Pedaling skill training system with visual feedback of muscle activity pattern

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Abstract
For cycling competitors, the pedaling exercise is typically accompanied by a binding pedal system. The purpose of this pedal system is to attach the body of the pedal and the sole of the cycling shoe together in order to allow the cyclist to rotate the crank efficiently. Although the importance of a pedaling skill that streamlines the muscle activity of the leg muscles recruited in the pedaling exercise has been widely recognized in the field of cycling, no instructional method based on scientific evidence has been established yet. Hence, this study first proposes an evaluation standard for the pedaling skill by using the muscle activity data of a skilled cyclist. Subsequently, the training system based on the proposed evaluation standard is developed. The system measures the surface electromyogram of the leg muscles and the angle of crank rotation during the pedaling exercise. In addition, the system employs principal component analysis to extract the features of the muscle activity pattern from a beginner and an intermediate cyclist. Furthermore, the online visualization of their pedaling skill, based on the results of the principal component analysis, is implemented to enable cyclists to objectively monitor their pedaling skill. The experimental results obtained from the developed training system and the relationship between the pedaling skill and the consistency of the muscle activity pattern are discussed. The experimental results revealed the significant aspects of the pedaling skills, in which the consistency of the muscle activity pattern and the motion of pulling the pedal up were relatively clear in the pedaling of the skilled cyclist.

Keywords: Principal component analysis, Electromyography, Pedaling exercise, Real-time assessment

1. Introduction
Recently, the specifications of a competitive bicycle have been improved as a result of new material development (Burke, 1996). Figure 1 shows the configuration of a competitive bicycle. At present, a variety of carbon materials has been utilized in the frame, pedals, wheels, handle, etc. It should be noted that the structure of the pedal has changed little in the last forty years. Binding pedal systems have become one of the features of recent competitive bicycles. These pedal systems hold the sole of the cycling shoe to the upper body of the pedal, which enables cyclists to convert their physical power to the impulsive force of the bicycle. With the binding pedal, a cyclist can not only push down on the pedal but also pull the pedal up, which improves the efficiency of the pedaling exercise. The pedaling motion that enhances the efficiency of the pedaling exercise has been viewed as a significant skill for a cyclist. This pedaling skill is essential to increase competitive performance. In addition, since the riding posture of a cyclist is basically determined by the positions of the saddle and the handle, the settings of these mechanical components have to be carefully adjusted in order to maximize the physical performance of the pedaling exercise. Therefore, cyclists have been required to master the pedaling skill after optimally setting the mechanical components of the bicycle in order to
improve their competitive performance (Hug et al., 2009, Raymond et al., 2005, Tokuyasu and Matsumoto, 2013). However, both the settings of the mechanical components of the bicycle and the improvement of pedaling skill depend on the subjectivity of the cyclist. These might come closer to the ideal forms for a cyclist by creating subjective criteria through the experience of cycling. The authors consider that the development of objective criteria for pedaling skill can contribute not only towards boosting the practice efficiency of cyclists but also towards promoting their competitive level.

Previous studies have discussed the optimization method for the saddle height, in which the changes in the activity pattern of the leg muscles recruited in the pedaling exercise were experimentally investigated. The results suggested that an experienced cyclist settled the saddle height to make the load of each leg muscle relatively small (Tokuyasu et al., 2014a). Additionally, we investigated the muscle activity pattern of highly skilled cyclists by using a multivariable analysis (Tokuyasu et al., 2014b). Chapman et al. (2008) also investigated the consistency of the muscle activity pattern of leg muscles during the pedaling exercise and concluded that there was little variation in the muscle activity pattern of highly skilled cyclists. These results mentioned that the variance of muscle activity decreases corresponding to the proficiency in pedaling skill of the cyclist.

Nevertheless, the relationship between the consistency of the muscle activity pattern and pedaling skill have not been clarified. Hence, the authors of this paper first focused on the importance of the evaluation criteria for pedaling skill. This paper proposes an evaluation criteria for pedaling skill based on the statistically analyzed muscle activity pattern of a skilled cyclist. Additionally, the procedures to evaluate the muscle activity pattern are promoted to make it possible to objectively monitor one’s own pedaling skill in training. The following sections describe the experimental environment and protocol relative to the visualization of the muscle activity pattern. Finally, the experimental results are shown and discussed with the objective to make the proposed system more practical.

