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Modulation of Weight Off-loading Level over Body-weight Supported Locomotion Training

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***Abstract*—With the evolution of robotic systems to facilitate overground walking rehabilitation, it is important to understand the effect of robotic-aided body-weight supported loading on lower limb muscle activity, if we are to optimize neuromotor recovery. To achieve this objective, we have collected and studied electromyography (EMG) data from key muscles in the lower extremity from healthy subjects walking over a wide range of body-weight off-loading levels as provided by a bespoke gait robot. By examining the impact of body-weight off-loading, it was found that muscle activation patterns were sensitive to the level of off-loading. In addition, a large off-loading might introduce disturbance of muscle activation pattern, led to a wider range of motion in terms of dorsiflexion/plantarflexion. Therefore, any future overground training machine should be enhanced to exclude unnecessary effect of body off-loading in securing the sustaining upright posture and providing assist-as-needed BWS over gait rehabilitation.**

Keywords-Gait rehabilitation; Robotic device; EMG; Body-weight supported locomotion training (BWSLT); Off-loading level

I. INTRODUCTION

Due to the neurological damage caused by spinal cord injury (SCI) and stroke, the patients suffer muscle weakness, reduction of sensation, and controlling movement result in the loss of the body weight supported (BWS) ability. The contribution on BWS is an important area in gait rehabilitation research. In view of labor-intensive manual-assisted BWS, gait devices are developed including body weight supported treadmill training (BWSTT) [1-2] and body weight supported locomotion training (BWSLT) [3-6]. However, it is an open question about how to choose suitable BWS for the effective training result.

To identify the underlying regulation of muscle pattern may lead to a better understanding of diagnostic power and progressive assessment, and providing a guideline for gait rehabilitation by using robotic devices. EMG analysis is a substantial component often used for the assessment of motor disturbance [7-9]. In order to evaluate machine-related changes, muscle patterns via EMG analysis are commonly investigated [2, 4, 10-11] and EMG-driven control has been implemented to provide an active rehabilitation program [12]. It was found that the effect of weight-supported change is considerably significant [13-14]. Modulation of off-loading level on treadmill training is also proposed for optimizing motor output during locomotor training [15]. When it comes to extend those conclusions to the overground walking training, it is necessary to study the muscle contribution changes with weight off-loading during body-weight supported locomotion training (BWSLT) with the help of gait device [16-17].

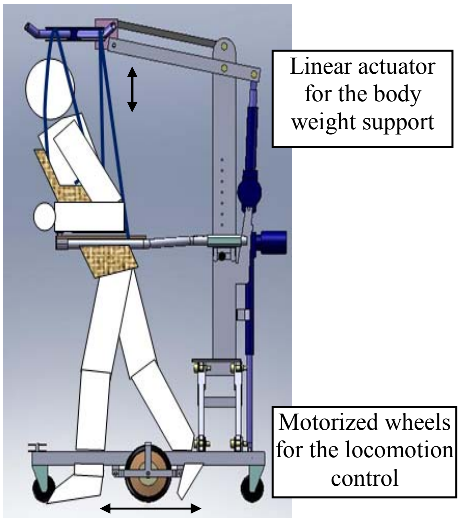


Figure 1. The body-weight supported locomotion training (BWSLT) device.

An automated partial BWSLT device has been developed with different weight off-loading levels to actuate the overground walking. Two motorized wheels are used for the locomotion control. The subject with a harness attached is walking with the BWS device. By increasing the height of the lever, the weight offloaded from the subject was increased, as shown in Fig. 1. In order to choose a suitable training off-loading level, we collected data from healthy subjects over a range of body weight off-loading to quantify muscle contributions, while EMG was recorded from major muscles on the lower limb. By observing the co-activation of different muscles, the group of muscles can be classified as support-related, propulsion-related, and balancing-related based on cross-talk between relevant muscles. We then investigated activation pattern and stance/swing duration of representative muscles from the representative muscles of group. After that, a spinal cord injury (SCI) volunteer subject was attended to this study. Modulation of off-loading level and the improvement with the gait device is discussed.

In Section II, the subject information, experiment setup, EMG data collection/processing method are presented. In Section III, the muscle patterns obtained from healthy subjects with different off-loading levels are provided for comparison. The muscle pattern of the trials is analyzed. Further suggestions are provided for modulation of our bespoke gait device. In Section IV, walking trials conducted on a SCI patent is provided. Concluding remarks in Section V provide an insight into future works of the gait rehabilitation device.

