Volitional Control of Ankle Plantar Flexion in a Powered Transtibial Prosthesis during Stair-Ambulation

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Abstract— **Although great advances have been made in the design and control of lower extremity prostheses, walking on different terrains, such as ramps or stairs, and transitioning between these terrains remains a major challenge for the field. In order to generalize biomimetic behaviour of active lower-limb prostheses top-down volitional control is required but has until recently been deemed unfeasible due to the difficulties involved in acquiring an adequate electromyographic (EMG) signal. In this study, we hypothesize that a transtibial amputee can extend the functionality of a hybrid controller, designed for level ground walking, to stair ascent and descent by volitionally modulating powered plantar-flexion of the prosthesis. We here present data illustrating that the participant is able to reproduce ankle push-off behaviour of the intrinsic controller during stair ascent as well as prevent inadvertent push-off during stair descent. Our findings suggest that EMG signal from the residual limb muscles can be used to transition between level-ground walking and stair ascent/descent within a single step and significantly improve prosthesis performance during stair-ambulation.**

I. Introduction

Intrinsic controllers for lower-limb prostheses use finite state machines whose transitions are triggered based on on-board sensor data. Such controllers have recently been shown to generate biomimetic and speed-adaptive behavior during over-ground walking [1, 2] but are incapable of transitioning between different terrains or perform adequately during stair ambulation. This severely limits the mobility of lower extremity amputees and has a substantial impact on their quality of life and social independence [3, 4]. A combination of top-down volitional and bottom-up reflex driven control of locomotion is required for seamless terrain transitions encountered everyday such as ramps and stairs [5]. Physiological studies have illustrated the potential use of residual limb EMG signal for volitional control of lower limb prostheses [6, 7]. This approach is hampered, however, as the signal is difficult to obtain due to the electrode placement within the prosthetic socket, cross-talk from adjacent muscles, noise from changes in skin conductance, mechanical artifacts, and other factors [8]. Until recently extrinsic (EMG) control has hence only been used to detect terrain transitions and change a concurrent intrinsic controller in a switch-like manner [9] (but also see [10, 11]).

Resrach supported by the Department of Defense award number 6920559 and 6920877. Oliver A. Kannape was further supported by the Swiss National Science Foundation grant PBELP3_140656.

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We here present preliminary clinical data on a hybrid, volitional EMG controller implemented within a neuromuscular reflex-model framework (positive force feedback [12, 13]). Unlike previous studies, user intention is not used to derive state transitions but to proportionally control push-off by a powered ankle-foot prosthesis, as recently illustrated for level ground walking [14]. We hypothesized that volitional control enables the amputee to generalize the behavior of the level ground walking state machine to stair ascent and descent, even though walking states differ between these three types of gait [15]. In particular we hypothesized that a) the amputee would be able to produce push-off torques and toe-off ankle angles comparable to that generated using the intrinsic controller and the biological limb during stair ascent and b) to prevent inadvertent ankle push-off during stair descent.

II. Background

A. Gait Cycle and State Machine

A complete human gait cycle can be divided into two main phases, namely stance and swing. The stance phase begins at heel-strike and terminates upon toe off; the swing phase takes up the remainder of the gait cycle. In order to enable lower limb amputees to walk with a biomimetic gait, intrinsic controllers for active ankle-foot prostheses aim to emulate the kinetics and kinematics of the biological limb [9]. This has lead to a further division of the stance and swing phases for a model of level ground walking. The stance phase consists of three sub-phases: controlled plantar-flexion (CP), controlled dorsiflexion (CD), and powered plantar-flexion (PP). The swing phase is divided into an early swing phase (ESW) and a terminal swing phase (TSW, see figure 1).

State transitions for stair ambulation differ slightly and start with an initial toe contact. During stair ascent the ankle then transitions from a first controlled dorsiflexion phase (CD1), to powered plantar-flexion (PP1), a second CD phase (CD2), and a second PP phase (PP2) before going into early and late swing phases. For stair descent the toe-contact is followed by a first controlled dorsiflexion phase (CD1, until heel-strike), followed by a second CD phase (CD2), PP and ESW/TSW. Importantly and unlike for level-ground and stair ascent walking, no torque is provided during stair descent powered plantar-flexion.

