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Neuromuscular Adaptations during Submaximal Prolonged Cycling

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***Abstract*— This study aims at evaluating the neuromuscular adaptations occurring during submaximal prolonged cycling tasks. In particular, we want to assess changes in surface electromyographic (sEMG) signal recorded during a pedaling task, performed by six subjects on a cycle-simulator at a constant power output, until voluntary exhaustion. Task failure was defined as the instant the subject was no longer able to maintain the required task. Electromyographic activity was recorded from eight muscles of the dominant leg and burst characteristics of sEMG signals were analyzed in order to assess the changes in muscle activity level produced by the occurrence of neuromuscular fatigue. In particular, three features were extracted from the sEMG signal for each burst: amplitude, location of the maxima and mean profile of the burst envelope. We have reported an increase in the amplitude parameter for all subjects only for Vastii while bi-articular muscles presented a high variability among subjects. Also the location of the maximal values of the mean envelope of the bursts was found to change when considering bi-articular or mono-articular muscles. The envelope profile was found not to be subject to alterations when comparing the end of the task with the beginning. We speculated that neuromuscular fatigue induces changes essentially in the mono-articular muscles which produce power. This phenomenon is highly correlated with the adopted pedaling strategy which, being not constrained, induces subjects to express the maximal power in the downstroke phase, related to knee extension and involving mainly mono-articular muscles.**

***Keywords*—sEMG, Cycling, Neuromuscular Fatigue**

I. INTRODUCTION

The possibility of tracking the athletes' muscles status when performing any sport is very attractive. In particular, surface electromyography (sEMG) could be a powerful non-invasive tool for this kind of analysis. The sEMG signal is generated by skeletal muscles and, reflecting the electrical activity of muscle cells, provides an insight into physiological mechanisms at the basis of any movement [1]. sEMG is related to the neural descending drive and to the number of active motor units and relative discharge rate and the pattern of muscle activation can reflects these characteristics [2] even if the amplitude cancelation phenomenon has to be taken into account [3]. In the field of cycling science, electromyographic analysis has been used for the assessment of muscle coordination changes, in particular those occurring with incoming fatigue [4-8]. In order to characterize the patterns of muscle activation, the analyzed features are essentially two: muscle activity level and activation timing with respect to the crank angle and pedal revolution. Timing parameters are determined considering signal onset and offset instants, which identify the duration of the single burst and they are generally calculated by fixing a threshold of about 1, 2 or 3 times the standard deviation [9]. The activation timings of muscles involved in the pedaling gesture with respect to the pedal revolution has been extensively reported in literature [10-14]. Gluteus Maximus is activated from the Top Dead Center (TDC) to the Bottom Dead Center (BDC), while Vastii are active just before the TDC until the first quarter (nearly 90°) of the pedal revolution cycle. The onset of Rectus Femoris precedes, on the other hand, the onset of Vastii even if the offset is just the same. Tibialis Anterior is activated during the upstroke phase (second half of the pedal revolution) and terminates just after TDC. The Gastrocnemii are activated after Tibialis activation and their activity stops just before the onset of the Tibialis itself. Finally, the Soleus is activated during the downstroke phase (first half of the pedal revolution). The different timings of activation reflect differences in muscles roles: the production of power is attributed to mono-articular muscles (Gluteus Maximus, Vastii, Tibialis and Soleus), while, on the contrary, bi-articular ones (Biceps Femoris, Rectus Femoris, Gastrocnemii) deal with the transfer of energy between joints in specific sectors of the crank revolution [15]. This information is a matter of importance when considering muscle coordination and the relative changes occurring with incoming neuromuscular fatigue. The latter is defined as an impairment in the force generation capacity of the neuromuscular system during sustained activities [16-17] and many studies, conducted during prolonged cycling exercises, reported muscle fatigue as the major limitation for athletes' performance [18-20]. Moreover, it has been hypothesized that neuromuscular fatigue induces changes in muscle activity level and activation timings [5] and in modular organization and muscle coordination also [21-22]. The aim of this study is to cover, in a descriptive way, the changes of the sEMG signal at an higher detail level considering the single bursts in order to assess if incoming neuromuscular fatigue produces changes in the single burst characteristics, and, as a result, in the characteristics of the whole signal.