II. METHODS

A. Subjects

Seven healthy subjects including five; males and two females, age between 24 to 25 years old, mean 24.4+1.7 (S.D.), weight between 60 and 78kg, mean 65.81+3.1 (S.D.), and height 1.71 and 1.79m, mean 1.74+0.23 (S.D.) were recruited. They have neither neurological injury nor orthopaedic disorder. The consent of the volunteer subject to participate in the device trials were obtained and documented. They were informed the experiment procedures but did not know the purpose of the study to avoid potential disturbance.

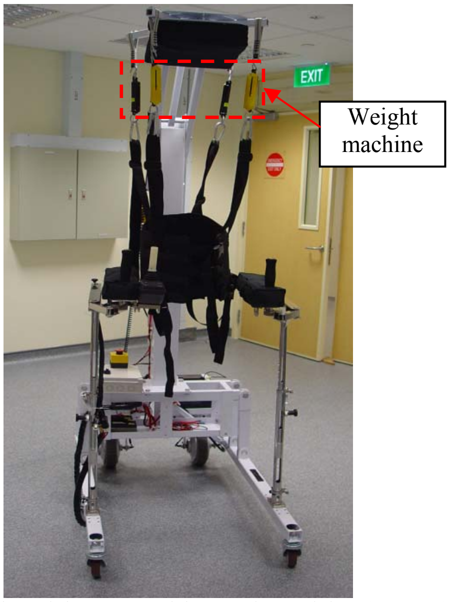


Figure 2. The body-weight supported locomotion training (BWSLT) device with weight machine to measure the off-loading level (a device developed together with the Singapore General Hospital).

B. Procedure

Figure 2 shows the designed automated partial BWSLT device with weight machine. In order to obtain different body weight supported levels, we have provided body off-loading at the standing position hanging with the device before device-assisted walking tests. Four weight machines are used to measure the total off-load weight. The off-loadings are normalized such as 50% body-weight off-loading. In this experiment on healthy subjects, full weight bearing (FWB, 0%), 5%, 10%, 20%, 40% and 70% are provided for comparisons.

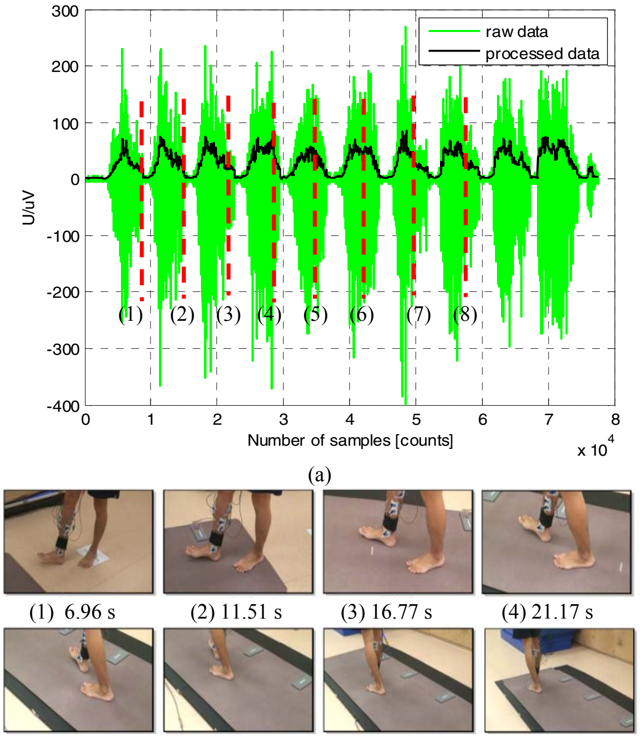
Subjects were given 10 minutes to familiarize with controlling of the BWSLT device. During the actual experiment, each subject performed the device-assisted walking over a distance of 6 m and repeated for five times. Throughout the entire experiment, the weight offload was kept constant at each respective weight offload. Each subject will be asked to walk at six different weight-offloads. Throughout this part of the experiment, the speed of the BWS device was kept constant at the lowest speed.

