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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.

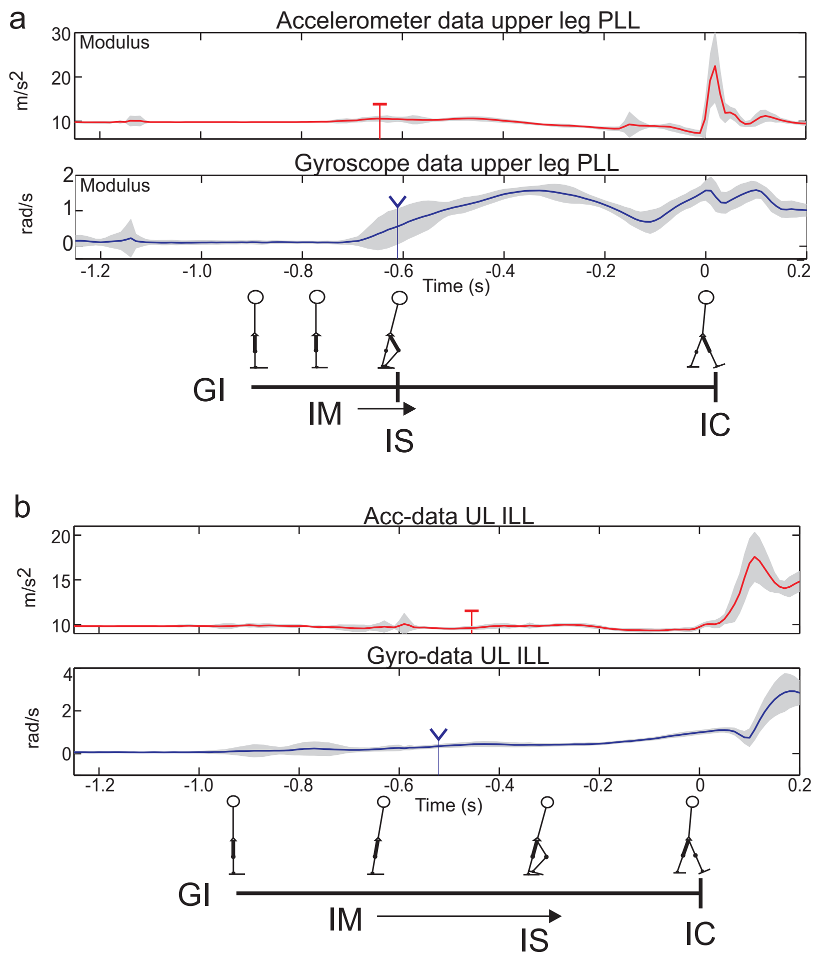

Fig. 1. An example of one representative amputee for detection of IM. (a) PLL condition (b) ILL condition. In red the ensemble average of the modulus of the upper leg accelerometer data, in blue the average modulus of the upper leg gyroscope data, the grey shaded areas are ±1SD. Per leading limb condition a schematic overview of GI for that leading limb is presented. Vertical lines show the average detections from this subject, the gyroscope data (Y) and the accelerometer data (T). In both leading leg conditions IC of the leading leg occurs at $t = 0$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

pre-selected muscles we calculated their timing with respect to IM, to determine if the on/offset per trial was before or after IM. For each subject we subsequently chose those muscles which met two criteria: 1) onset was before IM in all trials and 2) in total one trial was allowed to be excluded.

3. Results

Trial exclusion – for each leading leg condition there were five subjects that could perform the measurement, one subject was unable to perform ILL, another subject was unable to perform PLL. For the PLL condition 75 trials were included. Two subjects initiated one trial with the "wrong" leg of which one only performed 14

Table 2
IM and IS detection times before IC, from PLL and ILL.