![Fig. 1 Basic constitution of a road-racer bicycle.](image)

2. METHOD

2.1 Methodology

This study assumed that the cooperation of leg muscles forms pedaling skill. The ability to coordinate the muscles is intrinsically developed and its level is elevated according to the experiences of not only training but competition. In order to evaluate the cooperation of leg muscles in the pedaling exercise, the muscle activities of leg muscles in the pedaling motion have to be measured (Hug et al., 2009). Therefore, the surface electromyography (sEMG) of the leg muscles recruited in the pedaling exercise are measured in this study, in which the Rectus Femoris (RF), Biceps Femoris (BF), Tibialis Anterior (TA), and Gastrocnemius Medialis (GM) were selected, as shown in Fig. 2. In most of the previous researches, the pedaling exercise was discussed on the premise of symmetric property of right-and-left legs. This study also assumes the premise of symmetric property of right-and-left legs during pedaling exercise. A multi-channel amplifier (Nihon Kohden Co., MEG-6108) was adopted as the measurement instrument for the sEMG. In order to eliminate the noise originating from the power supplies and avoid aliasing effect, the settings of the
measurement instrument were set as follows: sampling frequency of 1 kHz, low-cut at 5 Hz, hi-cut at 500 Hz, and 60 Hz hum-filter. Then, the signals of sEMG were processed full-wave rectification.

Figure 3 shows the configuration of the experimental device, in which a cycle trainer is fixed to a rear wheel of a competitive bicycle (RS8, Bridgestone anchor). A power sensor (Power tap SL+, CycleOps) is installed in the shaft of the rear wheel, so the exercise load can be monitored on the cycle computer (Edge 800J, Garmin) mounted on the handle bar. The rotary encoder (E6C2-CWZ1X, Omron) mounted on the down tube of the bicycle measures the angle of crank rotation.

2.2 Experimental protocol

First, we describe the experimental protocol to establish the evaluation criteria for pedaling skill before discussing the method to visualize the muscle activity pattern. The categories of subjects who participated in the experiment were defined as follows: a skilled cyclist has a career of over fifteen years in cycling competitions with the binding pedals and teaching experiences; a beginner cyclist is a subject who has never used the binding pedals and has never experienced cycling competition; the other subjects are categorized in an intermediate cyclist.

This study assumed that there is little variation in the muscle activity pattern of a skilled cyclist. In fact, it has been reported that the patterns of leg muscle recruitment of highly trained cyclists vary very little (Raymond et al., 2005). Therefore, we first measure the muscle activity pattern of a skilled cyclist, and then the evaluation criteria for pedaling skill is established. This study employed a healthy male cyclist who has a cycling career of over twenty years. In order to measure his basic pattern of leg muscles, this study instructed him to pedal at 90 rpm with 50, 150, and 250 W of exercise load on the experimental device. The exercise load was adjusted by shifting the gear ratio of the bicycle while...
monitoring the cycle computer. In addition, this study calibrated the crank rotation angle of 0° by setting the right pedal at the highest position in its circular path. A measurer recorded both the angle of crank rotation and sEMG signals of the leg muscles for 30 s after the pedaling exercise became consistent. The subject had adequate rest to remove the effects of muscle fatigue and mental discomfort in the intervals of the experiments.

2.3 Establishment of evaluation criteria for pedaling skill

Firstly, the sEMG data for each leg muscle were processed with the root mean square method, and the average for every 15° of crank rotation angle was calculated. Additionally, the averages of all 24 periods were standardized and vectorized in Eq. (1), where \( e_{15n} \) \( (n = 1–24) \) indicates the averaged sEMG data for each leg muscle at each 15° of crank rotation. We defined Eq. (1) as an averaged sEMG pattern. The variable \( q_m \) can be considered as the pattern of a muscle for one rotation of the pedaling exercise. This study applied Eq. (1) to the sEMG signals from the RF, BF, AT, and GM, so that the muscle activity pattern can be defined as shown in Eq. (2). The subscript \( i \) indicates each type of subject.

\[
q_m = [e_{15}e_{30}...e_{345}e_{360}]
\]  

(1)

\[
m_p = [q_{RF} q_{BF} q_{AT} q_{GM}]
\]

(2)

\[
X_i = [m_{p1} m_{pS1} m_{pS2}]
\]

(3)

This study arbitrarily constructed two vectors, \( m_{pS1} \) and \( m_{pS2} \), of the muscle activity pattern from the measured sEMG data of the skilled cyclist. These vectors were utilized as criteria to evaluate the pedaling skill of a beginner and an intermediate cyclist. The muscle activity pattern of them as well as the skilled cyclist can be derived, and this is described as the vector \( m_p \). A matrix, \( X_i \), can then be formed as shown in Eq. (3), which comprises the patterns of muscle activity of either a beginner cyclist and a skilled cyclist or an intermediate cyclist and a skilled cyclist. We defined Eq. (3) as a muscle activation matrix, \( X_i \).

Secondly, this study tentatively employed a beginner and an intermediate cyclist, and the muscle activation matrix, \( X_i \), for each subject was developed. In order to statistically compare the pedaling skill of a subject with the skilled cyclist, principal component analysis (PCA) was applied to each matrix. Before the implementation of PCA to a matrix, \( X_i \), the process of dimensionless was conducted on the values of each vector of the matrix, \( X_i \), in order to make it possible to compare the muscle activities among the subjects, where the vector-valued average subtracted and divided by the standard variation.