C. Recording of Measurements

Every trial was video recorded and the corresponding EMG signals were saved simultaneously. The overground walking off-loading was measured by the BWSLT device with weight machines. EMG signals were recorded with the usage of three silver/silver chloride (Ag/AgCl) surface electrodes (Ambu Blue Sensors diameter 8mm), consisting of wet gel that acts as a conductive medium. They were adhesive to the skin of eight lower limb muscles: soleus (SO), tibialis anterior (TA), gastrocnemius medialis (MG), vastus lateralis (VL), rectus femoris (RF), bicep femoris (BF), semitendinosus/semimembranous (ST), and gluteus maximus (GM). An electrode was taken as the reference point, located at an electrically inactive site, while the others were placed at chosen site of muscles by pairs in parallel to the muscle fibers as one positive terminal EMG+ and one neighboring negative terminal EMG-. The electrodes were in contact with the skin, hence detecting the bioelectric signals reaching them during the whole recoding process. Since there was contact involved, the skin where the electrodes be placed need to cleaned with alcohol and even applied some abrasive gel to reduce the skin impedance. Moreover, consider the placing of the electrodes interfere the signals detection, a widely accepted guideline was applied to place them at the midpoint [7], where the muscle belly is located and maintain an inter-electrode distance of 15 to 30mm. Varying the inter-electrode distance will change the signal width and amplitude. Hence, it is important to fix the distance between subjects and muscles to allow better comparison [18]. The experiment will be conducted 10 minutes after the electrodes was properly placed. This is to provide sufficient time for the skin impedance to stabilize. All those EMG raw data were sent to the host computer by TeleMyoTM 2400 G2 Telemetry System both for online or offline processing. It should record eight muscles in the right leg. Since the system is portable, it allows overground walking incorporated with the video recording.

D. *Data Processing and Analysis*

EMG signals were full-wave rectified raw signal has both positive and negative amplitudes, which will result in a mean of zero. Full-wave rectification inverts the negative portions so that other averaging procedures can be done. This processing will retain the signal's energy, the root means square (RMS) was used for smoothing and the size of the window was 50 milliseconds. A 6Hz low-pass Infinite Impulse Response (IIR) filter was used with Butterworth approximation [19]. The raw and processed data are compared in Fig. 3(a). Our studies demonstrate that the processed data proportionally reflects the magnitude/ duration of muscle activation. Therefore, we focus on the processed data instead of the raw data. Subsequently, the processed data are divided cycle by cycle at every repetitive events of the right heel contact. Those events are picked up by the synchronized video recording in Fig. 3(b).



(a)

(1) 6.96 s (2) 11.51 s (3) 16.77 s (4) 21.17 s

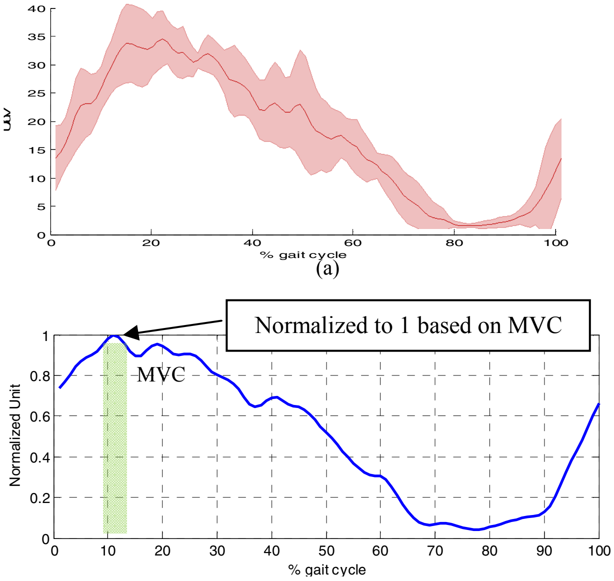
(5) 26.15 s (6) 31.12 s (7) 35.95 s (8) 41.21 s

(b)

Figure 3. EMG processing and average muscle: (a) The processed data with event markers on right heel contact; (b) Corresponding video recording of the right heel contact (HC).

