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Muscle Synergies are Consistent when Pedaling Under Different Biomechanical Demands

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***Abstract*—In this study we investigate the muscle coordination underlying the execution of a pedaling exercise across different biomechanical demands, by using the muscle synergies paradigm. 9 non professional subjects performed a cycling exercise using their preferred pedaling strategy (Preferred Strategy, PS) and then, through the use of a feedback based on the presentation of a real-time index of mechanical efficiency determined by means of instrumented pedals, they were helped to optimize their pedaling technique (Effective Strategy, ES). EMG activity was recorded from 8 muscles of the dominant leg. Nonnegative Matrix Factorization was applied for the extraction of muscle synergies. 4 modules were sufficient to reconstruct the repertoire of muscle activations for all the subjects during PS condition, and these modules were found consistent across all the subjects (correlation > 83%). 5 muscle synergies were necessary for the characterization in ES condition; 4 out of these modules were shared with PS condition, and the resulting additional module appeared subject-specific. These preliminary results support the existence of a modular motor control in humans.**

***Keywords*—Muscle Synergies, Cycling, sEMG, Index of Pedaling Efficiency.**

I. INTRODUCTION

IN our everyday life we easily accomplish a variety of motor tasks. One of the central and oldest issue in human motor control is how the Central Nervous System (CNS) is able to manage the numerous and highly redundant degrees of freedom of the musculo-skeletal system, and according to which neuro-physiological mechanism it generates the neural commands to reach different motor tasks [1]. The redundancy of the degrees of freedom together with the abundance of the actuators suggests the existence of complex computational mechanisms acting at the level of the CNS. Nevertheless, many researchers in the last few years focused their attention on the possibility of simplifying the CNS role in movement production. The existence of motor primitives at the level of the spinal cord [2] has been recently extended to the motor patterns observable at the level of the peripheral nervous system.

Surface Electromyography (sEMG) has been widely used as a valuable and non-invasive technique for the assessment of muscle coordination, aiming at inferring the neural strategies used by the CNS for the production of movement. Through the use of innovative computational methods, sEMG activity recorded from a large number of muscles involved in the execution of the task can be decomposed into the summation of a reduced number of modules, or muscle synergies, able to reconstruct the muscle activation repertoire through a linear combination of low dimensional elements. Muscle synergies provide a simplified explanation for motor control, and they have been recently investigated for many motor tasks in humans, like reaching movements of the upper limb [3][4], maintaining of the upright posture [5], pedaling [6], and walking in both normal and pathologic conditions [7][8], and these studies support the existence of a modular motor control in humans.

To the best of our knowledge, there is no previous study investigating the linkage between modular muscular coordination and its relation with pedal forces orientation in cycling. In this work we use the framework of muscle synergies to investigate the muscle coordination underlying the execution of a pedaling exercise carried out under different biomechanical demands in a population of non professional cyclists, in order to investigate the neural strategies used in the execution of the task and to evaluate if a shared modular motor control is present. The pedaling task will be described from a biomechanical point of view through the combined analysis of sEMG signals and the recording of the forces applied at the shoe-pedal interface.

II. MATERIALS AND METHODS

A. Participants

9 male subjects, aged 26.6 ± 2.7 and with no previous experience in professional cycling participated to the study. The subjects were instructed about the possible discomforts deriving from the experimental procedure and agreed through an informed consent.

B. Experimental protocol

The experimental protocol consisted of two different pedaling exercises performed on a cycle-simulator equipped with standard cranks and a couple of instrumented pedals. Before the execution of the two exercises, the subjects performed a 10-minutes warm up and an all-out sprint in order to determine the maximum reachable power output and the corresponding maximum level of sEMG activation in

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dynamic condition. The first exercise consisted of a 2-minutes cycling task with a strategy freely chosen by the subject (Preferred Strategy, PS), while the second exercise consisted of a 2-minutes effective pedaling task (Effective Strategy, ES). The subjects were helped to effectively project the forces on the pedal by means of a visual feedback of instantaneous efficiency [9], calculated as the ratio between F_{tg}, F_{tot} , that are defined in equations (1) and (2).

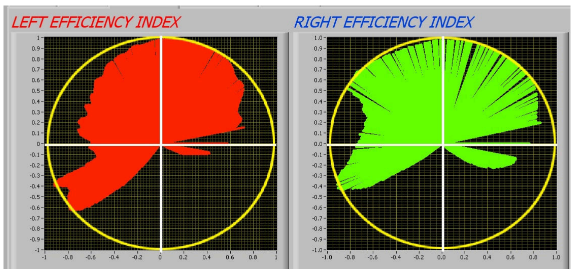

Figure 1: Visual feedback of the instantaneous mechanical efficiency, based on a polar plot diagram where each line has amplitude proportional to the instantaneous mechanical efficiency and phase proportional to the pedal angle. If the circle is entirely filled (red for left pedal and green for right pedal), then IE equals 1. The polar representation communicates also the information related to the different phases of the pedaling cycle with the associated theoretical optimal pedaling strategies. In this way the efficiency is directly related to each part of the cycling revolution.

