMPKs), allow early stance prosthetic knee flexion, ideal prosthetic knee kinematics during swing, and the ability to react to changes in walking speed. [1,2]

It is proposed that MPKs are beneficial for individuals with an amputation. Sawers and Hafner critically appraised the existing literature focusing on this proposition. [3] They found four trials [4–7] reporting an increase in preferred walking speed while using the MPK compared to a NMPK. They also found that comparison of other spatiotemporal variables were either inconsistent or not significant. Finally they found that the comparison of kinematic variables of walking with MPKs and NMPKs show "mixed and conflicting results".

The above-presented findings indicate that there is a low level of evidence for an added value of MPKs on gait mechanics. One of the factors contributing to this might be that the majority of

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studies compared MPKs and NMPKs at preferred walking speed. Because NMPKs are usually set to have optimal knee damping at preferred walking speed, their biomechanical behavior might be not that different from MPKs at preferred walking speed. They, however, are less able to respond to an increase or decrease of walking speed, because they can only adapt knee damping within pre-set and limited parameters. The Rheo Knee II, the subject of our study, is able to adapt knee damping to a greater extent than NMPKs. To be able to do so, the Rheo Knee II incorporates a magnetorheological fluid, which is a carrier oil in which magnetic particles are dispersed. Based on the information from a knee angle, knee angular velocity, and a force sensor, an algorithm controls electromagnetics [1]. The magnetic particles in the carrier oil form torque-producing chains in response to the electromagnetic field [1]. By changing the magnetic field, the Rheo Knee II can constantly vary the amount of knee damping during the stance and swing phase with a frequency of 50 Hz [1]. It is thought that the control algorithm of Rheo Knee II leads to optimal knee damping irrespective of walking speed, whereas NMPKs have non-optimal knee damping at slower or faster walking speeds. This premise was tested by Herr and Wilkenfeld, who found that in two out of four subjects peak prosthetic knee flexion during swing while walking with the Rheo Knee remained around 70° (set target of the Rheo Knee during these measurements) irrespective of walking speed [1]. Contrastingly, knee flexion while walking with the NMPK increased with walking speed [1]. In the other subjects this was not visible, as they did not reach 70° of prosthetic knee flexion during swing [1].

Having more optimal prosthetic knee kinematics during swing can be beneficial for individuals with an amputation. Having too little prosthetic knee flexion might lead to problems with prosthetic foot clearance which, in turn, might lead to an premature ankle plantar flexion of the intact leg during mid-stance (vaulting) to assist with prosthetic foot clearance [8]. Having too much prosthetic knee flexion during swing might also be undesirable, as the prosthetic knee has to be extended at the beginning of the stance phase. A larger peak prosthetic knee flexion during swing means that a larger movement trajectory has to be completed. The mechanism by which the prosthetic knee is extended during swing is not well studied, but in children without an amputation velocity-related forces and muscle activity of predominantly the stance leg have been described [9]. During early and mid-stance, the hip abductors and extensors of the stance leg move the pelvis center of mass upwards [9].This movement creates an external knee extension moment [9]. During slow walking stance limb muscle activity has shown to be the main contributor to knee extension during swing, while at faster walking the velocity-related forces are dominant [10]. Whether these mechanisms are seen in individuals with an amputation and whether they are influenced by a user-adaptive prosthetic knee is unknown.

The aim of this study is to compare walking with a NMPK to walking with the Rheo Knee II across different walking speeds. We hypothesized an increased preferred walking speed while walking with the Rheo Knee II. In addition, we hypothesized comparable peak prosthetic knee flexion during swing across all walking speeds while walking with the Rheo Knee II, while peak prosthetic knee flexion during swing would increase with walking speed in the NMPK condition. Finally, we hypothesized a reduced vaulting of the intact leg at lower walking speeds and reduced vertical pelvic acceleration during initial swing of the prosthetic leg while walking with the Rheo Knee II when compared to the use of a NMPK. To contribute to the existing body of knowledge, we also analyzed spatiotemporal and kinematic variables reported in existing literature.

2. Methods

2.1. Subjects

For this randomized cross-over trial we recruited persons with a transfemoral amputation or knee disarticulation from the Netherlands and Belgium. The inclusion criteria were: (i) at least one year post amputation; (ii) functional level from K2 (limited outdoor) or higher [11]; (iii) never previously fitted with a microprocessor-controlled knee. Exclusion criteria were: (i) other musculoskeletal problems influencing walking ability; (ii) stump problems/poor socket fitting; (iii) body weight >125 kg (maximum specification weight for the Rheo Knee II); (iv) knee centre-floor distance below 41 cm.

The Ethical Research Committee Twente, Enschede, the Netherlands approved the study protocol (NL 30112.044.09). All subjects provided written informed consent before the start of the measurements.

2.2. Prosthetic adjustments

We randomly assigned the subjects to start measurements with their own non-microprocessor controlled prosthetic knee or with the Rheo Knee II. In both prosthetic knee conditions, the LP Vari-Flex® with EVO™ (Össur®) prosthetic foot was provided. After eight weeks of acclimatization the first set of measurements was performed after which subjects crossed over to the other prosthetic condition. After another eight weeks, the second set of measurements was performed and subjects left the research study. Full details regarding the process of prosthetic adjustments have been published before [12].

Participants did not undergo a gait training program while walking with the Rheo Knee II or their own NMPK to make the comparison as little affected by gait training factors as possible.

2.3. Protocol

Data were collected using the CAREN system (Motek Forcelink BV, Amsterdam, the Netherlands) at the Military Rehabilitation Centre 'Aardenburg', Doorn, the Netherlands. The CAREN system consists of an instrumented single-belt treadmill and a twelve infrared-camera Vicon motion capture system (Oxford Metrics Ltd., Oxford, UK).

We used the modified Helen-Hayes marker set, including 37 reflective markers, which were placed according to the Vicon full-body Plug-in-Gait model. In addition, we placed 2 markers on the rope connecting the safety harness to an overhead frame. During a preliminary trial, we asked subjects to place their full bodyweight on the safety harness. The distance between the two markers in this condition was used in the data-analysis to check if subjects made use of the safety harness. The sample rate of the Vicon system was set at 100 samples per second.

Trials were performed at preferred walking speed, 70% preferred walking speed +and 115% preferred walking speed We hypothesized that 70% preferred walking speed would be reflective of in-house ambulation. For reason of uniformity, we would ideally have studied walking at 130% preferred walking speed. We however, hypothesized that this might be too high for a proportion of our study population which would reduce the size of our study sample. We therefore felt that 115% preferred walking speed was a safer option. The treadmill speed was fixed. We determined preferred walking speed during a familiarization trial. In this trial, walking speed was gradually increased until participants indicated that the speed was comfortable. After this, the walking speed was increased with 0.1 m/s and the participant was asked whether this was more comfortable or uncomfortable. In case the walking speed