It is known that the absolute magnitude of EMG is not consistent for individuals. Therefore, many researches focus on the shape of EMG profile, times of peak or onset/cessation of myoelectric activity [20]. In this study, we choose the tendency of EMG profile for comparison between different subjects, i.e. average profile changes of EMG. The event of right heel strike is taken as the start point of the gait cycle and it completed at the next event occurs, i.e. heel strike of the same leg [21]. The entire gait cycle are normalized to 0-100%. Next, the mean and peak EMG values of the muscle pattern are obtained for each trial for different subjects and different weight off-loading levels.

Consider that the absolute value of EMG signal between subjects is not comparable as mentioned due to the variation of muscle strength. Therefore, the muscle voluntary contraction (MVC) normalized profiles are proposed for comparisons [7]. We take the maximum of all the trials of same subject as the MVC. Consequently, different muscle groups are normalized in the MVC analysis for future comparison (see Fig. 4).



(a)

(b)

Figure 4. Normalized EMG average muscle pattern via muscle voluntary contraction (MVC), MVC are the maximum value in this study: (a) average muscle pattern with +/- SD; (b) normalized by MVC average muscle pattern.

III. RESULTS

After processing and normalization of EMG signals, the activation pattern of the lower limb muscles reveals almost symmetry to the contra-lateral leg with a 50% phase lag. For clarity, only one side is presented here. Function-based muscle contributions are summarized in this section. Three major functions during walking are provided as: locomotion propulsion, loading supported, and balance control [22]. Locomotion propulsion occurs before toe-off of the current body-weight supported foot. Muscle groups such as soleus (SO) and gastrocnemius medialis (MG) active in the middle phase of GC that provides propulsion for swing the lower limb forward. Loading supported occurs after heel contact the ground when the body weight shifts from the counterpart lower limb to the current limb. Muscle groups such as vastus lateralis (VL) and gluteus maximus (GM) active in this initial phase of gait cycle that will absorb the loading response and initiate the stand phase. Balance control functions throughout stance phase and swing phase to keep the walking posture. Muscle groups, such as tibialis anterior (TA), rectus femoris (RF), bicep femoris (BF), and semitendinosus/semimembranous (ST), activatie more than one burst during entire gait cycle. As a result, different muscle patterns are classified under different functions. Muscles work for the same function can be grouped together and share a similar muscle pattern.

Furthermore, different off-loading levels have different EMG gait patterns. Thus, a comparison on the EMG gait patterns across different off-loading levels will identify any region with significant or mirror changes. Three representative muscles of those groups are presented: propulsion-related changes, support-related changes, and balancing-related changes.

A. Propulsion-related Muscle Changes

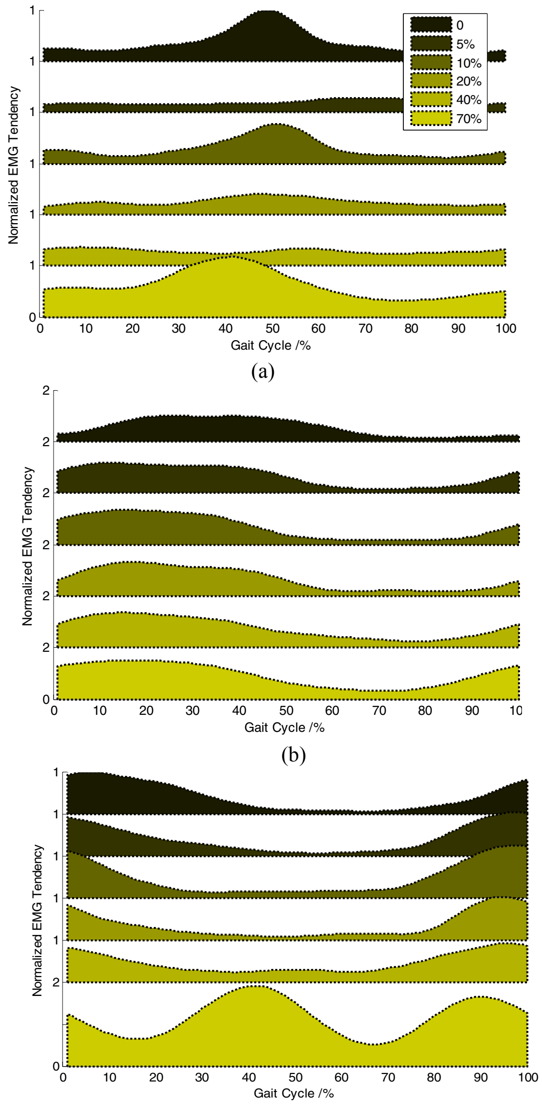
Muscle activity patterns of this group are sensitive to the off-loading changes; see soleus (SO) in Fig. 5(a). They change with respect to shape, duration, and volume. In several cases, they remained inactive that would have no benefit to rehabilitation. The reason for this is that the device provides all of the forward propulsion for the subject, instead of by his/her own muscle activation. However, the large off-loading achieves a high level of assistance. This may be due to the height of the BWS top lever being so high that subjects were unable to make contact with the ground.