	Subject	Max #	IM								IS	
			UL Acc (s) mean (SD)	#	LL Acc (s) mean (SD)	#	UL Gyro (s) mean (SD)	#	LL Gyro (s) mean(SD)	#	FS mean (SD)	#
PLL	A1	15	**−0.81(0.05)**	15	−0.68(0.26)[a]	15	−0.60(0.05)	14	−0.66(0.03)	15	–	0
	A2	16	**−0.77(0.05)**	16	−0.75(0.06)[a]	15	−0.79(0.11)	15	−0.76(0.05)	15	−0.77(0.08)	16
	A4	13	**−0.72(0.05)**	13	−0.72(0.06)	13	−0.70(0.06)	11	−0.52(0.11)[b]	13	–	0
	A5	16	**−0.86(0.05)**	16	−0.86(0.05)	16	−0.75(0.05)	15	−0.81(0.04)[b]	16	−0.63(0.49)	12
	A6	15	**−0.66(0.04)**	15	−0.65(0.04)	15	−0.62(0.11)	9	−0.62(0.16)	15	–	0
ILL	A2	16	−0.52(0.19)	16	−0.32(0.24)	3	**−0.57(0.08)**	16	−0.49(0.07)[b]	16	−0.66(0.24)	13
	A3	9	−0.60(0.00)	1	–	0	**−0.79(0.02)**	9	−0.33(0.11)[b]	9	−0.77(0.34)	4
	A4	16	−0.40(0.32)	13	−0.05(0.46)[a]	8	**−0.76(0.08)**	16	−0.63(0.16)[b]	9	−0.41(0.29)	9
	A5	16	−0.61(0.12)	16	−0.58(0.14)[a]	16	**−0.67(0.05)**	16	−0.68(0.07)	16	−0.43(0.14)	15
	A6	16	−0.45(0.26)	16	−0.24(0.30)[a]	16	**−0.57(0.07)**	16	−0.54(0.09)[b]	16	−0.56(0.24)	15

Average IS and IM timing before IC. max # is maximal number of trials available in subject. In bold the best performing detection method for IS/IM.
[a] Lower leg accelerometer data significantly different from upper leg ($P < 0.05$).
[b] Lower leg gyroscope data significantly different from upper leg ($P < 0.05$).

trials instead of 16 due to fatigue. In one other subject in one trial no IC was detected using the footswitches, this trial was left out. For the ILL condition 73 trials were included, no trials were excluded, however, one subject was only able to perform nine trials.

3.1. Detection of IS and IM

PLL – The upper part of Table 2 shows the results of IS/IM detection from the PLL condition. Only two subjects showed IS in the footswitch data. Only the upper leg acc-data detection allowed all trials to be included, therefore the upper leg acc-data was used for IM detection for PLL. IM detection in the upper leg acc-data was significantly earlier in two subjects compared to the lower leg acc-data. IM detection using the upper leg acc-data was in one subject 260 ms earlier than IS, in the other there was no difference. Fig. 1 shows an example of the detections.

ILL – The lower part of Table 2 shows the results of IS detection for the ILL condition. Only the upper leg gyro-data allowed detection of IM in all trials in all subjects. Therefore the upper leg gyro-data was selected for IM detection for ILL. In four subjects these detections were significantly earlier than those at the lower leg. IM detection using inertial sensors was on average (range) 50 ms (−180 ms to 170 ms) later than using footswitches, but more trials were included when using inertial sensors.

3.2. Detection from EMG

Fig. 2a shows an example of muscle on/offsets with respect to IC. In the first 500 ms some on/offset detections were found, but not in all trials. Subsequently all muscles are silent for 500 ms, which was seen in both conditions for all amputees. Muscles with EMG onsets with a median before or at the average IM were pre-selected (see for example Fig. 2a). From pre-selected muscles, per trial the onset with respect to IM was calculated (see Fig. 2b).

Onset detections between IM and IC occurring in all trials were rare. Offset detections occurring in all trials before IM or between IS and IC were also rare or with large SD. Therefore in the following analysis only the onset detections before or at IS were taken into account. Of those muscles meeting the two criteria, the average timing before IM and the SD were calculated (Table 3).

PLL – In four subjects at least one muscle was found that met the criteria, of which they had the TFL in common. The TFL had the lowest SD in all subjects and its onset was on average 78–140 ms before IM.