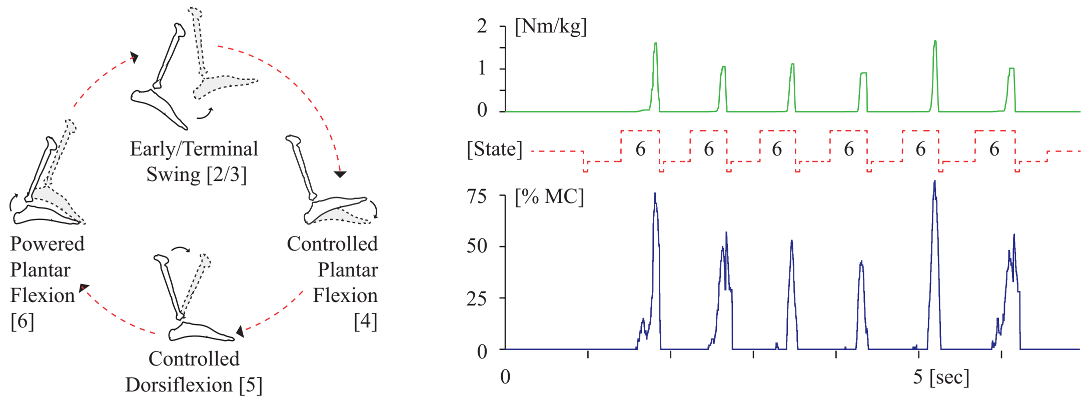

Figure 1 – Intrinsic state machine and proportional EMG control. The state machine aims to enable the kinetics and kinematics of the biological limb during level-ground walking. Here, the participant was able to activate his gastrocnemius muscle, indicated by the blue line (bottom graph) to change the torque commanded during powered plantar-flexion, top green trace. EMG activity was only used during the PP phase (state 6) as indicated by the red, dotted trace. The volitional control enabled the participant to request maximal power during stair ascent and no power during stair descent without requiring a specialized state machine.

III. Hardware

A. *BiOM Ankle-Foot Prosthesis*

The ankle–foot prosthesis used for this study was developed by BiOM, LLC and is a successor to the series of prototypes developed in the Biomechatronics Group of the MIT Media Laboratory. It is a self-contained device having the mass (1.8 kg) and size of the intact biological ankle–foot complex. The basic architecture of the electromechanical design consists of a unidirectional spring in parallel to an actuator with a series spring [16, 17]. The prosthesis is capable of varying impedance during stance, providing power during powered plantar flexion and performing position control during swing.

1) *Powered Plantar-Flexion and Proportional Myoelectric Control*

The PP state is important as it emulates the biological triceps-surae, which generates nearly 80% of the mechanical work required to complete each gait cycle [18, 19]. The push-off provided before toe-off adapts to the participants walking characteristics. An increase in the sensed prosthetic ankle joint torque triggers an increase in the torque generated by the actuator during mid- to late stance phase, resulting in an increase in net positive ankle work production. When the intrinsic controller is used, the gain term (P_{FF}) in equation (1) depends on the walking velocity. When proportional myoelectric control is used the gain component is linearly dependent on the EMG signal, i.e. if muscle activation remains below a previously determined threshold the PFF term will be multiplied by 0, if EMG activation is maximal, the multiplier is 1. During late stance PP, when the ankle begins to plantar-flex a spring function is applied, having stiffness K and equilibrium θ_0 to ensure a biomimetic plantar-flexion toe-off angle.

$$\tau_{Pff} = P_{FF} * \tau^{x}_{measured} + K_0(\theta - \theta_0) \quad (1)$$

B. *EMG Unit*

1) *Measurement Module*

The EMG measurement module consists of a single board computer (RaspberryPi Version 2, Raspberry Pi Foundation, Cambridgeshire, UK), a 16-channel analog signal amplifier (RHA2216, Intan Technologies, Los Angeles, CA) and a 16-bit analog to digital Converter (AD7980, Analog Devices, Norwood, MA). EMG signal was recorded using Philips SmartTrace electrodes (Philips, Amsterdam, Netherlands), which were placed above the gastrocnemius muscle and patella of the residual limb, inside the participant's liner.