B. Support-related Muscle Changes

For the muscle group contribute to the loading absorption, experiments under different off-loading are carried out. It is clear that the muscle power decreases first and then increases with the increasing of weight off-loading, see gluteus maximus (GM) in Fig. 5(b). It is effective to increase the off-loading weight to decrease the muscle power of body weight supported. However, the large off-loading of body weight stimulated muscle activity to high level by pulling up the trunk elicits extra dorsiflexion/plantarflexion to compensate walking motion that greatly altered the muscle pattern.

C. Balancing-related Muscle Changes

Muscles in multiple phase active muscle group simplify their activity pattern if compared to walking without the help of the BWS device, as shown by looking at the bicep femoris (BF) in Figs. 5(c). We also carried out independent experiments on a major movement of lower limb including hip hyperextension/extension/flexion, knee flexion/extension, and ankle dorsoflextion/platerflextion, in stance, sitting and lying down position. Muscles can be activated to different levels for the same motion in every subject trial. Gravity varied in different testing postures is one of the possible explanations. Muscles take advantage of gravity to move the skeleton during the dynamic walking process, while this does not happen in sitting and lying position. Therefore, the adaptation to gravity changes walking with and without constraints from BWS device might result in the simplification of muscle patterns.



(a)

(b)

(c)

Figure 5. Muscle activation pattern changes with normalized off-loading level and muscles are grouped together based on similar activation pattern: (a) soleus (SO); (b) gluteus maximus (GM); (c) bicep femoris (BF).

IV. CLINICAL RELEVANCE

In order to verify the results, we have conducted clinical trials. One volunteer subject is involved in our initial study. The subject is a 66-year old Asian male, C5 spinal cord injury, with resulting in loss of function below shoulder. Progressive physical exercises have improved his sense of control. However, routines to strengthen his muscles cost are high, with training involving at least three assistants. He required assistance for his lower limbs, pelvis, trunk and upper body in order to be able to transfer, support, balance, and ambulate per session. His goal is to improve ambulation abilities as well as recovery of motor function. Safety precaution certification and the consent of the volunteer subject to participate in the device trials were obtained and documented. It is worth noting that he was so excited to be able to walk with the BWSLT device that made him felt like walking independently without the help of any caregiver, first time after the injury.