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II. MATERIALS AND METHODS

A. Participants

Six male subjects (age: 26.2±1 yr.) voluntarily participated to the experimental protocol after being informed about the aim of the study and possible risks. All participants reported no previous experience of training in cycling exercises. The study was performed according to the Declaration of Helsinki.

B. Experimental Design

The experimental protocol consists of a submaximal cycling test performed until voluntary exhaustion and at a constant power output on a cycle-simulator. Forces applied to each pedal have been acquired using a novel system based on instrumented pedals [23-25]. At the beginning of the session each participant performed a 10 s all-out trial in order to determine the peak power output (PPO) and the maximal value of RMS-EMG reached in correspondence of this point. Subjects were asked to remain seated throughout the exercise. Power output was fixed at 20% of PPO. Throughout the entire exercise, subjects used a visual feedback to maintain the power output at a constant level. They were also instructed to maintain the pedalling cadence in the range 65-75 rpm and to stop when they started to feel tired and painful at muscular level. In this way, the exhaustion was defined as the moment when the power output exerted by the participant fell below 18% of PPO.

C. Muscle Activity

Surface electromyographic signals were obtained from eight muscles of the dominant leg: Gluteus Maximus (GMax), Biceps Femoris (BF), Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VM), Gastrocnemius Medialis (GAM), Tibialis Anterior (TA), Soleus (SOL) (Fig. 1). sEMG data were recorded using a wireless system (FREEEMG 300, by BTS Bioengineering S.p.A.) provided with eight bipolar wireless channels, sampled at 1000 samples/s and digitized with a 14 bit A/D converter. Skin was shaved and cleaned in order to decrease skin impedance. Pre-gelled Ag/AgCl surface electrodes were placed over the surface of the muscle, parallel to muscle fibers orientation according to SENIAM recommendations [26]. sEMG signals were recorded throughout the entire trial and then an off-line analysis was performed.

D. Instrumented pedals

Two instrumented pedals fitted on the cycle-simulator allowed recording the three components of force applied on the pedal with an accuracy of 0.1%. The full scale value is ±2000N. The pedal, designed to maintain the same characteristics of a commercial clipless pedal, using a strain gauge based load cell, permits the measurement of the three force components. Strain gauges are connected according to a full Wheatstone bridge configuration. Moreover, an encoder, placed between the pedal frame and the pedal spindle, permits to obtain the relative angle between the pedal and the crank. Signals are recorded and converted on board by means of a microcontroller and digitized data are transmitted via Bluetooth^{TM} to a remote PC. The use of this novel system allows to calculate the power output profile throughout each pedal cycle and to separate the contribution of the two legs, not possible in commercial systems [27]. The total power output is, in fact, calculated as the sum of the separate contribution of power output for the left and right leg and in accordance with the formulas:

$$P_{tot} = F_{tg} * l_{ped} * \varpi \quad (1)$$

$$F_{tg} = F_x * \cos(\vartheta_p) + F_z * \sin(\vartheta_p) \quad (2)$$

where P_{tot} is the total power output, F_{tg} is the tangential force to the crank, l_{ped} is the length of the crank arm, ϖ is the angular velocity, F_x and F_z are the components of force in the pedal reference system and θ_p is the angle between pedal and crank.

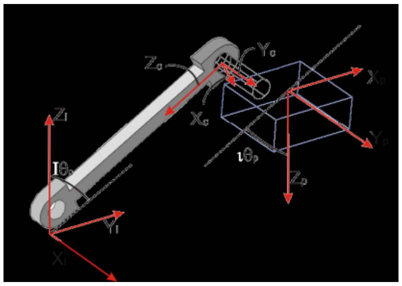

Figure 1. Representation of pedal forces as they are fixed in the reference system of the pedal and of the crank.

