Cycling Power Optimization System Using Link Models of Lower Limbs with Cleat-Shaped Biaxial Load Cells

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Abstract

A new optimization system of cycling power was investigated in this paper. The developed system consisted of a newly designed biaxial load cells and analytical system using mechanical model of lower limb. The new biaxial load cells which were made by stainless steel (SUS304) were attached to the bottom of cycling-shoes instead of the plastic cleats. Cyclists are able to connect their cycling-shoes to pedals by the developed load cells. The sizes of load cells were almost same as plastic cleats (Shimano Corp) and measure the magnitude and direction of right and left pedal force using 16-strain gages, respectively. The analytical system solves the link model of human limbs to identify the positions and angles of each segment of lower limbs. The lower limbs model consisted of 3 segments, thigh, shank and foot. All position of every lower limb segments, joint torques and forces were calculated by this system. Additionally, the relationships between ankle angle and crank angle were also modelled by image-analysis software (TEMA 3D) with the high-speed camera (Photron FASTCAM SA4). This cycling power optimization system were applied to the amateur and expert cyclists to investigate applicability of our system.

Keywords: Visualization, Pedaling-effectiveness, Biaxial load cell, Cleat-size load cell

1. Introduction

Thomas et al. (2007) and Guillaume et al. (2006) developed the pedal power sensor with piezoelectric force sensors in order to evaluate the relationship using cycle ergometer. Also, Umberto et al. (2011) reported that the change of upper body position influenced a power output and muscle activation pattern. Hanaki et al. (2012) investigate effects of seat post angle on the power output.
In addition, some cycling power meters have been available commercially such like the SRM power meter. Commercial power meters output the average power calculated by the crank torques which were communicated by the wireless data transmission system.

This paper investigates a newly developed power optimization system for competitive cyclists. This system consisted of two technical issues which were development of cleat sized load cells and visualization system.

The first technical issue was that we developed original cleat shaped load cells which measure horizontal and vertical load independently (Fig. 1). The load cells were possible to install to sole of cycling shoes by two steel bolts without special jigs or special processing. The shape and size of load cells are almost same as commercial plastic cleats which were manufactured by the Shimano Corporation. Thermo-mechanical treatment process are applied to the SUS304 body of the load cell after machining process. Development of cleat shaped biaxial load cells permit participants to apply their own bicycle and shoes to the performance test. It would be very important issues for serious competitor to use their own materials without change of body position. Also the wired load cells provide us accurate information about pedaling forces.

The second technical issues was that we developed a visualization system of performance test results which works on general laptop PC (Fig. 2(a) and Fig. 2(b)). This system analyzed the position and angle of crank, pedal, toe, heel, knee and greater trochanter during pedaling by a link mechanism and a free body diagram of cyclist’s lower limb. The pedaling forces and joint torque were calculated and visualized on the laptop PC just after the performance tests. We applied this system to amateur cyclists to investigate tendency of the force and torques during pedaling and key-point for better and stronger pedaling.

Fig. 1. Cleat sized biaxial load cell (a)Direction of vertical and horizontal forces, (b) Overview of the loadcell

Fig.2 (a) Visualized results of developed system working on PC, (b) Participant of performance tests
2. Construction of Visualization System

2.1 Cleat-Sized Biaxial Load Cells

The load cells were designed to attach to the bottom of cycling shoes in place of plastic cleats. 2-set of wired 8-strain gages bridge circuits were introduced to each load-cell, respectively. The load cells could be connected to the bicycle pedals to measure vertical and horizontal force from the bottom of the shoes. Load capacity was ±1,000 N in the vertical direction and ±500 N in the horizontal direction. The load cells were calibrated using weights and the nonlinearity of load cells were under 1%. Cyclists were able to use their own bicycles for performance tests and to measure the pedaling force of each leg independently.

2.2 Pedaling Visualization System

In the pedaling visualization system, position and angle of crank, pedal, toe, heel, knee and greater trochanter are calculated by lower limb model which is shown in Fig. 3(a). The positions of greater trochanter, knee, heel, toe and ankle were defined as vector $\vec{X}_1, \vec{X}_2, \vec{X}_3, \vec{X}_4$ and $\vec{X}_6$, respectively. The length of thigh, shank, foot and crank were defined as $L_1, L_2, L_3$ and $L_4$. Moreover, $L_5$ was the length between ankle and heel and $L_6$ was the length between toe and heel. $L_1, L_2, L_3, L_4$ and $L_6$ were supposed constants and were measured before performance tests.

The positions of the bottom bracket and the greater trochanter were supposed to fixed points.

