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# Statistical analysis of surface electromyographic signal for the assessment of rectus femoris modalities of activation during gait

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A B S T R A C T

Aim of the present study was to identify the different modalities of activation of rectus femoris (RF) during gait at self-selected speed, by a statistical analysis of surface electromyographic signal from a large number (hundreds) of strides per subject. The analysis of ten healthy adults showed that RF is characterized by different activation modalities within different strides of the same walk. RF most recurrent modality (observed in 53 ± 6% of total strides) consists of three activations, at the beginning of gait cycle, around foot-off and in the terminal swing. Further two modalities of RF activation differ from the most recurrent one because of the lack of activity around foot-off (26 ± 6%) or the splitting into two (or three) small activations around stance-to-swing transition (17 ± 2%). Despite the large variability, our statistical analysis allowed to identify two patterns of activation that characterize completely the behavior of rectus femoris during gait. The first pattern, around stance-to-swing transition, can be monophasic, biphasic or triphasic and is necessary to control knee extension and hip flexion from pre-swing to initial swing. The second pattern, from terminal swing to following mid-stance, is likely due to the contribution of low-level RF activity and cross-talk from surrounding vastii.



## 1. Introduction

The assessment of the activation patterns of the muscles of quadriceps femoris (QF) group, such as vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF), is recently receiving increasing attention in human gait analysis (Agostini et al., 2010; Barr et al., 2010; Nene et al., 2004). In particular the discussion focuses on the analysis of the signal taken from RF, the only biarticular muscle among the QF group, where different modalities of activation have been reported. Single activation of RF around stance-to-swing transition has been typically found utilizing fine-wire electromyography (fwEMG) (Barr et al., 2010; Nene et al., 2004; Perry, 1992). Further activations during loading response, like those reported for the vastii, have been found by means of both surface electromyography (sEMG) (den Otter, 2004; Ounpuu et al., 1997; Sienko Thomas et al., 1996) and fwEMG (Annaswamy et al., 1999) studies. These differences in detecting and then interpreting RF signal were often attributed to different methods (sEMG vs. fwEMG) of recording muscle activity (Barr et al., 2010; Nene et al., 2004), but no clear evidence has been found in literature.

It is known that a single motor task can be performed in many ways with a similar end result (Bernstein, 1967). This motor redundancy suggests that the nervous system is capable of producing different myoelectric activity patterns for a given movement, including gait task. This means that a single muscle can show a different number of activation intervals in different strides of the same walk, even when environmental and external conditions are fixed. It is, therefore, important to recognize the natural variability associated with muscle activity during free walking in order to improve the interpretation of EMG signals. This can be achieved by recording and analyzing the electromyographic signal over a large number of steps per subject, which allows to detect the different modalities (i.e. different number of activations within different strides of the same walk) of muscle activation. From this point of view, data on RF modalities of activation, reported by cited studies, are limited by the small number of gait cycles considered during an assessment session. A study over a larger number of steps should be considered. This goal, hard to be fulfilled by means of fine-wire EMG, because of its invasiveness and being not a completely painless technique, appears to be reachable by means of surface EMG.

Thus, the aim of the present study was to identify the different modalities of activation of rectus femoris in healthy adults during gait at self-selected speed, by analyzing surface EMG signal from a large number (hundreds) of strides per subject. The study is based on the recent availability of robust techniques for the detection of muscle activation intervals, and specific tools for statistical gait analysis (Bonato et al., 1998; Balestra et al., 2002; Staude et al., 2001).

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## 2. Materials and methods

### 2.1. Subjects

Ten healthy adult volunteers were recruited (age: 24.7 ± 0.6 years; height: 169 ± 2 cm; weight: 56.7 ± 1.5 kg; body mass index (BMI): 19.9 ± 0.3 kg·m$^{-2}$). Exclusion criteria included history of neurological pathology, orthopedic surgery within the previous year, acute or chronic knee pain or pathology, BMI ⩾ 25, or abnormal gait. Before the beginning of the test, all participants signed informed consent.