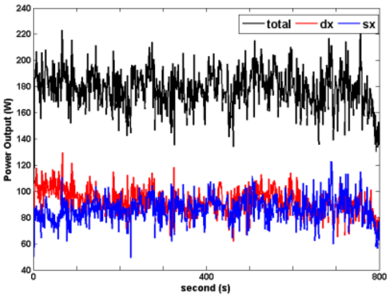

Figure 2. The black line represents the total power output profile, the blue line the power output profile calculated over the left leg and the red line the power output profile calculated over the right leg. As can be noticed the total power output profile is kept constant.

E. sEMG Data Analysis

Each raw sEMG recording was filtered using a band-pass Butterworth digital filter in the band 20-350 Hz and normalized to the peak RMS sEMG value reached during all-out task [28]. Linear sEMG envelopes were estimated by an adaptive algorithm, optimized for dynamic conditions [29]. The onset and offset of muscle activity were detected by means of the double threshold detector [30]. For each burst the envelope profile was extracted and the position of its maximum value was calculated as a percentage of the burst duration. Mean envelopes were then derived by averaging the envelopes of the burst resulting in each phase.

An amplitude parameter was also calculated as the area under the envelope profile between onset and offset of each burst.

A. *Statistical Analysis*

Data were visually inspected and descriptive statistics was calculated for each data set. For each subject and each muscle data were compared between the initial and the final phase of the task. In particular, the initial phase corresponds to the first 100 s of the task, while the final one encloses the last 100 s before the exhaustion point. The extracted parameters were compared by means of statistical tests. In particular, a paired t-test analysis was performed in order to assess differences among location of the maxima with respect to the burst duration in the comparison initial phase vs. final phase. A one-way ANOVA was performed for the assessment of differences among amplitude of the envelopes of each burst of the sEMG signal using both phases (initial vs. final) as factors. Finally, the Pearson coefficient between mean envelope profiles was determined for the assessment of similarities among them. The level of significance was set at 0.05 for all data analysis. The signal processing and statistical analysis was performed using MATLAB (Version 2010a, MathWorks Inc., Natick, Massachusetts, USA).

III. RESULTS

A. *Burst Amplitude (BA)*

The envelope amplitude of each burst for each muscle and each subject were statistically compared between initial phase and final phase of the task. The results coming from one-way ANOVA reported a significant difference for only Vastii when comparing the initial and the final phase. Other muscles, and in particular bi-articular ones, reported an high variability among subjects (Fig. 4) resulting in a not significant difference.

B. *Location of the maxima (ML)*

A shift of the maximal value of the mean envelope towards the final stage of the burst for the bi-articular muscles (BF, RF, GAM) and a shift to the initial stage for mono-articular muscles (VL, VM, TA, GLU, SOL) are present when the final phase is compared to the initial phase of the task. The results of the t-test confirmed this behavior for only BF and SOL.

C. *Envelope Profile*

In order to assess similarities between shapes of burst envelopes in the comparison initial vs. final phase of the task, a cross-correlation analysis was performed. The Pearson coefficient values showed a moderate correlation only for BF and TA (around r = 0.66 for BF and r = 0.69 for TA), while other muscles reported a high correlation between shapes of the burst profiles (mean values across subjects: r =0.92 for RF, r = 0.94 for VL, r = 0.92 for VM, r = 0.94 for GLU, r = 0.83 for GAM and r = 0.89 for SOL). Envelope profiles are however all positively correlated, except for one muscle of one subject.

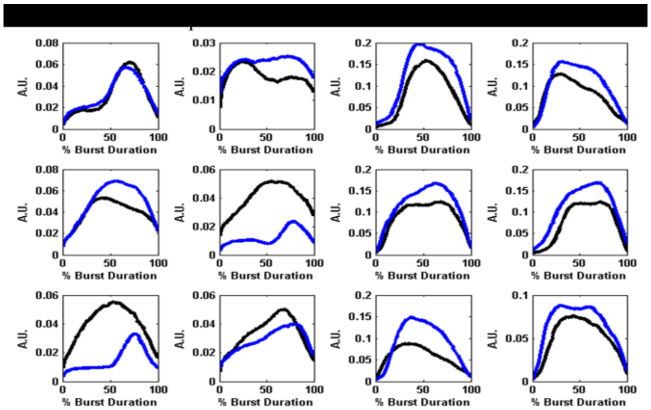

Figure 3. In the left side the mean envelope of BF for all subjects with respect to the percentage of the burst duration are depicted. In the right side of the figure the mean envelope of VL is represented. The black line is representative of the envelope profile at the beginning of the task, while the blue line depicts the envelope profile at the end of the exercise.