2) *Signal Processing*

The EMG signal was sampled at 1kHz and high-pass filtered using a 4th order Butterworth filter with a cutoff frequency of 80Hz. It was subsequently rectified before being averaged over a moving window of 150ms. This average value was then used to scale the EMG signal to a percentage of the maximum P_{FF} gain set during tuning of the BiOM using the thresholds explained in the following paragraph. The scaled EMG value was sent to the BiOM at a frequency of 125Hz and used solely in the PP phase. This helps avoid common EMG caveats due to motion artifacts, that occur e.g. at heel-strike.

IV. Methods

A. *Experimental Procedure*

1) *Tuning and Threshold Detection*

At the beginning of the study the BiOM was tuned for the participant by a prosthetist to normalize the work performed by the prosthesis. An EMG threshold value was then determined to distinguish between an intentional activation of the Gastrocnemius muscle and baseline noise due to motion artifacts and involuntary muscle activation. This was achieved by asking the participant to walk for 10 steps with no voluntary muscle activation, followed by ten steps with close to maximal muscle activation. The thresholds were

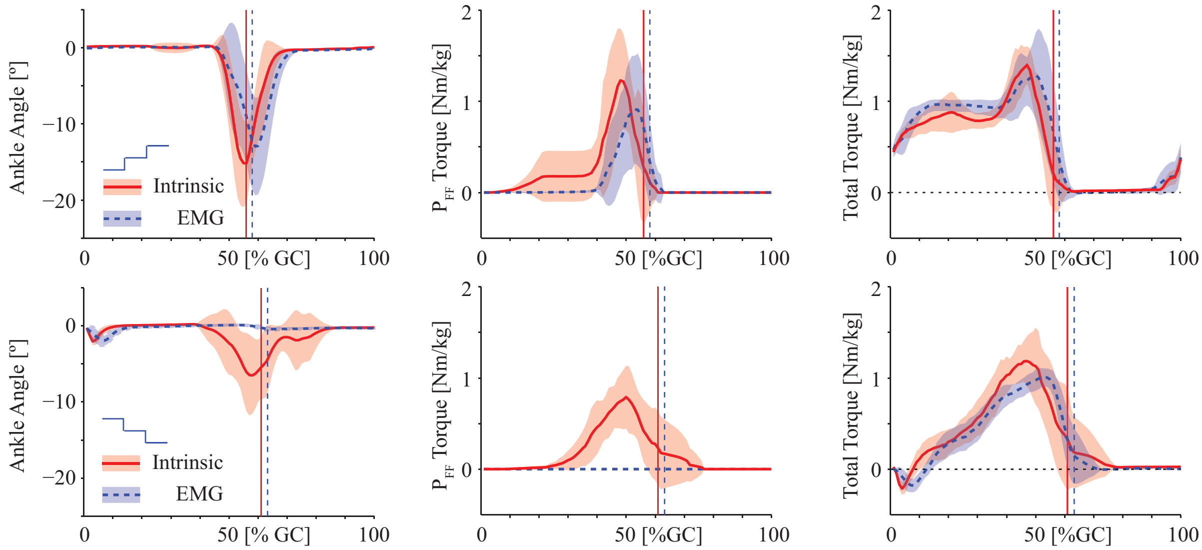

Figure 2 – Ankle-Angle, PFF torque, and total estimated torque over the gait cycle. During stair ascent (top row) the participant was able to reliably activate his gastrocnemius muscle to modulate the power provided by the powered ankle-foot prosthesis during PP phase. He could thereby achieve the same ankle-angle and overall torque profile as with the intrinsic controller. Maximal PFF torque was higher for the intrinsic controller; however, this was not reflected in the overall torque profile. Importantly, as indicated in the bottom row, minimizing gastrocnemius activity prevented the prosthesis from inadvertently providing power during stair descent. This was not the case while walking with the intrinsic controller as indicated by the larger ankle-angle and PFF torque.

then manually set so that there was no interference due to involuntary muscle activation while at the same time ensuring maximal activation can be reached. These thresholds were used by the signal processing unit to scale the moving average EMG window to 0-100% of the maximal gain, see figure 1.

2) Stair Ambulation

Stair ambulation was performed in a fire exit staircase with 12 steps (height: 16.5cm, depth: 28.5cm). The participant walked up and down the flight of stairs three times with either the EMG control (block 1) or the intrinsic control (block 2). The EMG side always led.