The acceleration of ankle angle $\dot{\gamma}$ was approximated with the following function using image analysis software TEMA 3D (Photron Corp., Japan).

\[
\dot{\gamma} = a_i \sin(b_i \alpha + c_i) + a_i \sin(b_i \alpha + c_i) + a_i \sin(b_i \alpha + c_i) + a_i \sin(b_i \alpha + c_i),
\]

where $a_i, b_i$ and $c_i (i=1,2,3,4)$ are constant parameters for each participants, $L_7$, $\theta_2$ and vector $\vec{X}_4$ were calculated using ankle angle $\gamma$.

\[
L_y = \sqrt{L_x^2 + L_z^2 - 2L_xL_z \cos \gamma}, \quad \theta_2 = \sin^{-1}\left(\frac{L_x}{L_y} \sin \gamma\right), \quad \vec{X}_4 = \left(\frac{L_x \cos \alpha}{L_y \sin \alpha}\right)
\]

$L_x$, $\theta_2$ and $L_6$ in Fig.3 were calculated as follows:

\[
L_y = \sqrt{(x'_1 - x'_2)^2 + (y'_1 - y'_2)^2}, \quad L_6 = L_y \sin \theta_1, \quad \theta_1 = \cos^{-1}\left(\frac{L_y^2 + L_5^2 - L_7^2}{2L_5L_7}\right).
\]

Thus, knee position $\vec{X}_2$, $\vec{X}_5$ and ankle position $\vec{X}_6$ were calculated as follows:

\[
\vec{X}_2 = \left(\frac{x_5 + a_x L_6}{y_5 + a_y L_6}\right), \quad \vec{X}_5 = \left(\frac{x_4 + n_x (L_5 \sin \theta_1)}{y_4 + n_y (L_5 \sin \theta_1)}\right), \quad \vec{X}_6 = \left(\frac{x_2 + \frac{L_7}{L_6} (x_4 - x_6) \cos \theta_2 + (y_4 - y_6) \sin \theta_2}{y_2 + \frac{L_7}{L_6} (y_4 - y_6) \cos \theta_2 + (x_4 - x_6) \sin \theta_2}\right)
\]

Here, $\vec{X}_5$ was temporary position for computational calculation, $\vec{e}_1$ is unit vector of $\vec{X}_1 - \vec{X}_4$ and $\vec{a}$ is the orthogonal vector of $\vec{e}_1$. $\theta_2$ in Fig.3(a) was constant and heel position $\vec{X}_3$ were given as follows:

\[
\theta_3 = \cos^{-1}\left(\frac{L_5^2 + L_8^2 - L_9^2}{2L_5L_8}\right), \quad \vec{X}_3 = \left(\begin{array}{c} x_4 + \frac{L_3 - L_8 \cos \theta_3}{L_3} (x_6 - x_4) + \frac{L_8 \sin \theta_3}{L_3} (y_6 - y_4) \\ x_4 + \frac{L_3 - L_8 \cos \theta_3}{L_3} (y_6 - y_4) + \frac{L_8 \sin \theta_3}{L_3} (x_4 - x_6) \end{array}\right).
\]
From the above equations, all joint positions of the lower limbs relative to crank angle \( \alpha \) were determined and pedal angle \( \beta \) was calculated.

\[
\beta = \cos^{-1}\left(\frac{x_3 - x_4}{L_3}\right)
\]

From pedal angle \( \beta \), the vertical and horizontal pedaling force components from the ground were calculated with conversion of measured forces.

\[
f'_x = -f_x \sin \beta + f_x \cos \beta, \quad f'_z = f_z \cos \beta + f_x \sin \beta
\]

where \( f_x \) and \( f_z \) were vertical and horizontal pedaling force components from the cycling shoes, respectively. The tangential pedaling force \( f_t \) and normal pedaling force \( f_n \) were calculated by crank angle \( \alpha \), as follows;

\[
f_t = f'_x \cos \alpha + f'_z \sin \alpha, \quad f_n = -f'_x \sin \alpha + f'_z \cos \alpha
\]

Here, only the tangential pedaling force \( f_t \) was converted to bicycle driving force and the normal pedaling force \( f_n \) was used to adjusting balance of pedaling.

2.3 Joint Torque Calculation by Free Body Diagram

To calculate joint torque, the free body diagram (in Fig.3(b)) of lower limbs were applied. The free body diagram was supposed to separate to 3 segments (thigh, shank and foot). Equations of motion for translation were defined as follows:

\[
m_k \ddot{\mathbf{x}}_k = \mathbf{f}_{k,P} + \mathbf{f}_{k,D} + m_k \ddot{\mathbf{g}}
\]

Here, \( \ddot{\mathbf{g}} \) is gravity vector, \( m_k \) are mass of each segments and \( \mathbf{f} \) is force. \( k \) is segment number. \( k=1 \) means the foot segment, \( k=2 \) means the shank segment, and \( k=3 \) means the thigh segment, respectively. Equation of motion for rotation were defined as follows:

\[
\dot{\mathbf{J}}_k \ddot{\theta}_k = \mathbf{P}_{k,cgP} \mathbf{J}_{k,P} - \mathbf{P}_{k,cgD} \mathbf{J}_{k,D} + \mathbf{T}_{k,P} + \mathbf{T}_{k,D}
\]
Here, $\omega_k$ were the angular velocity, $I_k$ were the moments of inertia and $T_k$ were the joint moments. The body segment inertia parameters which was determined by Ae et al. (1992) were applied to calculate center of gravity and the mass of segments $m_k$.