TABLE I. BURST AMPLITUDE AND MAXIMA LOCATION

		BA		ML	
BF	*Initial*	3.6±1.2	-	52±17.3	*
	Final	3.2±0.9		71.6±8.7	
RF	*Initial*	3.9±0.9	-	42.8±9.9	-
	Final	4.8±1.1		47.5±7.7	
VL	*Initial*	7.5±1.5	*	50.3±17.1	-
	Final	10.3±1.8		45.5±17.3	
VM	*Initial*	7.7±1.5	*	51.6±13.5	-
	Final	9.9±1.9		52.8±15.2	
TA	*Initial*	5.2±1.5	-	39.3±16.8	-
	Final	4.7±1.3		37.8±20.7	
GLU	*Initial*	1.9±0.6	-	69.6±6.3	-
	Final	2.4±0.5		67±15.3	
GAM	*Initial*	3.8±0.8	-	60.3±12.1	-
	Final	3.3±0.6		68±11.9	
SOL	*Initial*	3.3±0.6	-	62.5±6.1	*
	Final	4.3±0.7		52.8±9.8	

- n.s., * $p < 0.05$, ** $p < 0.005$.

IV. DISCUSSION AND CONCLUSIONS

The present study aims at describing what happens at the burst level of the sEMG signal when subjects perform a submaximal pedaling exercise at a constant power output until voluntary exhaustion. Three features were extracted from the sEMG signal: amplitude, location of the maxima and profile of the mean envelopes of the bursts. All these parameters were considered for both initial and final phase. We have found an increase in the amplitude of the mean envelope for all subjects only for VL and VM muscles. This could be due to the primary role of power producers of Vastii muscles in the pedaling gesture. It can, in fact, be inferred that VL and VM are the muscles mainly affected by neuromuscular fatigue and the increase of amplitude of the sEMG signal is just a sign of this [31]. The location of the maximal value of the mean envelope of the bursts was found to change when considering bi-articular or mono-articular muscles. In particular, a statistical difference was found for BF and SOL, accounting for a shift to the right and to the left respectively. Despite these changes the shape of the envelope of the burst at the end of the task is highly correlated with the one at the beginning of the exercise, indicating the absence of structural alterations in the burst profile. The obtained results permit to hypothesize that neuromuscular fatigue induces changes observable essentially in the Vastii which are involved especially in the downstroke phase. The typical pedaling strategy consists of pedaling by exerting the major part of force in the first half of pedal revolution without pulling up during the second phase. It seems clear that, pushing down the pedal involves the knee extensors (i.e. Vastii) that have the role of power producers. Other muscles, especially the bi-articular ones, have the main role of transferring energy between joints, and thus, in this kind of task, they are not corrupted by neuromuscular fatigue. This was confirmed by the high variability in the amplitude of the envelope. This variability is reflected also in the moderate correlation of the shape of the mean burst envelope and location of maximal values. So, we can speculate that neuromuscular fatigue influences the power-producing muscles, which are furthermore constrained by the imposed constant power output, more than other muscles that present high variability in the sEMG signal, not only for burst amplitude but also for shape and location of maximal values. The pedaling strategy adopted by all subjects is, in fact, concentrated mainly in the propulsive phase of the pedal revolution. Therefore, we can speculate that changing the pedaling technique with external constraints could lead to a decreased variability in bi-articular muscles. For example, the use of an external feedback for the pull-up action could imply a major involvement of bi-articular muscles that could result in a common behavior across all muscles also for amplitude feature when neuromuscular fatigue occurs. Further studies may be necessary to verify this hypothesis.

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