PS and ES exercises were performed at the 25% of the peak power output expressed by the subjects during the all-out sprint, in order to avoid the occurrence of neuromuscular alterations due to muscular fatigue. The subjects were instructed to assume a comfortable seated position on the saddle and to maintain it during both the all-out sprint and the PS and ES exercises.

C. *sEMG Data Collection*

sEMG data were recorded from the following 8 muscles of the dominant leg: Gluteus Maximus (Gmax), Biceps Femoris (BF), Gastrocnemiius Medialis (GAM), Soleus (SOL), Rectus Femoris (RF), Vastus Medialis (VAM), Vastus Lateralis (VAL) and Tibialis Anterior (TA). A pair of Ag/AgCl electrodes was applied on each of the above-mentioned muscles, following the recommendations of the SENIAM project [10]. Skin was gently shaved and cleaned before the application of the surface electrodes. sEMG data were recorded through a wireless system (FREEEMG, by BTS s.p.a.) consisting of 8 bipolar wireless channels, sampled at 1000 samples/s and digitized at 14 bits.

D. *Force Data Recording*

In order to measure the horizontal (F_x) and vertical (F_z) components of the force applied to each pedal, together with the pedal angle θ_p (measured from the Top Dead Center, TDC), a couple of custom instrumented pedals have been used [11]. F_x, F_z and θ_p were acquired at 500 samples/s, digitized at 10 bits and synchronized with the sEMG data. The shoes were fastened to the pedal by means of KEO cleats fixed under the shoes. F_x, F_z and θ_p were used to determine the forces in a reference system in accordance with the circle spanned by the pedal, as shown in figure 2. Tangential force F_{tg} and total force F_{tot} were first calculated according to the following equation:

$$F_{tg} = F_x \cos(\theta_p) + F_z \sin(\theta_p) \tag{1}$$

$$F_{tot} = \sqrt{F_x^2 + F_z^2} \tag{2}$$

and then the index of mechanical efficiency IE was determined as reported in equation (3):

$$IE = \frac{\int_0^{2\pi} F_{tg}(\theta_p) d\theta_p}{\int_0^{2\pi} F_{tot}(\theta_p) d\theta_p} \tag{3}$$

IE was shown to the subjects in real-time in order to help them to effectively project the forces on the pedal.

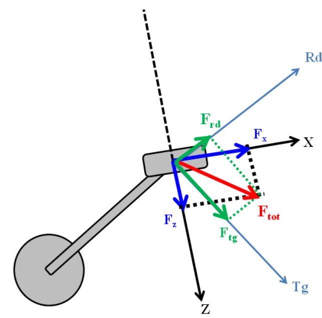

Figure 2: Pedal forces in the fixed reference system (F_x and F_z) and in the reference system in accordance with the pedal circle.

E. *Muscle Synergies Extraction*

sEMG data were band pass filtered (20-350 Hz) to remove artifacts and reduce noise, and then they were full-wave rectified and low-pass filtered at 4 Hz in order to obtain the linear envelopes [12]. The sEMG signal from each muscle was normalized to the peak sEMG root mean square value obtained during the all-out sprint [13]. Time scales were normalized by interpolating the sEMG envelope samples on 100 data points corresponding to the percentage of the pedaling cycle. Each envelope was averaged across 20 consecutive pedaling cycles in order to obtain a representative activation profile for each muscle [7]. Synergies were extracted by means of a Nonnegative Matrix Factorization algorithm [14]. NMF was applied to the matrix $\boldsymbol{M}$ containing the envelopes of the 8 sEMG signals; $\boldsymbol{M}$ is composed by 8 columns, one for each muscle, and 100 rows. NMF algorithm approximates $\boldsymbol{M}$ in the form $\boldsymbol{M} \approx \boldsymbol{WxH}$, where $\boldsymbol{W}$ is the 8xS matrix of the synergy vectors, $\boldsymbol{H}$ is the Sx100 matrix of the time varying activation coefficients, and S is the number of muscle synergies to be set before the application of the algorithm. NMF convergence is guaranteed through the use of multiplicative update rules at each step of the iterative algorithm, and it is based on the minimization of the Frobenius norm ‖ ***M-WH*** ‖. Each muscle synergy vector ***W*** was normalized to the maximum value of the muscle in the synergy to which they belong, and the corresponding time-varying activation coefficient ***H*** was scaled by the same quantity.