### 2.2. Recording system: signal acquisition and processing

Signals were acquired by means of a multichannel recording system for statistical gait analysis (Step 32, DemItalia, Italy). Each subject was instrumented with foot-switches and sEMG probes on the left lower limb. Three foot-switches (size: 11 × 11 × 0.5 mm; activation force: 0.2 N) were attached beneath the heel, the first and the fifth metatarsal heads of each foot. Single differential (SD) sEMG probes with fixed geometry constituted by Ag-disks (manufacturer: DemItalia, size: 7 × 27 × 19 mm; inter-electrode distance: 12 mm, gain: 1000, high-pass filter: 20 Hz) were attached over the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF2, reference position 2), and medial hamstrings (MH), following the SENIAM recommendations (Freriks et al., 1999) (Fig. 1). Two further probes were attached over the rectus femoris, +2 cm (RF1, position 1) and −2 cm (RF3, position 3) far from reference position RF2 in the direction of the line from the anterior spina iliaca superior to the superior part of the patella, as depicted in Fig. 1. The electrodes RF1 and RF3 were positioned carefully, in order to avoid the possible EMG amplitude decrease occurring when the electrodes are placed over the innervation zone or myotendinous junction (DeLuca, 1997). After positioning the sensors, subjects were asked to walk barefoot over the floor for 6 min at their natural pace, following the path schematized in Fig. 2. Natural pace was chosen because walking at a self-selected speed improves the repeatability of EMG data (Kadaba et al., 1989), while variability increases when subjects are required to walk abnormally slow (Powers et al., 1996; Winter and Yack, 1987).

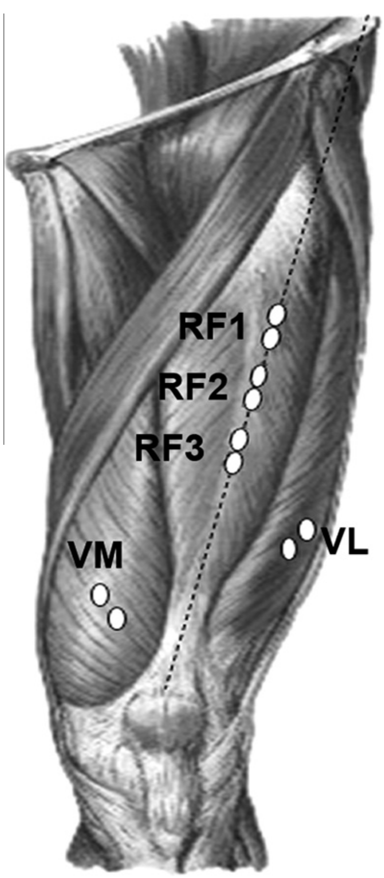


**Fig. 1.** Frontal view of the electrode placements in left lower limb: VM = vastus medialis, VL = vastus lateralis, MH = medial hamstrings, RF1 = rectus femoris in position 1, RF2 = rectus femoris in position 2, RF3 = rectus femoris in position 3.

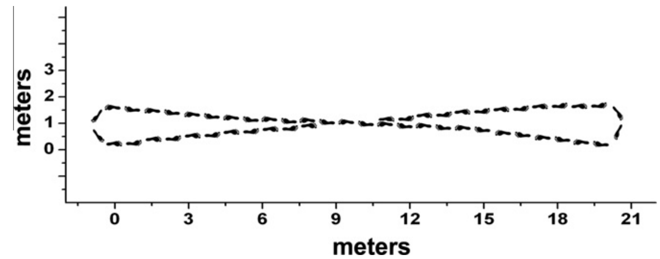


**Fig. 2.** Schematized representation of the path walked by the recruited subjects during the experiment; subjects walked barefoot over the floor for 6 min at their natural pace.

Foot-switch signals were converted to four levels corresponding to Heel contact (H), Flat foot contact (F), Push off (P), Swing (S) and processed to segment and classify the different gait cycles. EMG signals were high-pass filtered and then processed by a double-threshold statistical detector that allows to obtain, in an user-independent way, the muscle activation intervals (Bonato et al., 1998).

### 2.3. Statistical analysis

In the present study only gait cycles consisting of the sequence of H–F–P–S and corresponding to straight walking were considered. For each subject and each muscle, mean (over the total strides) activation intervals and relative frequency of activation during walk were calculated for each activation modality.

A statistical representation of mean amplitude of muscle activation over our population was achieved as follows. The statistical tool embedded in the recording system provides, for each subject, mean muscle activations in function of the percentage of gait cycle; the amplitude of the mean activations is quantized in three levels (Bonato et al., 1998). In the present study, the three amplitude levels, considered in ascending order, were associated with the value of 1, 2 and 3, respectively. A global quantized mean signal over all 10 subjects, ranging from 0 (no signal) to 30 (maximum value), was obtained for each percentage unit of the gait cycle, as the sum of the amplitude levels of every single mean signal provided by the recording system. This global mean signal was, in turn, subdivided in four intervals ranging from 0 to 4 (no muscle activation), from 5 to 10 (low-level activation), from 11 to 20 (medium-level activation), and from 21 to 30 (high-level activation). The purpose of this quantization is mainly to allow a statistical description, in function of the percentage of gait cycle, of the mean muscle activation intervals over the whole population and to find the signal peak of the myoelectric activity.

## 3. Results

For each subject a mean (±SE) of 373 ± 10 strides has been considered. From the total of 3730 strides considered, 134 strides (3.6% of total strides) have been removed from the analysis because they did not follow the H–F–P–S foot-switch pattern. The