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Quantification of Different Pedaling Strategies in Inter-Lower Limbs between Cyclists of Different Road Racing Experiences

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Abstract: Gaining insight into the prevention of localized muscle fatigue has been an urgent challenge in cycling competitions. While studies have investigated muscle coordination only in a single lower limb in order to clarify efficient pedaling, known as pedaling skills, one of the cyclists' pedaling strategies, few studies have assumed a kind of asymmetrical muscle coordination in both the left and right lower limbs. In this paper, the authors aimed to quantify the difference in the strategy between road cyclists with different cycling experiences by investigating the structure of inter-lower limb muscle coordination. Six healthy male cyclists with different cycling experiences were volunteered: club cyclists for more than 4 years (n = 3) and elite cyclists for more than 10 years (n = 3). As they pedaled for 30 seconds under the experimental condition of 150 W at 90 rpm, we measured a total of 10 muscle activity patterns from the lower limbs by using surface electromyography and a crank rotational angle. Next, we extracted the muscle coordination to explain how both the lower limbs coordinate to employ skills by applying non-matrix factorization. The results found asymmetrical muscle activity patterns between the lower extremities regardless of cycling experience, which indicated muscle coordination compensating for the asymmetry to raise pedaling efficiency. These findings should contribute to understanding not only different pedaling strategies but also to preventing localized muscle fatigue. Future work should investigate the muscle coordination pattern of both lower limbs against the effect of muscle fatigue.

Keywords: *Surface electromyography, non-negative matrix factorization, pedaling strategy, cycling, muscle coordination*

1. INTRODUCTION

The central nervous system (CNS) dominates the musculoskeletal system, which generates very flexible movements. From the perspective of skeletal muscles, a flexible movement is achieved by the complex but harmonious combinations of multiple muscles. Such coordination of muscles is acquired in motor learning processes [1]. For example, although cyclists' performance depends on both physiological and biomechanical factors, the exercise efficiency of pedaling is greatly influenced by the muscle coordination of the lower limb, which is often called pedaling skills [2]. Here, it should be noted that cyclists are able to not only push forward and down on the pedals but also pull the pedals up, because they use clipless pedals that fix the pedals to the shoes via cleats. Furthermore, preventing non-traumatic injuries, such as repetitive strain injury and localized muscle fatigue, is an urgent challenge. With this goal in mind, acquiring the muscle coordination of both the left and right lower limbs has become a critical factor for high-efficiency pedaling in competitive cycling.

In modern times, muscles that play a major role in pedaling exercise have been investigated by measuring the surface electromyography (sEMG) of the lower extremity. However, a variation observed in the muscle activity pattern was affected by the mechanical constraints. Therefore, it does not reflect the cyclists' own pedaling strategy [3]. Here, related works have reported that a muscle synergy, representing the coordination of muscles, reflects a neuromotor strategy during pedaling, with a slight adjustment of either the activation timing or the magnitude of the muscle synergy under the different mechanical constraints. It is known that the muscle synergy in cycling reflects cyclists' pedaling skills as a strategy. It has also been reported that three or four muscle synergies accounted for the majority of the variability in the sEMG signals of a single lower limb during pedaling [3,4]. Nevertheless, the understanding of muscle coordination is limited to a single lower limb, because related studies have assumed that muscle coordination is a symmetrical strategy between the lower limbs. Therefore, this study aimed to quantify the pedaling strategy by investigating the muscle coordination formed by both the lower limbs as pedaling skills.

2. METHOD

2.1 Subjects

Six healthy male cyclists participated in the experiment: club cyclists, consisting of three cyclists who had participated in cycling competitions for 4 years (age: 20 ± 1.2 years, height: 1.69 ± 0.41 m, body weight: 58.3 ± 1.67 kg, dominant leg: right) and elite cyclists, consisting of three cyclists who had participated in competitive cycling for more than 10 years (age: 40 ± 1 years, height: 1.74 ± 1.32 m, body weight: 69.7 ± 7.73 kg, dominant leg: right). Informed consent was conducted in both verbal and written form before the start of the experiment.