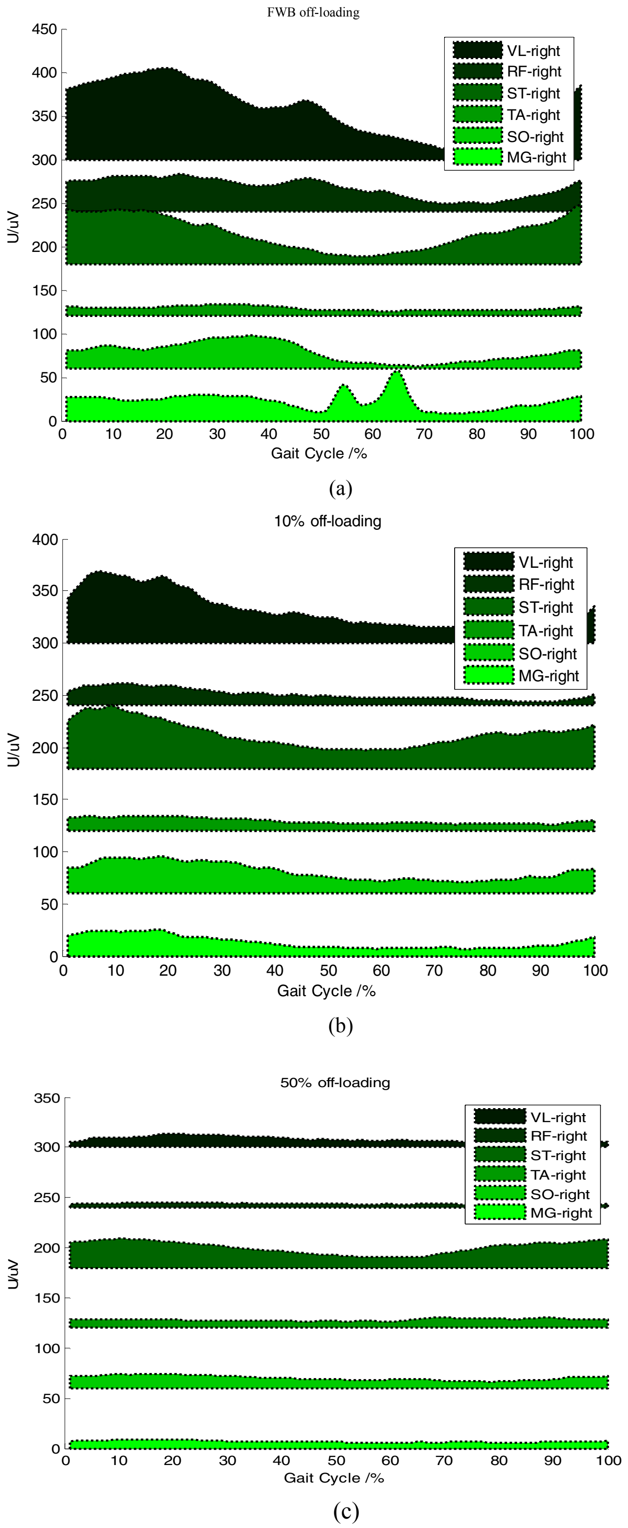


Figure 6. Comparison of muscle activation pattern between FWB, 10% and 50% body off-loading device-assisted walking: (a) FWB body off-loading level for six muscles of the SCI volunteer subject; (b) 10% body off-loading level for six muscles of the SCI volunteer subject; and (c) 50% body off-loading level for six muscles of the SCI volunteer subject.

In our experiment, we provide full weight bearing (FWB), 10%, and 50% body off-loading to evaluate rehabilitation effects. Procedures and processing were used as the same as those in the previous experiments for healthy persons. Only six muscles are collected for comparison because of the convenience in the attachment of the electrodes to the subject.

In the experiment, we can see the SCI subject can walk easily with the help of BWS off-loading. The FWB experiment demonstrates the maximum muscle activation is good for the muscle training. A 50% off-loading greatly affects the muscle pattern. Many of his muscles remain inactive with the help the machine. Therefore, the less off-loading level for the subject provides a better muscle training. As the least off-loading need to prevent falling down, which much be secured for the safety consideration, we skipped larger off-loadings for the safety consideration.

V. CONCLUDING REMARKS

An automated partial body-weight supported locomotion training (BWSLT) device has been developed and employed. The BWSLT device has provided overground locomotion with body weight supported. To set the guideline the overground training machine, especially on how to tune the body weight off-loading level, we studied the muscle contribution over walking cycles with the device. The experiments cover both healthy volunteers and a SCI volunteer subject. They have walked with the device under different body off-loading rates. We found that (1) muscle contributions are sensitive to weight off-loading, even remained inactive with the changing of body weight assistance; and (2) a large off-loading of body weight introduces extra muscle activation bursts, caused by the compensation motion of the foot in terms of dorsiflexion/plantarflexion. Therefore, any future overground training machine should be enhanced to exclude unnecessary effect of body off-loading in securing the sustaining upright posture and providing assist-as-needed BWS during gait rehabilitation.

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Abbreviations and Acronyms

BF	bicep femoris
BWS	body weight support
BWSLT	body weight support locomotion training
BWSTT	body weight support treadmill training
EMG	electromyography
FWB	full weight bearing
GC	gait cycle
GM	gluteus maximus
HC	heel contact
IIR	infinite impulse reponse
MVC	muscle voluntary contraction
MG	gastrocnemius medialis
RMS	root means square
RF	rectus femoris
SCI	spinal cord injury
SD	standard deviation
SO	soleus
ST	semitendinusus/semimembranous
TA	tibialis anterior
VL	vastus laterali