F. Choosing the Number of Modules

The dimensionality of the data, that is the number of synergies extracted, was chosen according the Variance Accounted For by the whole reconstruction *WH (VAF)* and by the reconstruction for each muscle *(VAF_m)*, calculated as shown in equations (4) and (5):

$$VAF = \frac{\sum_{i=1}^{8}\sum_{j=1}^{K}(M_{ij} - R_{ij})^2}{\sum_{i=1}^{8}\sum_{j=1}^{K}(M_{ij})^2} \quad (4)$$

$$VAF_m = \frac{\sum_{j=1}^{K}(M_{mj} - R_{mj})^2}{\sum_{j=1}^{K}(M_{mj})^2} \quad (5)$$

where $R = WH$ is the matrix reconstructed by the synergy model, K is the number of samples (i.e. 100 samples) and m denotes the muscle taken into account for VAF_m calculation. The proper dimensionality of the data was chosen according to the following criterion: the number of extracted synergies was varied between 1 and 8, and the smallest number of synergies S able to account for at least the 90% of the variance of the whole data and the 90% of the variance of the single sEMG signals was chosen [8][12].

III. RESULTS

4 modules were sufficient to reconstruct the repertoire of muscle activations in PS condition (Fig.3 upper panel). These modules were found consistent across all the subjects, showing a mean inter-subject correlation of 83% in the muscle weighting vectors ***W***, with slight adaptations in the time-varying activation coefficients ***H*** representing the variability in sEMG patterns, particularly visible for H4, which is a synergy involving the co-activation of the bi-articular muscles GAM and BF. 5 modules were necessary for the ES condition, with 4 out of these 5 modules shared with PS condition (Fig.3 middle panel); one additional module was found to be specific for the condition ES and shows a subject-specificity in ***W***, (Fig.3 lower panel) reflecting the variability in the sEMG patterns showed in the execution of a not-learnt task. Besides this variability, W5 is characterized by the sharing of BF muscle activation, which is functionally involved in the pull-up action during the upstroke phase when the pedaling is performed effectively. The extracted modules have a functional interpretation, since they explain well the behavior of the different muscles along the pedaling cycle in the different pedaling conditions, and their activity covers the whole pedaling cycle. For what concerns the power production in the down-stroke and up-stroke phases, when passing from PS to ES all the subjects showed an augmented recruitment of the synergies #3 and #4, together with the additional synergy which involves the activation of BF.