2.2 Experimental device and exercise protocol

The experimental device consisted of a road bike (RS8, Bridgestone anchor), clipless pedals (PD-5800, Shimano), a rotary encoder (E6C2-CWZ1X, Omron), and a power meter (Power Tap, CycleOps). The rotary encoder was used for detecting the crank rotational angle by using a belt that was connected to the rotor of the crank. Both the cadence and workload were measured by a cycle computer (Edge 800J, Garmin). A wireless myoelectric probe (BTS FREEEMG 1000, BTS Bioengineering Corp) with an electrode (H124SG, Covidien) was used to measure the sEMG signals. Fig 1 (a) shows that the crank angle and sEMG signals were synchronously measured at 1k Hz. Fig 1 (b) shows 10 muscles in the left and right lower limbs: the hip abductor muscle (TFL), hip flexor and knee extensor muscle (RF), hip extensor and knee flexor muscle (BF), ankle dorsiflexion muscle (TA), and knee flexor and ankle plantarflexion muscle (GM) were measured. Both a Ham filter (60 Hz) and bandpass filter (15–490 Hz) were applied to the sEMG signals to eliminate noise. The experiment was conducted in a laboratory capable of setting the room temperature and humidity at 21 ℃ and 65%, respectively. It is reported that the exercise efficiency of the lower extremity is maximized under a cadence of 90 rpm among cyclists [5]. Thus, the experimenter instructed the subjects to pedal under an exercise load of 150 W with a cadence of 90 rpm for 30 s. By shifting the gear ratio, the exercise load during the pedaling was adjusted. In order to adapt to the experimental environment, the cyclists warmed up via a pedaling exercise in the laboratory 1 hour before the experiments began and adjusted the saddle height to their own preferred height. During the experiment, the subjects grasped on to the hoods of the handlebar.

2.3 Muscle synergy analysis

First, we calculated the root mean squared (RMS) values of the sEMG signals with the time interval required for the crank angle of 5 deg across 1-30 cycles. Second, we normalized the RMS of the sEMG signals by the peak value for each muscle per cycle. Third, we created the

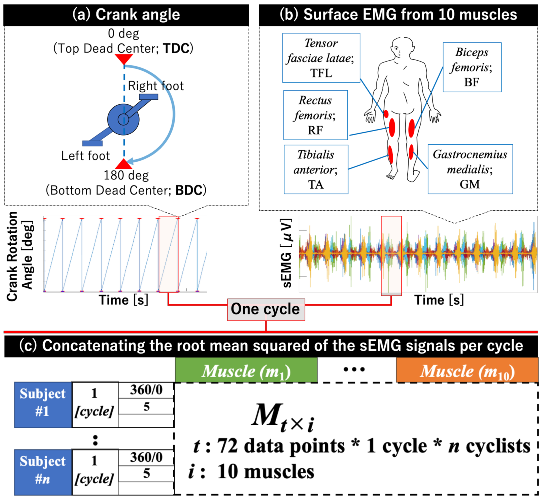


Figure 1: Overview of sEMG signals processing. (a) The definition of the crank angle. The Top Dead Center (TDC) and Bottom Dead Center (BDC) were defined as 0 deg and 180 deg. The clockwise crank rotation was defined as positive. (b) The muscles measured for both the left and right lower limbs. The red box highlights the total of the 10 sEMG signals according to the crank angle per cycle. (c) The root mean squared of the sEMG signals was concatenated across the club cyclists ($n = 3$) per cycle. The same was done for the elite cyclists ($n = 3$).

matrix $\mathbf{M}$ ($t \times i$) by concatenating the RMS of the sEMG signals per cycle between the club cyclists as well as between the elite cyclists, as shown in Fig 1 (c). Then, we applied non-negative matrix factorization (NMF) to the $\mathbf{M}$ of the club and elite cyclists per cycle. The matrix was decomposed into the synergy activation coefficient $\mathbf{C}$ ($t \times s$) and synergy vector $\mathbf{W}$ ($s \times i$) by minimizing the Frobenius norm between $\mathbf{M}$ and $\mathbf{W} \times \mathbf{C}$ for every cycle. The subscript i represents the number of muscles (i = 1-10) and t represents the data points of the crank angle for every 5 deg (t = 1-72) multiplied by the number of subjects. The number of synergies s determines the dimension of both the $\mathbf{C}$ and $\mathbf{W}$, which are key for understanding the extent to which the CNS dominates a set of grouped muscles. The number of synergies was chosen by means of variance accounted for. The VAF of each muscle was calculated as per the following equation [4]:

