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Segmentation of stairs ascent and descent for neuroprosthetic motor control

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***Abstract*— The work presents the development of a segmentation algorithm for stairs ascent and descent. The algorithm is based on a Finite State Machine that uses leg angular position and linear acceleration in order in the sagittal plane to detect 4 different subphases of each activity. The algorithm was implemented in a neuroprosthetic device and was validated in realtime with 6 healthy subjects and different negotiating speeds. This type of algorithm allows motor neuroprostheses to stimulate muscle groups properly in order to assist motor tasks during daily life activities or rehabilitation therapies.**

Keywords: neuroprosthesis, muscle activation, activity segmentation, activity phase-detection algorithms

I. INTRODUCTION

People who suffer from some form of paralysis due to spinal cord injury (SCI), stroke, or other neurological disorders can use orthotic devices to improve their rehabilitation therapies or even in chronic cases, to improve their daily quality of life. These can be as simple as mechanical devices or modern robotic exoskeletons. The aim of these devices is to assist a motor task during training or functional activities. Most advanced approaches try to optimize the complete neuromotor process including smart actuation paradigms (e.g. assisted as needed) and hybrid approaches (combined functional electrical stimulation with exoskeletons), and unobtrusive daily assistive devices among others [1] [2] [3].

Motor neuroprostheses are one of these promising technologies [4]. They could be used alone or combined with exoskeletons in order to drive and promote functional movement and recovery by means of functional electric stimulation. Historically, they have been successfully used for drop foot impairment. However, most advanced setups require multiple stimulation channels and the capability to detect when to applied this electric pattern to each specific muscle involved in the task. Moreover, if these devices are going to be used during daily activities, they have to be capable to detect the type of activity the user is perfoming, such as walking, climbing stairs o sitting up.

Several works have been developed to recognize phases and states during lower limb activities. Most of them are focused on gait [5]. Ye and colleagues applied gait segmentation to control FES in treadmill therapies [6]. Loreiro and colleagues implemented a segmentation algorithm in a motor neuroprosthesis based on the work by Negard [7] [8]. However, none of them includes segmentation of activities such as stairs ascent and descent.

This work presents the development of an algorithm to segment stairs ascent and descent. The algorithm can be implemented in a motor neuroprosthesis similar to the one used by Loreiro [8]. In this way, each subphase can be associated with a stimulation pattern replicating the actuation approaches described in [6] and [7].

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II. MATERIALS AND METHODS

There are several algorithms that have already been used for the detection of human activities. The inputs from the sensors act as a data stream for these algorithms. In this work, we use the angular position of one leg (one-sided configuration) and its vertical acceleration, both sagittal plane. The goal of the algorithm is to identify a discrete number of subphases. These subphases are predefined based on biomechanical knowledge and the functional description of the activities. There are several approaches to implement these detectors, such as those based on observation [5], finite state machines (FSM) [8] or machine learning techniques [9], [10], among others.

A. Finite State Machine Classification

We opted for an FSM algorithm, due to its wide use in event detection, its simplicity, and its low computational cost (suitable for online detection) compared to other methods. Likewise, this was the algorithm used by Casco and colleagues [8] for the implementation of the gait in H-GAIT H-GAIT, within a similar scenario. Proposed FSM is shown in Figure 1. It consists of 4 states, and a transition matrix, that is used to calculate at each iteration which is the next state to transition depending on the detected events. These events have a certain weight depending on the current state and possible next states.

Transition Matrix

	S_0	S_1	S_2	S_3
S_0	$P_{0,0}$	$P_{0,1,n}(E_0,...,E_n)$	$P_{0,2,n}(E_0,...,E_n)$	$P_{0,3,n}(E_0,...,E_n)$
S_1	$P_{1,0,n}(E_0,...,E_n)$	$P_{1,1}$	$P_{1,2,n}(E_0,...,E_n)$	$P_{1,3,n}(E_0,...,E_n)$
S_2	$P_{2,0,n}(E_0,...,E_n)$	$P_{2,1,n}(E_0,...,E_n)$	$P_{2,2}$	$P_{2,3,n}(E_0,...,E_n)$
S_3	$P_{3,0,n}(E_0,...,E_n)$	$P_{3,1,n}(E_0,...,E_n)$	$P_{3,2,n}(E_0,...,E_n)$	$P_{3,3}$

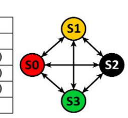

Fig. 1: Transition matrix and State diagram of FSM aimed at the segmentation of lower limb activities.

We proceeded to design this algorithm for the target activities of this work: stairs ascent and descent. Four events associated directly with the subphases into which the activities can be divided and defined. This segmentation was made

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based on the segmentation proposal made by Alison et al. [11].