3. Performance Test

3.1 Participants and test condition

Pedaling performance tests were carried out and test results were analyzed to evaluate the applicability of developed system. Participant was an amateur male cyclist. In performance tests, a road bike (Via Nirone 7-ALU, Bianchi Corp.) and a room training machine (V270, Minoura Corp.) were applied. Also, the participant was ordered to keep cadence as 100rpm during pedaling performance test. Horizontal and vertical loads of right and left legs were recorded in 30 seconds by the high-speed digital recorder (EDX-100A by Kyowa Corp.). Cadence and pedal angle were also recorded by the digital recorder using magnetic sensor. Recording frequency of digital recorder was 500 Hz. Wired transmission was applied to the connection between the load cells and digital recorder.

Small tracking markers were taped to the joint of ankle, knee and toe to investigate relationships between ankle angle and crank angle. The positions of markers were recorded by the high-speed camera (Photron FASTCAM SA4). The relationships between ankle angle and crank angle given as equation (1) were modelled by image-analysis software (TEMA 3D). Modeling of the relationships between ankle angle and crank angle were conducted before the performance test. The experiment was approved by the ethical committee of the University of Tsukuba.

3.2 Results and discussion

Original recorded results of left pedaling force was shown in Fig. 4(a). The length of the arrows corresponds to the magnitude of human leg power. Also, the direction of the arrows represents the direction of human leg power. From this figure, it can be seen that the cyclist applied leg power in the lower direction at the bottom, dead center position. Thus, much of the power was not converted into driving force and pedaling force was almost downward force.

The effective pedaling force $f_i$ is possible to separate to two components $f_i^{(+)}$ and $f_i^{(-)}$. $f_i^{(+)}$ is a component in the positive direction. $f_i^{(-)}$ is in the negative direction. $f_i^{(+)}$ works effectively as a driving force, and $f_i^{(-)}$ disturbs crank rotation. In addition, the radial component $f_n$ was a non-effective force, which does not influence driving force. Thus, pedaling effectiveness $E$ is defined with the following equation as a function of crank angle $\alpha$:

$$E(\alpha) = \frac{f_i^{(+)}}{\sqrt{f_i^{2} + f_n^{2}}} \times 100(\%) \quad (11)$$

From Fig.4, it could be confirmed that adjustment of the direction of pedaling force was one of important key-point of pedaling techniques. To clarify this key-point, virtual improvement of pedaling force direction were supposed. Here we suppose improvement rate of pedaling force angle as $I.R.$ and it was defined as the percentage of linear projection to the tangential direction. As examples, $I.R.$=100% means that all pedaling force were produced to tangential direction and $I.R.$=0% means that all pedaling force were produced to radial direction. In Fig 4(b) (c), (d), (e), improved results ($I.R.$ were 10%, 20%, 50% and 100%) were shown. From these results, pedaling effectiveness $E$ was calculated using equation (11) and relationships between $I.R.$ and pedaling effectiveness $E$ were plotted in Fig. 5(a). In Fig. 5(b), relationships between joint torques and $I.R.$ was shown. Relationships between $I.R.$ and pedaling effectiveness $E$ showed linear tendency from 0% to 60% of $I.R.$ From these results, effectiveness of adjustment of pedaling force direction shows importance for competitive cyclists. On the other hand, strongly adjustment of pedaling force might be a cause of knee injury.
4. Conclusion

In this research, a new visualization training system for cycling pedaling technique was developed. Cleat-sized biaxial load cells were developed to measure the direction and magnitude of pedaling forces. The measured force was converted into effective and non-effective forces using a lower-limb model and joint torques were calculated free body diagrams of lower limbs. Effect of adjustment of pedaling force direction and risk of joint injury were possible to be investigated using this system. Effect of information about power output and pedaling effectiveness on the cyclist’s performance would be discussed in future works.

Fig. 4 Original and virtual pedaling force (a) Original result, (b) I.R.=10%, (c) I.R.=20%, (d) I.R.=50%, (e) I.R.=100%

Fig. 5 (a) Average of pedaling effectiveness, (b) Extension and flexion torque of lower limb

Reference