$$\mathrm{VAF}_{\mathrm{muscle}_i} = 1 - \frac{\sum_{t=1}^{n} (\mathbf{m}_{t,i})^2}{\sum_{t=1}^{n} (\mathbf{M}_{t,i})^2}$$

where $\mathbf{m}$ represents the reconstructed input signal. The $\mathrm{VAF}_{\mathrm{muscle}}$ of each muscle returns the synergy number that sufficiently reconstructs the input signal in spite of the dimensional reduction. In this study, the synergy number where the mean value of the $\mathrm{VAF}_{\mathrm{muscle}}$ across 10 muscles reached 80% was chosen. In this paper, we focused on the mean of the synergy activation coefficient of 72 rows by s columns across the subjects per cycle as C describing the level and timing of muscle coordination. Finally, the median value across all 30 cycles of both the synergy vectors and synergy activation coefficients were obtained to quantify the pedaling strategy by investigating the muscle coordination between the lower limbs as pedaling skills. Regarding the physiological meaning of muscle synergy, the synergy vector is related to adjusting the level and timing of muscle coordination via the CNS, whereas the synergy activation coefficient is related to selecting the muscles' coordination patterns via the CNS [1].

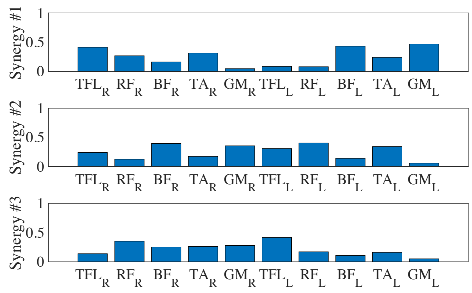
3. RESULTS

3.1 Muscle coordination between lower limb muscles

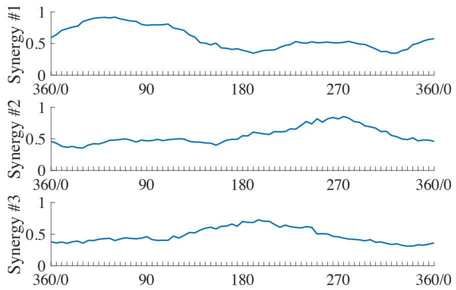
Figs 2 and 3 show the median value across all 30 cycles of both the synergy vectors and synergy activation coefficients, which corresponds to the resulting number of synergies: 3 for the club cyclists and 2 for the elite cyclists, respectively. It should be noted that the initial crank angle was defined by the position of the right foot at 0 deg. Thus, the crank angle on the X-axis in Figs 2 (b) and 3 (b) starts from 180 deg when the left lower limbs are discussed.

In the results of the club cyclists, we obtained three synergy vectors as well as synergy activation coefficients. First, the first synergy showed that the TFL_R, RF_R, and TA_R on the right leg and the BF_L and GM_L on the left leg were strongly activated when the right pedal was at around 90 deg. This cooperative activity between the hip abductor muscle, hip flexor and knee extensor muscle, and ankle dorsiflexion muscle on the right leg meant that the club cyclists tended to push the right pedal forward and down at around 90 deg. Meanwhile, the cooperative activity between the hip extensor and knee flexor muscle and the knee flexor and ankle plantar muscle on the left leg meant that they tended to pull the left pedal upwards and down at around 270 deg. Second, the second synergy showed the reversed result between the right and left lower limbs as shown in the first synergy, although the activation level between the first and second synergy vectors as well as the synergy activation coefficients differed. Finally, the third synergy showed that the muscles of the right leg were highly activated compared to those of the left leg when the crank angle was at around 180 deg, which meant that the club cyclists tended to mainly push the right pedal down at around 0 deg on the dominant leg.

In the results of elite cyclists, we obtained two synergy vectors as well as synergy activation coefficients. The first synergy showed that all the lower limb muscles except the TA_L and GM_L were highly activated when the crank angle

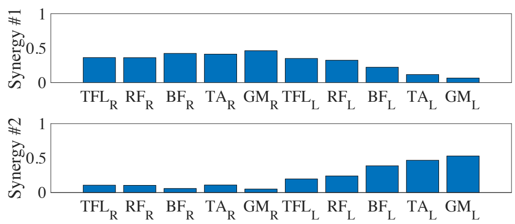


(a) the median value across all 30 cycles of the synergy vectors for the club cyclists.