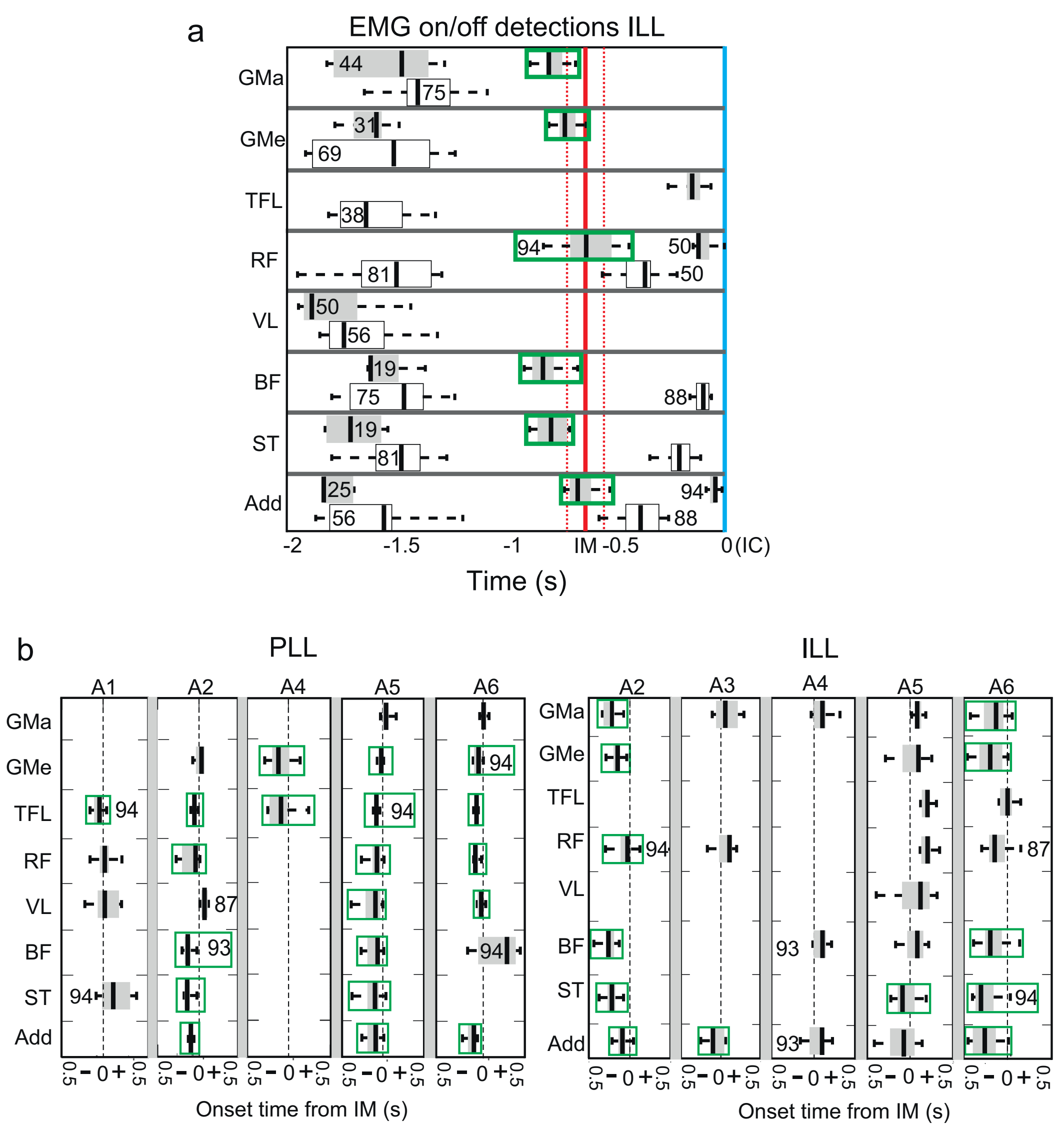

Fig. 2. (a) An example of the on/offset detections a representative amputee over time, from the ILL condition. The red vertical line indicates the average IM of this subject over all trials using detections from the modulus of the gyroscope data, the dotted lines are ±1SD. The blue vertical line is IC. White boxes are offset detections and in grey the onset detections. If a number is presented at the box, this is the % of trials in which this detection was found, if no number is given the detection was found in all trials. The onsets marked in green are those closest to IM, with the required number of trials. (b) EMG onset detections with respect to IM, as determined by the inertial sensors, for the PLL (left) and ILL (right) condition. The 0-lines indicate IM. Boxes placed on the left side of the 0-line, mark detections before IM (−) and on the right hand side they occur after IM (+). Boxes marked in green are those detections per muscle per subject, where the median of the detections lies before IM. If a number is presented at the box this represents the % of trials included, if no number is presented all trials of this subject were included. If no box is present, the median detection is either after IM or not enough trials could be included in the EMG detection. In each boxplot the thick line represents the median, the box shows the 25 and 75 percentiles and the whiskers mark the complete range.

Table 3
EMG onset detection before IM, for PLL and ILL.

PLL	Mean (SD)	#	Mean (SD)	#	Mean (SD)	#		
Subject	A1	15	A2	16	A5	16	A6	15
GME	–	–	–	–	–	–	−0.097 (0.088)	14
TFL	−0.06 (0.046)	15	−0.078 (0.023)	16	−0.089 (0.028)	15	−0.111 (0.047)	15
RF	–	–	–	–	−0.079 (0.073)	15	−0.104 (0.090)	15
VL	–	–	–	–	−0.128 (0.146)	15	–	–
BF	–	–	−0.134 (0.052)	15	−0.089 (0.089)	15	–	–
ST	–	–	−0.138 (0.057)	16	−0.111 (0.104)	15	–	–
AD	–	–	−0.097 (0.020)	16	–	–	−0.128 (0.056)	15

ILL	Mean (SD)	#	Mean (SD)	#
Subject	A2	16	A6	16
GMA	−0.226 (0.078)	16	–	–
GME	−0.156(0.063)	16	−0.190 (0.139)	15
BF	−0.248 (0.077)	16	−0.152 (0.137)	15
ST	−0.221 (0.071)	16	−0.235 (0.141)	14
AD	–	–	−0.233 (0.155)	15

#, the nr. of trials included (on the top row the max. nr. of trials for this subject), subjects without EMG onset detections before IM in at least all but one trials are excluded.

ILL – In two subjects four muscles were found with EMG onset detection before IM. In the others the criteria were not met. One of the subjects shows detections with SD comparable to IM detections, the other one has SD between 137 and 155 ms.