B. Stairs ascent

The FSM is based on the transition matrix shown in table 1. However, in this work, only sequential transitions between states were considered. Thus, there are four main events that cause a new transition between states. These are:

Event 0: State 0 $\rightarrow$ State 1. It occurs when the angle exceeds 50% of the previously detected minimum angle (it is automatically updated every cycle) and the acceleration exceeds 85% of the component of gravity in the sagittal plane. The subphase that is related to this event is identified as "Push up".

Event 1: State 1 $\rightarrow$ State 2. It occurs when a positive acceleration peak is 20% greater than the component of gravity in the sagittal plane. The subphase that is related to this event is identified as "Foot off".

Event 2: State 2 $\rightarrow$ State 3. It occurs when the minimum negative peak of the angle is detected. The subphase that is related to this event is called "Forward continuance".

Event 3: State 3 $\rightarrow$ State 0. It occurs when the maximum positive acceleration peak is detected. The subphase that is related to this event is identified as "Weight acceptance".

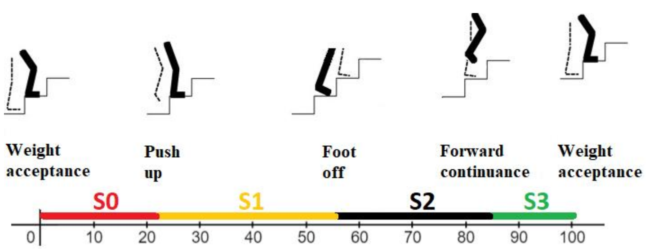


Fig. 2: Subphases (states) of the subphases of stairs ascent used in this work, with the percentage of the activity that is reached at each moment, related to the states (S0, S1, S2, S3) of the algorithm.

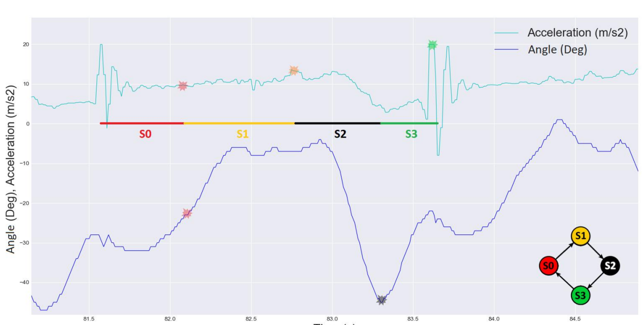


Fig. 3: Vertical acceleration (blue line) and angular position (cyan line) during a stairs ascent cycle (one step), related to the states (S0, S1, S2, S3) of the algorithm.

C. Stairs descent

The FSM is similar to the previous one. Again, there are four main events that cause a transition between neighbor states. These are:

Event 0: State 0 $\rightarrow$ State 1. It occurs when the angle exceeds the average between the minimum and maximum previously detected (it is automatically updated for each cycle). The subphase that is related to this event is "Controlled lowering".

Event 1: State 1 $\rightarrow$ State 2. It occurs when the minimum peak of the angle is detected. The subphase that is related to this event is named "Forward continuance".

Event 2: State 2 $\rightarrow$ State 3. It occurs when the maximum peak of the angle is detected. The subphase that is related to this event is called "Foot placement".

Event 3: State 3 $\rightarrow$ State 0. It occurs when a positive acceleration peak is 50% greater than the component of gravity in the sagittal plane. The subphase that is related to this event is identified as "Weight acceptance".

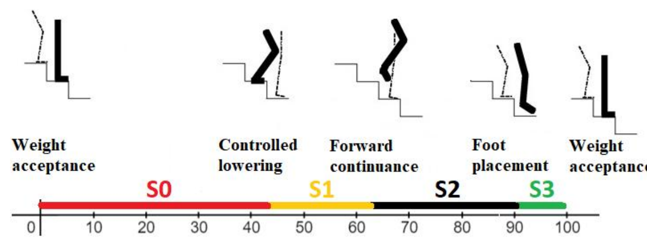


Fig. 4: Classification of the subphases of descent using the FSM Fretes2020, with the percentage of the activity that is reached at each moment, related to the states (S0, S1, S2, S3) of the algorithm.

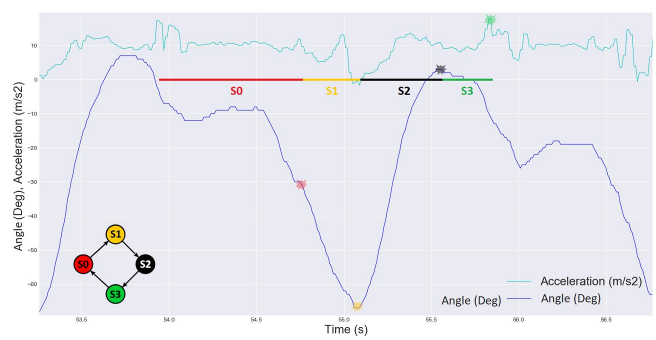


Fig. 5: Vertical acceleration (blue line) and angular position (cyan line) during a stairs descent cycle, related to the states (S0, S1, S2, S3) of the algorithm.