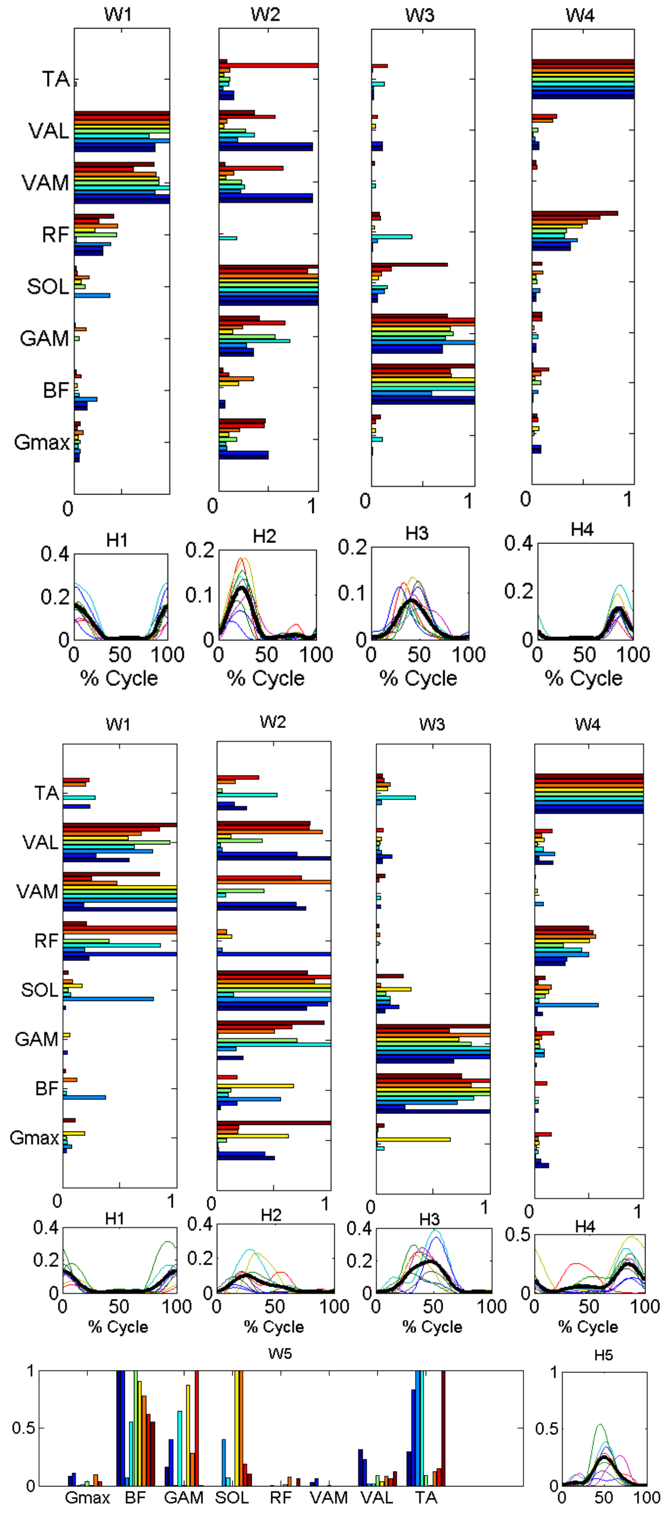

Figure 3: Upper Plot: W and H extracted during PS condition. Middle Plot: W and H shared in ES condition. Lower Plot: W and H specific for the condition ES. Different colors are related to different subjects

As it can be seen from Fig.4, there is a visible change in the force orientation throughout the pedaling cycle that leads to a significantly improved IE (IE_{ES} = 0.41±0.07, IE_{PS} = 0.72 ±0.13, p<0.01), leading the F_{tg} to almost completely coincide with the F_{tot} trends.

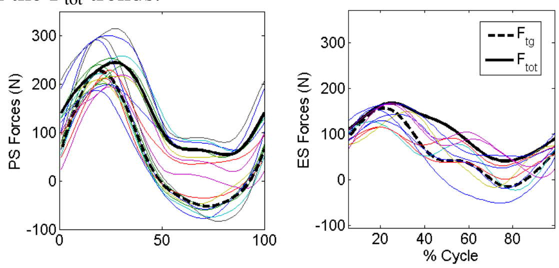

Figure 4: Force orientation throughout the pedaling cycle for PS and ES conditions. Average force profiles are reported in black.

IV. DISCUSSION AND CONCLUSION

The results support the existence of a modular motor control in humans. When the subjects perform a pedaling exercise by using their preferred strategy, their muscle activation repertoire can be well reconstructed by using 4 modules, whose structure extracted with NMF is stable across subjects. This stability is particularly present in the synergy weighting vectors ***W***, while a slight variability is visible in the time-varying activation coefficients ***H*** of the synergy #3 involving the co-activation of two bi-articular knee flexors (BF and GAM). This may indicate that a well-learnt motor task like pedaling is achieved by the linear combination of the same reduced number of modules. When a change in the biomechanical demand is present (as in the case of a feedback-driven strategy), the new mechanical requirement is satisfied by the subjects through the use of an already learnt modular structure, that is the 4 modules also present in the pedaling condition PS, plus one additive module emerging from the application of NMF that it is necessary to properly reconstruct the muscle activations of the subjects. We speculate that this specific muscle synergy may represent a neural adaptation reflecting short term learning, where the subjects tend to adopt an already learnt muscle coordination and add variability to achieve the imposed mechanical output, mainly consisting of power production for the pull-up action. The structure of the extracted muscle synergies has a functional interpretation in terms of force orientation during the pedaling cycle: synergy #1, involving the co-activation of the knee extensors, acts during the first part of the cycle and it is key to the force production in the down-stroke phase. Synergy #2 is characterized by the co-activation of two ankle plantar-flexors (GAM and SOL) and may be responsible of the ankle angle variations during the cycle. Synergy #3 intervenes during the second part of the cycle, when the knee passes from an extended position just after the bottom dead centre to a flexed position at the end of the up-stroke. Synergy #4 is a highly stable synergy appearing during the transition phase up to the end of the pedaling cycle, passing through TDC. Interestingly, the synergy vectors of these 4 modules are strongly similar to those extracted in other studies on human walking [8][12], and this supports the existence of modules shared between different tasks [15]. With respect to the study carried out in [6], where 3 synergies were extracted during cycling, here we extracted 4 synergies, and this is probably due to the differences in the normalization procedures that were adopted; nevertheless, the synergies extracted in both the studies have a similar functional interpretation and structure. Further studies should analyze the effect of training on the structure of muscle synergies in cycling, in order to establish if a modification in modularity occurs, or if the modular structure is kept constant by simply changing the neural descending drive, by scaling in amplitude and shifting in time the motor modules; this could be key to the functional evaluation of a cycling training or a rehabilitation program. It is worth noting that the observed neural adaptation doesn't take into account optimization principles for the execution of the task, such as minimization of energy expenditure or muscular fatigue; this could be a key factor to a possible reorganization of the modularity in task execution.

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