4. Discussion

The use of inertial sensors for motion detection is relatively easy and requires low computational levels and low sampling frequencies. EMG on the other hand is more difficult and requires a much higher sampling frequency, but it can show movement onset before the start of the actual movement [5]. EMG is only useful when combined with inertial sensors for determination of motion and body position, i.e. the state of the prosthesis, this is necessary for correct movement onset detections. EMG can be beneficial for gait initiation detection if it has consistent and earlier detections than the inertial sensors. A faulty detection could lead to a fall and is undesirable. Therefore we only allowed one trial to be excluded per muscle per subject.

PLL – For the PLL condition, the modulus of the upper leg acc-data was able to correctly detect IM in all available trials and detected IM the earliest and with the lowest variability. The upper leg acc-data detections were up to 129 ms earlier than the lower leg detections. In two subjects these differences were significant. Transfemoral amputees are only able to actively control the upper leg, this is the part of the prosthesis which is moving first, followed by the lower leg. Upper leg sensors will therefore show earlier IM detections than the lower leg sensor. From the acc-data lifting of the prosthetic leg is seen, which coincides with IS. For the PLL condition IM detection is therefore similar to IS detection, even though the footswitches could not confirm this.

In four amputees one or more muscles showed onset detection between 63 and 138 ms prior to IM in the required number of trials. In all four amputees TFL-EMG was a predictor of IM, with comparable variability to the inertial sensors. The only subject that did not show any EMG-onset in all trials before IM walked with a waking aid, which may have led to a later muscle onset.

ILL – For the ILL condition, the upper leg gyro-data appeared to be superior to the acc-data in detecting IM for the ILL condition. This was the only detection method where all trials could be included. IM was detected from the initial forward movement, which is initiated before IS. Therefore the IM detection may not necessarily coincide with IS of the leading leg. In four subjects IS was detected at the same time or earlier than IM. In one subject IM was later (90 ms) than IS, but with high variation.