D. Evaluation Protocol

Six healthy subjects participated in the validation process. The participants did not report any impairment or morbidity that could interfere with the assessment of physical activities. The participants declared explicitly their consent with the experimentation protocol. The activities carried out by the subjects consisted of ascending and descending stairs. They were developed at a slow and comfortable speed for each subject. Each participant performed 12 repetitions of both the ascent and descent of the stairs.

Regarding the performance of the algorithm with different speeds, the speed of the execution of the activities was controlled by means of an audible metronome, in such a way that one step corresponded to each beep. The test speeds for the ascent and descent of stairs were: 50, 52, 54, 56, 58, and 60 steps/min. The stairs used during the activities is shown in Figure 6.(a). It consists of 10 steps, whose heights vary between 175 and 185 mm. The subjects were equipped with the H-GAIT NP, [8], located on the back of the right leg, at calf level. The location of the NP can be observed in Figure 6.(b).

(a) (b)

Fig. 6: (a) Stairs used during the ascent and descent experiment. (b) Location of the H-GAIT NP device on the user's leg during the development of activities.

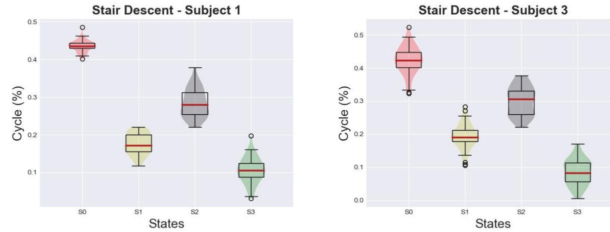
III. RESULTS

The H-GAIT device transmitted the information from the sensors as well as the subphase status of the Fretes2020 FSM implemented in the NP.

In this work, a database of both activities was prepared according to the protocol described above. The database consisted of data packets sent by the NP every 10 ms while subjects performed the task of ascending and descending stairs. The format of the data packets is as follows: [Timestamp;Angle;Acceleration;Current state]. The data were stored and processed in *python* to obtain the information. The detection was validated offline and the percentage of the duration of each state was also calculated offline.

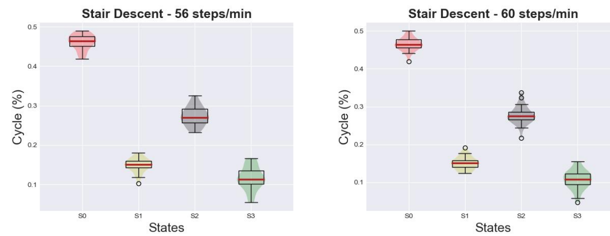
It is observed that even varying the speed or the Test Subject, the relationship of the percentage of duration between states is maintained at a general level. That is, regarding to stairs ascent, State 1 is the one with the longest duration. It is followed by States 2, 0, and 3, in that order respectively. For all subjects and speeds, the duration of the states corresponds to the percentage distribution defined in Section II-B (Figure 2).

In relation to the descent of stairs, there is a uniform behavior in the duration of each State and less dispersion of the data compared to the ascent. By varying both the Speeds and the Test Subjects, the relationship of percentages of duration



(a) (b)

Fig. 7: Duration (% of the cycle) for each state when performing stairs descent activity for Subjects 1 (a) and Subject 3 (b).



(a) (b)

Fig. 8: Duration of each state expressed as a percentage of the cycle (one step) for stairs descent activity, at speed of: (a) 56 steps/min and, (b) 60 steps/min.

between the States is maintained. This behavior corresponds directly to the distribution of percentages defined in Section II-C (Figure 4), with State 0 being the one with the highest percentage, followed by States 2, 1, and 3 respectively.

IV. FUNCTIONAL COMPENSATION BASED ON SEGMENTATION ALGORITHMS

Based on detected subphases, stimulation parameters can be configured to evoke proper muscle activation patterns. Muscle activation profile were obtained from previous works [12] [13] [14]. Using a NP like the one used by Loreiro, each of the four channels can be programmed independently to generate current pulses with ascending and decending ramps. Figures 9 and 10 show the normalized muscle activations while Figures 11 and 12 show the electrostimulation patterns that can be achieved with the H-GAIT NP [8].