This section introduces the experimental results for the intermediate cyclist as an example. In accordance with the experimental protocol, the muscle activity pattern between the intermediate cyclist and the established criteria were statistically compared by PCA to establish and verify the visualization procedure of muscle activity pattern. Note that a measurer recorded both the angle of crank rotation and sEMG signals of the leg muscles for 30 s after the pedaling exercise became consistent as we did in section 2.2. The matrix \( X_{intermediate} \) was composed from the sEMG signals of the intermediate cyclist and the skilled cyclist. It has been experimentally known that the cumulative contribution ratio of the first and the second principal component exceeds 90 %; therefore, this study focused on the scores of the first principal component and the second principal component. The signs of the first eigenvector and the second eigenvector are shown in Fig. 4a. In the cases in which the subject was either a beginner or an intermediate cyclist, it was experimentally known that most of the signs of the eigenvectors were as follows in this study: For the obtained first eigenvector, if the sign of the first factor becomes opposite of the sign of the other two factors, then the signs of all factors of the second eigenvector become the same. Conversely, if the sign of the first factor of the second eigenvector becomes opposite of the sign of the other two factors, then the signs of all factors of the first eigenvector become the same. According to the experimental rules, this study presumed that a skilled cyclist is trained in alternating the contraction and relaxation of muscles to effectively rotate a crank. For this reason, the interpretation of the principal component indicated the degree of muscle activation in the case of the signs of all factors of either the first eigenvector or second eigenvector become the same. Then, the significance of the principal component coefficients can be considered as shown in Fig. 4b.
However, it is not intuitive for us to see the result of PCA scores scattered in a two-dimensional score sheet as shown in Fig. 4b and Fig. 5a. Then, the two-dimensional PCA score sheet is converted to a circular graph as shown in Fig. 5b. In the circular graph, the color of each circle shows the type of leg muscle and the timing of muscle activation corresponds to the crank rotation angle. The radius of each circle reflects the distance from the origin of each PCA score, which shows the degree of tendency of muscle activation and difference between the subject and evaluation criteria in this study.

The experimental results of the intermediate cyclist are shown in Fig. 6, in which this subject performed pedaling exercise under various exercise loads prior to the online procedures for the visualization of the muscle activity patterns. It can be confirmed that the BF contracted from 180° to 270° and also relaxed from 0° to 180° in the phase of pulling the pedal up under 50 W of exercise load, as shown in Fig. 6a. It should be noted that for the experiment with the exercise load of 150 W, the relaxation pattern of the BF disappeared, as shown in Fig. 6b. Additionally, both the contraction pattern and the relaxation pattern of the BF disappeared in the experiment with the exercise load of 250 W, as shown in Fig. 6c. These results suggested that this subject could not pull the pedal up as the exercise load increased. The movement of pulling the pedal up has been considered one of the essential motions for effective pedaling.

Fig. 4 The example flow of how to interpret the results of the principal component analysis applied to the matrix $X_i$ (The intermediate cyclist at the exercise load of 150 W, for example).
2.4 Online visualization procedure

Our system would enable cyclists to objectively monitor their pedaling skill by providing the procedures for the visualization of the muscle activity patterns online. Here, the matrix, $X$, needs to be continuously updated during the pedaling exercise. The muscle activity patterns of the skilled cyclist, $mp_{S1}$ and $mp_{S2}$, are constantly used as the evaluation criteria in the online procedure for the visualization of pedaling skill. Only the muscle activity pattern of a

Fig. 5 Example of the visualization of the pattern of muscle activity based on the conversion of the two-dimensional PCA score sheet to the circular graph.

Fig. 6 Pedaling skill evaluation of the intermediate cyclist using the developed visualization method for muscle activity pattern under various exercise loads, 50W, 150W, and 250W, where the averaged muscle activity pattern of pedaling exercise for 30 s were described.
beginner or an intermediate cyclist is updated every five crank rotations. The online processing of PCA and the notation system using a circular graph as shown in Fig. 5b are adopted in this paper.

Figure 7 shows the graphical user interfaces and a photograph of the training system, in which a trainee is monitoring his own muscle activity pattern while pedaling. The measured data and the visualization results are sequentially recorded in the computer, so that the consistency of the muscle activity pattern can be evaluated after training with this system.

3. RESULTS

First, the consistency of the muscle activity pattern of the beginner cyclist was experimentally investigated in this study. Figure 8 shows the visualization results of the muscle activity pattern for the beginner cyclist, where Fig. 8a, Fig. 8b, and Fig. 8c show the results of 50, 100, and 150 implementations of the PCA, respectively. Similarly, figure 9 indicates the results for the intermediate cyclist who is the same subject as we employed in experiment in section 2.3.