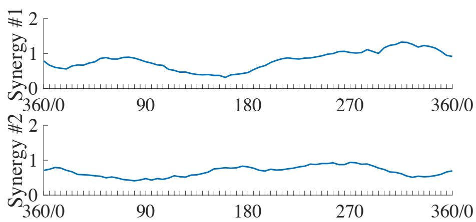


(b) the median value across all 30 cycles of the synergy activation coefficients for the club cyclists.

Figure 2: Muscle coordination pattern between the lower limb muscles of the club cyclists. Fig. 2 (a) shows the synergy vectors. The X-axis and Y-axis in Fig. 2 (a) represent the muscles of the lower limbs and number of synergies. Fig. 2 (b) shows the synergy activation coefficients. The X-axis and Y-axis in Fig. 2 (b) represent the crank rotational angle and the number of synergies.



(a) the median value across all 30 cycles of the synergy vectors for the elite cyclists.



(b) the median value across all 30 cycles of the synergy activation coefficients for the elite cyclists.

Figure 3: Muscle coordination pattern between the lower limb muscles of the club cyclists. Fig. 3 (a) shows the synergy vectors. The X-axis and Y-axis in Fig. 3 (a) represent the muscles of the lower limbs and the number of synergies. Fig. 3 (b) shows the synergy activation coefficients. The X-axis and Y-axis in Fig. 3 (b) represent the crank rotational angle and the number of synergies.

was at around 90 deg and 330 deg, which meant that the elite cyclists tended to push the right pedal down and forward by the TFL_R, RF_R, and TA_R and pull the pedal upwards and backwards by the BF_L and GM_L. In addition, the cooperative activation of both the TA_R and GM_R, which was related to ankle stabilization, was mainly seen in the cyclists' dominant leg. Second, the second synergy showed the BF_L, TA_L, and GM_L were strongly activated compared to the right leg muscles. These muscles remained activated the whole cycle. In particular, both the TA_L and the GM_L were greatly activated, which meant that the elite cyclists tended to stabilize the ankle in their non-dominant leg.

4 DISCUSSION

4.1 Pedaling strategy of inter-lower limb muscles that differentiates club and elite cyclists

The number of synergies resulted in 3 for the club and 2 for the elite cyclists. Related studies that reported the relationship between the number of synergies and the performance in motor tasks showed that a reduction in the number of synergies in post-stroke individuals in their paretic side indicated impairments in lower-limb muscle coordination [4]. However, understanding the relationship between the number of synergies and the motor strategy should be accompanied by an investigation of the muscle coordination within the synergy in a given motor task.

Dorel et al. [6] reported that the muscle activity of cyclists for both the hip extensor and knee flexor muscles increased in accordance with the increase in force production, which indicated the compensation of potential fatigue and the decrease in the activity of the knee extensor muscles by the increase in the activity of the hip extensor muscles. In this study, these kinds of muscle coordination were strongly confirmed in the first and second synergies of the elite cyclists. Recent studies also indicated that the muscle coordination associated with the "pulling up action" by the hamstring muscles could reflect the level of pedaling skills [7]. Interestingly, although the pulling up action was confirmed in both the intermediate and elite cyclists, this muscle coordination showed asymmetry in both the lower limbs. As shown in the elite cyclists, the strong activation of the ankle stabilization muscles in the dominant leg combined with the weak activation in the non-dominant leg in the first synergy and the strong activation of the ankle stabilization muscles in the non-dominant leg in the second synergy indicated that there was a compensatory muscle coordination to increase the effectiveness of pedaling, which differentiated the pedaling strategy between cyclists with different competitive cycling experiences.

5. CONCLUSION

This study investigated the differences in muscle coordination in both the lower limbs in cyclists with different cycling experiences. First, we measured the sEMG from both the lower limbs' correspondence to the crank angle. Then, NMF was applied to the RMS of the sEMG signals. The results found asymmetrical muscle activity patterns between the lower extremities regardless of cycling experience, which indicated muscle coordination compensating for the asymmetry to raise pedaling efficiency. These findings should contribute to understanding not only different pedaling strategies but also to preventing localized muscle fatigue. Future work should investigate the muscle coordination pattern of both lower limbs against the effect of muscle fatigue.

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