B. Participant

A bilateral transtibial amputee (male, weight: 75.0kg, height: 189cm) wore the device under investigation on his right leg and a BiOM with an intrinsic controller on the left. The study was approved by MITs Committee on the Use of Humans as Experimental Subjects (COUHES) and the participant gave informed consent prior to commencing the study.

C. Statistics

Two-tailed, paired Student's t-tests were used to compare dependent variables at a significance level of α=0.05.

V. Results and Discussion

The participant was able to use the volitional controller within minutes of walking and to successfully push off with each step, both for level ground walking and stair ascent. Similarly, during stair descent, muscle activation always remained below the activation threshold, preventing the BiOM from inadvertently providing power.

A. Stair Ascent

The maximum angle at toe-off did not differ between volitional and intrinsic control (19.2º±1.1 (EMG) to 19.2º±0.7 (intrinsic), p=0.9) indicating that the participant could reliably recruit his residual limb muscle to control powered plantar-flexion during stair ascent. These values are within the range of the biological ankle (13º-31º) and significantly higher than for a passive prosthesis (5º) [20, 21], Table 1. Toe-off timing was slightly but significantly later using EMG control (58.1%±3.9 (EMG) to 56.0%±2.5 (intrinsic), t(17)=2.27, p=0.036). The peak PFF torque commanded was significantly higher when walking with the intrinsic controller (peak PFF torque: 1.72±0.43Nm/kg (intrinsic), 1.3±0.43Nm/kg (EMG)) although this was not reflected in the overall peak estimated torque (peak estimated Torque: 1.76±0.08Nm/kg (EMG), 1.71±0.20Nm/kg, p=0.19 n.s.). As illustrated in figure 1 only 3 of the possible 5 states were used during stair ascent, i.e. early swing, terminal swing, and powered plantar flexion. This is most likely due to the fact that the BiOM maximally dorsiflexes in the swing phase, preventing a further controlled dorsiflexion state as would be suggested by the aforementioned state transitions.

B. Stair Descent

As hypothesized, the participant successfully prevented the BiOM from inadvertently providing power during plantar flexion in stair descent. This was reflected in the commanded PFF torque and ankle angle at toe-off. The angle was 0.5º±0.04º with EMG and 12.6º±1.7 with intrinsic control (t(16)=-48.47, p<0.0001). Due to the level-ground walking state machine the prosthesis did not plantar-flex in terminal swing phase like the biological limb (18º-40º [20, 21]). As the participant did not contract his calf muscles during stair descent beyond the threshold level, commanded PFF torque remained 0.0Nm/kg for EMG control, but rose to 1.2±0.1Nm/kg for intrinsic control ($t(16)=33.7$, $p<0.0001$). The maximum estimated torque using EMG control was 1.0±0.1Nm/kg compared to 1.5±0.1Nm/kg with the intrinsic control ($t(16)=26.1$, $p<0.0001$).

TABLE I. DYNAMIC BEHAVIOR OF THE POWERED PROSTHESIS

Prosthesis	**Ascent** (mean peak values)		**Descent** (mean peak values)	
	Toe-Off Angle [º]	***Joint Moments [Nm/kg]***	***Toe-Off Angle [º]***	***Joint Moments [Nm/kg]***
BiOM (EMG)	-19.2±1.1	1.76±0.08	-0.5±0.04	1.2±0.1
BiOM (intr.)	-19.2±0.7	1.71±0.20	-12.6±1.7	1.5±0.1
Seattle Light F[1]	5	n.a.	3	n.a.
Biol. Norm[1,2]	-13 to -31	1.45±0.15	5	1.38±0.16

1) [20], 2) [21]

VI. CONCLUSION

The hybrid volitional control presented here allows a transtibial amputee to proportionally modulate push-off of the prosthesis enabling not only level-ground walking but also seamless transitions from level ground walking to stairs and improved stair ambulation. The ankle angle and overall torque profiles of the BiOM using EMG control matched the those of the intrinsic controller and was within the biological limb's range of motion during stair ascent. Furthermore, no inadvertent push-off occurred during stair descent powered plantar-flexion with the volitional controller. Together these results suggest that EMG signals from the residual limb muscles, in combination with a neuromuscular reflex model framework, can be used to directly and reliably control a powered ankle-foot prosthesis – without an abstracted interpretation of the EMG signal. Future studies are required to add further volitional control to the terminal swing phase of the gait cycle and enable plantar-flexion of the prosthesis to dampen the impact during stair descent.

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