It is notable that the contraction phase of the RF varied among the cases of 50, 100, and 150 PCAs as shown in Fig. 8. In addition, the TA and GM were significantly relaxed throughout the pedaling exercise, which indicates that the beginner cyclist could not keep the ankle angle consistent due to the increased exercise load. Also, increasing the activation of the RF in order to pedal with a high exercise load is an example of the inconsistent pattern of muscle activity of a beginner cyclist.

Second, the inconsistency of the muscle activity pattern of the intermediate cyclist was confirmed in Fig. 9a and Fig. 9b, in which the activity pattern of the BF changed in both the muscle contractions and muscle relaxations throughout the pedaling exercise. Additionally, the activity pattern of the BF changed at 100 and 150 implementations of the PCA, as shown in Fig. 9b and Fig. 9c, wherein the RF and TA contracted in the phase of pulling forward and down. It should be noted that the BF was relaxed in the phase of pulling up the pedals. This is also an example of the muscle activity pattern of a beginner and an intermediate cyclist.
Fig. 8 Consistency evaluation of muscle activity pattern of the beginner cyclist under 50W of exercise load.

(a) 50 PCAs  (b) 100 PCAs  (c) 150 PCAs

Beginner subject’s muscle contraction

Beginner subject’s muscle relaxation

Fig. 9 Consistency evaluation of muscle activity pattern of the intermediate cyclist under 50W of exercise load.

(a) 50 PCAs  (b) 100 PCAs  (c) 150 PCAs

Intermediate subject’s muscle contraction

Intermediate subject’s muscle relaxation

: Rectus femoris  : Biceps femoris  : Tibialis anterior  : Gastrocnemius medialis

: Rectus femoris  : Biceps femoris  : Tibialis anterior  : Gastrocnemius medialis
4. DISCUSSION

Although the importance of pedaling skill has been well known among cyclists all over the world, neither an effective teaching method nor an instructional system has been established. Therefore, cyclists cannot comprehend their own muscle activity pattern and compare their pedaling skill with a skilled cyclist. The system we have proposed in this paper enables cyclists to modify their pedaling motion by monitoring their own muscle activity pattern. In particular, the online usage of principal component analysis of the muscle activity pattern enables the visualization of this feature of the pedaling motion.

The experimental results described in Fig. 8 and Fig. 9 indicated the inconsistency of the muscle activity pattern of the beginner and the intermediate cyclist, respectively. Because the second and third factors in Eq. (3) are not updated during the training phase and only the first factor is updated, trainees can objectively understand the consistency of their own muscle activity pattern. First, it should be noted that the experimental results for the intermediate cyclist, shown in Fig. 6, indicated the lack of the motion of pulling the pedal up under the condition of high pedaling load. Second, the experimental results for the beginner cyclist, shown in Fig. 8, indicated that the ankle angle was not consistent while pushing the pedal down. In addition, as shown in Fig. 9, the muscle activity pattern of the intermediate cyclist indicated that the motion of pulling the pedal up was not maintained, even at the same exercise load. According to these findings, this study considers both the consistency of the muscle activity pattern and the motion of pulling the pedal up as the most significant aspects of the pedaling skill. For implementation in future work, this study will collect the experimental results in order to generalize the features of the muscle activity pattern according to the pedaling skill of the cyclist.

The authors estimated that the muscle activity patterns of beginners are individually different because they have never used the binding pedal system. It should be noted that anybody can master the pedaling skill; however, the features of the muscle activity pattern might be slightly different because the physical properties, such as muscle mass and flexibility vary among individuals, even if they are of the same height. In addition, the settings of the mechanical components of a bicycle also vary among individuals.

This study used the sEMG signal to quantitatively estimate the amount of muscle activity. However, the sEMG is easily affected by not only the physical conditions of a subject but also the experimental environment. Therefore, the authors are planning to investigate the relationship between the muscle activity pattern and the settings of the mechanical components. Future studies will develop a numerical model of the lower limb, in which the length of the leg bones and the saddle position are dynamically changed during the pedaling motion. By using this simulation model, we will investigate the influence of the saddle position based on the manipulability of the lower limb.

5. CONCLUSION

This study proposed a training system for pedaling skill by focusing on the visualization of the muscle activity pattern. These procedures, from the measurement of the sEMG of the leg muscles and the angle of crank rotation to the implementation of principal component analysis, were developed to be used online. The experimental results revealed the significant aspects of the pedaling skill: the consistency of the muscle activity pattern and the motion of pulling the pedal up were relatively clear in the pedaling of the skilled cyclist. This study continues the experiment by collecting data from both intermediate cyclists and skilled cyclists, and we will reveal the crucial differences in pedaling skill between them. Additionally, this study will numerically investigate the relationship between the saddle position and the muscle activity pattern.

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