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Detection of the onset of gait initiation using kinematic sensors and EMG in transfemoral amputees

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ABSTRACT

In this study we determined if detection of the onset of gait initiation in transfemoral amputees can be useful for voluntary control of upper leg prostheses. From six transfemoral amputees inertial sensor data and EMG were measured at the prosthetic leg during gait initiation. First, initial movement was detected from the inertial sensor data. Subsequently it was determined whether EMG could predict initial movement before detection based on the inertial sensors with comparable consistency as the inertial sensors.

From the inertial sensors the initial movement can be determined. If the prosthetic leg leads, the upper leg accelerometer data was able to detect initial movement best. If the intact leg leads the upper leg gyroscope data performed best. Inertial sensors at the upper leg in general showed detections at the same time or earlier than those at the lower leg. EMG can predict initial movement up to a 138 ms in advance, when the prosthetic leg leads. One subject showed consistent EMG onset up to 248 ms before initial movement in the intact leg leading condition.

A new method to detect initial movement from inertial sensors was presented and can be useful for additional prosthetic control. EMG measured at the prosthetic leg can be used for prediction of gait initiation when the prosthetic leg is leading, but for the intact leg leading condition this will not be of additional value.

1. Introduction

The two phases of gait initiation in transfemoral amputees (TFA) are different from non-amputees [1,2]. In the first phase, preparations are made for the step execution; the weight is shifted to the trailing leg which ends at initial swing (IS) of the leading leg [1,3,4]. In TFA this first phase is short when the prosthetic leg leads (PLL), and relatively long when the intact leg leads (ILL), compared to non-amputees [1]. The second phase starts at IS and ends at initial contact (IC) of the leading leg. In TFA this phase is long when the PLL, but relatively short when the ILL, compared to non-amputees [1].

If gait initiation can be predicted in TFA, the prosthesis can be controlled such that it is prepared for lifting of the prosthesis, in case the PLL. Prosthetic control during gait initiation may also provide a stable knee in case the ILL. If future prostheses can provide push-off, gait initiation detection may also become very useful.

Timing of push-off is very important and therefore accurate prediction of gait initiation is also important [5]. IS and IC of the leading leg are for both PLL and ILL important to be detected, to provide control inputs for supported prosthetic gait initiation. In non-amputees gait initiation could be predicted up to 260 ms in advance for both leading leg conditions, using electromyography (EMG) and inertial sensors [5]. A study by Zhang et al. [6] showed that detection of the beginning of the swing phase from stance to walking using EMG, in one amputee, up to 152 ms before the event. They used a custom made liner and it was not mentioned which leg was leading.

To determine if inertial sensors or EMG at the upper leg are of additional value for prosthetic control we studied detection of the onset of gait initiation in six amputees using inertial sensors and EMG, both from the prosthetic leg. No modification of the socket or liner was introduced. From this data we investigated a new method for detection of the onset of gait initiation the leading leg of TFA,

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using inertial sensors. Subsequently we determined if EMG provides additional information to the inertial sensing, and if gait initiation can consistently be predicted in TFA from inertial sensing and/or EMG.

2. Methods

2.1. Participants

Six unilateral amputees participated in this study, three transfemoral amputees (TFA) and three through the knee amputees (TKA). Demographic variables of the amputees can be found in Table 1. Inclusion criteria were: have a unilateral TFA or TKA regardless of the reason for amputation; be between 18 and 70 years old; be a prosthetic user able to walk independently with or without a walking aid (K-level 2–4). An informed consent was obtained before the experiments, and the study was approved by the local Ethics Committee.

2.2. Measurements

Footswitches, placed mid-heel and under the first metatarsal head of each foot, gave spatio-temporal information. Two inertial sensors (Xsens, Enschede, the Netherlands), placed at the frontal side of the upper and lower (prosthetic) leg, halfway between the hip and the knee and between the knee and the ankle. Kinematic data was measured at 100 Hz. Subjects wore their own low-heeled shoes.

EMG registration was performed on eight upper leg muscles of the residual part of the prosthetic leg: gluteus maximus (GMa), gluteus medius (GMe), tensor fasciae latae (TFL), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), semitendinosis (ST) and the adductor magnus (ADD).