In two amputees four muscles were found that could predict IM up to 248 ms in advance. In one amputee the consistency in the EMG detections was comparable to the inertial sensors detections. The other amputee showed a variability of up to 155 ms, which will make exact timing of prosthetic control difficult.

Prediction of gait initiation using EMG may be beneficial in the PLL condition. Amputees may benefit from this, as around 70% initiates gait with the prosthetic leg [1]. When the prosthetic leg initiates gait, the knee needs to flex first and at IC of the prosthetic leg it needs to be fully extended. The prediction of gait initiation can be used to prepare the knee for flexion. Timing is essential, initiating flexion too early might lead to a knee collapse.

For the ILL condition the prosthesis should either ensure a locked knee when the leading leg goes into IS, or in future an actuated ankle could generate push-off after IS. For the ILL condition, detection of IM of the leading leg using inertial sensors will leave sufficient time for push-off control, but it may be late to ensure a knee-lock. However, subjects already stand on their prothesis, therefore controlling knee-lock before gait initiation with the intact leg may not be of additional value and neither will EMG. In non-amputees push-off starts, approximately 300 ms after IS of the leading leg [5]. This suggests that even if IM is detected later than IS it would still leave enough time for prosthetic control.

4.1. Methodical considerations

During gait initiation, initial swing detection using foot switches was more reliable than heel-off detection, therefore IS detections were used for comparisons with the inertial sensors. Footswitch data can detect IC of the prosthetic or intact leg due to the high impact of the heel strike, but are unsuitable for IS or heel-off detections in the PLL condition. This is most likely caused by the weight balance of the amputees. When standing still amputees tend to place their weight more above the intact leg than above the prothetic leg, this will not trigger the footswitches in the prosthetic leg [5].

For the ILL condition IS also remained undetected in many trials using the footswitches. This may have been caused by the weight placement of the amputee or the placement of the footswitches. More weight is often placed at the heels which may leave the toe-switches inactivated. Heel-off was also not detected in all subjects in the ILL condition, probably because the sensors were too far back to detect stance, but they did detect initial contact. The two amputees where the detection rate was the lowest for ILL (A3 and

A4) were also the two amputees walking with a walking aid, which may have caused the reduction in detections.

Although all detection methods are suitable for online detection, there is a need for a real-time decision algorithm. The EMG onset detector had a total time delay of 40 ms, which in the PLL condition still leaves enough time to control the knee. Both detectors of the inertial sensors started with a 100 ms of relative rest condition, to determine if a subject is standing still. This will not lead to extra time delays due to detection, provided the subject is actually standing still before gait initiation. Changes in the gait pattern or changing from a different activity than stance to gait are not taken into account, other activities also need to be investigated.

Rather than using footswitches, a force-plate or a force sensor inside the prosthesis may provide a better estimation of the actual IS of the leading leg. Motion analysis may however still be faster, as the motion starts before the leg is lifted.

In this study the feasibility of using EMG and inertial sensors for gait initiation detection was determined using only a limited number of amputees. The variety in the amputee group was also large, which may have effected the results. The ILL condition showed differences between the amputees. This may be because of the variety in the group or the low number of subjects, but also because they may not be used to initiating gait with the intact limb. However, results from the PLL condition suggest that similar results can be found in all amputees, one subject might also be included after he received additional training. This suggests that the variety and low number of subjects did not effect the outcome for the PLL condition.

4.2. Conclusions

A new method is proposed to accurately detect IM from inertial sensors at the upper prosthetic leg, in both the PLL and ILL condition. For detection of IM in the PLL condition, the modulus of the upper leg accelerometer data performed best, for the ILL condition the modulus of the upper leg gyroscope data performed best. From sensors at the upper leg for both conditions, more trials could be included and in some subjects IM detections were significantly earlier. In four amputees onset of the TFL in the PLL condition was up to 111 ms earlier than IM detections. For the ILL condition EMG provides no additional value. Using inertial sensors (at the upper leg) for gait initiation detection can be of additional value to prosthetic control in both leading limb conditions the usability of EMG seems limited.

Conflicts of interest statement

The authors state that there are no conflicts of interest in the research.

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