V. CONCLUSIONS

The presented segmentation algorithm is a reliable method to detect stairs ascent and descent of stairs in real time. With such algorithms, motor neuroprosthetic devices can be implemented to assist users during daily life activities or during rehabilitation processes. The result has shown that even varying the Speed or the Test Subject, the duration percentage relationship is maintained at a general level between states. Finally, the stimulation profiles were defined according to the parameters available in the H-GAIT NP, in

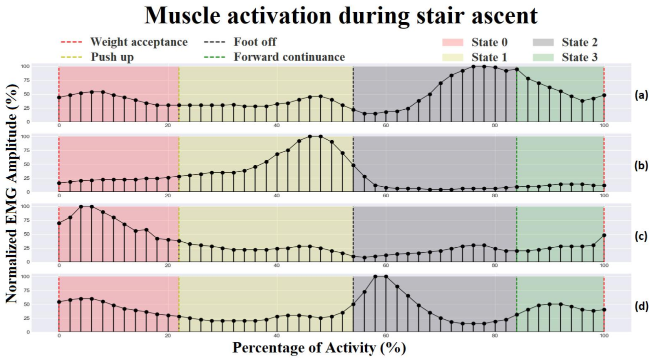


Fig. 9: Normalized muscle activation patterns during stairs ascent of muscles: (a) Tibialis Anterior, (b) Gastrocnemius, (c) Rectus Femoris, and (d) Hamstrings.

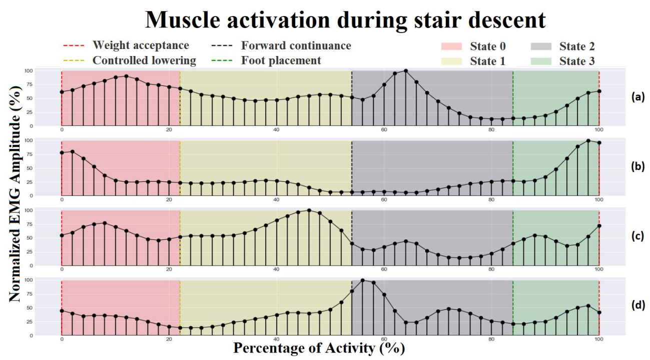


Fig. 10: Normalized muscle activation patterns during stairs descent of muscles: (a) Tibialis Anterior, (b) Gastrocnemius, (c) Rectus Femoris, and (d) Hamstrings.

order to simulate the muscle activation patterns and thus provide the assistance required by the user while ascending or descending the stairs. Future work will include the evaluation of the algorithm in pathological subjects. When using a FSM algorithm, it is recommended to use dynamic thresholds that are updated every cycle of activity, adapting to the cadence of the activity and the possible atypical patterns of each person.

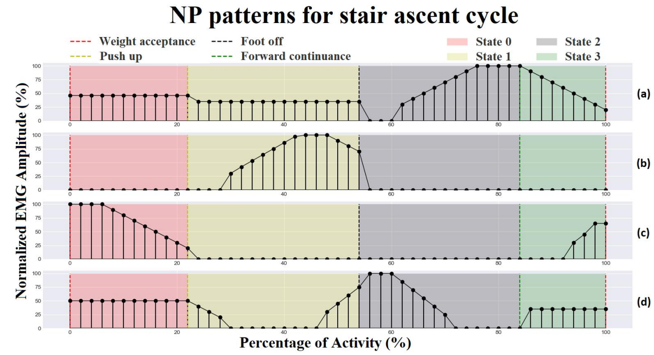


Fig. 11: Example of a stimulation profile of H-GAIT NP (four channels) based on the normalized patterns of muscle activation during stairs ascent for each muscle: (a) Tibialis Anterior, (b) Gastrocnemius, (c) Rectus Femoris, and (d) Hamstrings.

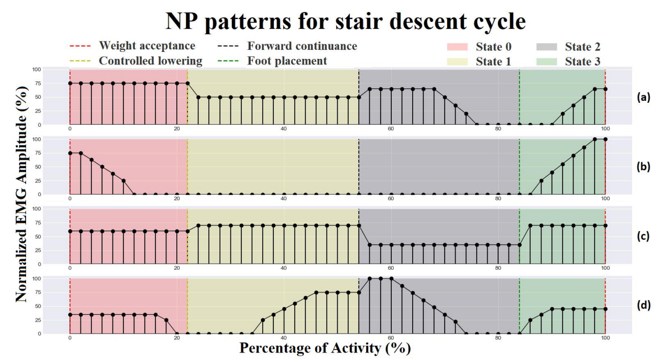


Fig. 12: Example of a stimulation profile of the H-GAIT NP (four channels) based on the normalized patterns of muscle activation during stairs descent for each muscle: (a) Tibialis Anterior, (b) Gastrocnemius, (c) Rectus Femoris, and (d) Hamstrings.

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