Electrodes were placed according to the SENIAM standards [7]. Because normal anatomy is disturbed at the amputated side EMG was checked prior to the measurements, by selective contraction of the measured muscle. On each muscle two self adhesive electrodes (Ambu, BRS) were placed approx. 1 cm apart. EMG measurements were performed with a 16 bipolar channel Porti-system (TMSi, Oldenzaal, the Netherlands) at 2048 Hz. A synchronization pulse (sync) at the start and end of each measurement was used to synchronize the Porti and Xsens systems.

2.3. Procedures

Subjects were required to stand upright, the initial posture. Data recording was started. After five seconds in the initial posture the subjects were asked to press the sync and start walking. After five paces they were asked to stop, turn around, return to the initial posture, wait 2–3 s, press the sync and walk back (one trial). One measurement consists of four trials and two measurements were performed for each leading leg condition, 16 gait initiations per condition. In addition a stance measurement was performed where subjects were asked to stand in one spot for 30 s.

2.4. Data analysis

Footswitch data was used to detect IC, which was detected in all trials and therefore used to overlap the trials [5]. The overlapped trials were subsequently cut into trials, from 2 s before IC until IC.

Initial swing (IS) detected from the footswitches, was defined as the moment where both sensors under one foot lost contact with the floor.

Initial movement (IM) was detected using the modulus of the 3D accelerometer and gyroscope data of the upper and lower prosthetic leg [8]. The modulus of the accelerometer data (acc-data) during quiet stance is 9.81 m/s^2, upon lifting of the leg a peak in the data is seen [8]. In the modulus of the gyroscope data (gyro-data) the forward body motion was clearly visible (Fig. 1). The inertial sensor data was expressed in the body coordinate system based on a sensor-segment calibration procedure as described by [5]. The inertial sensor data, expressed in body coordinates, was subsequently low-pass filtered at 10 Hz with a second order, butterworth filter.

The thresholds for both detection methods of IM were determined from the stance measurements, because subjects were usually not standing completely still. The average of the moduli during stance was used as a baseline for IM detection, both acc-data and gyro-data had to be at least 100 ms within 1 SD of the baseline before IM detection was attempted. The threshold for IM detection for both methods was: mean stance measurement + 5*SD. This was the lowest threshold that did not detect any movements during stance. Both detections methods were analyzed for the upper and the lower limb to determine the most consistent, and the earliest detection of IM.

Detections of IM and IS were performed with respect to IC. Significant differences in timings were tested using the Mann–Whitney–Wilcoxon test with $P < 0.05$. Per leading limb condition the best method was selected first by determining the number of included trials and subsequently the consistency.

EMG data were high pass filtered at 10 Hz and low pass filtered at 500 Hz with a second order butterworth filter and subsequently cut into trials, from 2 s before IC until IC. For on/off detection the data was rectified and integrated in a window of 20 samples, a post-processor of four windows, set the total detection time delay to 40 ms.

The threshold for on/off detection was determined per muscle, per subject as the mean rectified and integrated 30 s resting-EMG plus three times the SD [9–11].

First the EMG on/offsets were determined per muscle, subject and trial with respect to IC. We subsequently preselected the muscles whereby EMG on/offsets were closest to IM. From those

Table 1
Overview of the details of the amputees.

Subject	Age (years)	Sex	Type	Reason amputation	Stump length (m)	Knee	Foot	Time (months)
1	52	M	TKA	T	0.56	C-leg	C-walk	24
2	46	M	TKA	T	0.59	Rheo knee	Vari-Flex Evo	8
3	29	F	TKA	D	0.56	C-leg	1E56	5
4[a]	64	M	TFA	V	0.41	Total knee	Elation	6
5	61	M	TFA	V	0.41	Total knee	Elation	5
6	62	M	TFA	T	0.35	C-leg	1E56	133

TFA, transfemoral amputee; TKA, trough the knee amputee; T, trauma; V, vascular; D, dystrofy.
[a] Walked with walking aid, time since amputation.