Joint Torque Evaluation of Lower Limbs in Bicycle Pedaling

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Outline

**Previous study**

Via Nirone 7-ALU (Bianchi Corp.) was applied for tests

**This study**

Wattbike (Wattbike Corp.) was applied for tests

Relationship between normal force in the rotation direction of a bicycle crank and ankle angle

1 amateur cyclist as a subject

5 amateur cyclists as subjects

Joint torque and joint torque power were evaluated by pedaling system of this study
Purpose / Introduction

Evaluating joint torque of lower limbs using our bicycle pedaling system

Mechanism of bicycle pedaling
The driving force is obtained by human leg power
leg power applied to pedals is categorized two forces
- Effective force
  Tangential component of leg power
- Non-effective force
  Normal component of leg power

Not all leg power is converted into driving force
To reduce futile forces in bicycle pedaling,
Directions of human leg power applied to pedals are crucial
In previous research,

- We developed newly biaxial load cells
  The load cells are designed to imitate cleats
  The advantage of this load cells is to be able to measure force of biaxial directions
  Cyclists can be use their own bicycles for performance test

Almost same size

Rated capacity of horizontal direction
±500N

Rated capacity of vertical direction
±1000N

Plastic cleat made in Shimano Corp.
Developed biaxial load cells
Introduction

In previous research,

- Modeling of lower limbs was conducted for the following 2 reasons,
  - To convert the measured force into effective and non-effective force
  - To obtain kinematic data for the lower limb motion

Images of pedaling motion

Image analysis using high-speed camera

Link mechanism of lower limb motion

- $X_1$: Greater trochanter
- $X_2$: Knee
- $X_3$: Ankle
- $X_4$: Toe
- $\gamma$: Ankle angle
Introduction

In previous research,

The modeling of lower limb motion have weak point
- Each time the pedaling output and cadence changes, the ankle angle was obtained directly from image analysis using high-speed cameras.
In this study, an approximation method of relationship between the ankle angle and normal force in the rotation direction of a bicycle crank was proposed.

In previous research, image analysis using high-speed camera was conducted. Images of pedaling motion were captured using a high-speed camera. The link mechanism of lower limb motion was analyzed, with key points labeled as:

- $X_1$: Greater trochanter
- $X_2$: Knee
- $X_3$: Ankle
- $X_4$: Toe

The angle $\gamma$ represents the ankle angle.
Modeling of lower-limb motion

Test condition

- Subjects: 5 amateur male cyclists
- Applied bicycle: Wattbike (Wattbike Corp.)

Pedaling output: 200, 250, 300 W  Cadence: 80, 90, 100 rpm
Recording frequency: 500 Hz
Horizontal and vertical loads of legs were recorded for 30 seconds

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Height [m]</th>
<th>Mass [kg]</th>
<th>BMI [kg/m^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>22</td>
<td>1.75</td>
<td>62.65</td>
<td>20.45</td>
</tr>
<tr>
<td>B</td>
<td>23</td>
<td>1.75</td>
<td>73.65</td>
<td>24.25</td>
</tr>
<tr>
<td>C</td>
<td>24</td>
<td>1.72</td>
<td>65.40</td>
<td>22.10</td>
</tr>
<tr>
<td>D</td>
<td>23</td>
<td>1.65</td>
<td>64.10</td>
<td>23.68</td>
</tr>
<tr>
<td>E</td>
<td>24</td>
<td>1.70</td>
<td>67.20</td>
<td>23.25</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.894</td>
<td>0.0389</td>
<td>3.83</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Modeling of lower-limb motion

These figure showed that this relationship was not significantly affected by pedaling output and cadence in downstrokes.

\[ \gamma = \gamma_1 f_n + \gamma_2 \] : linear equation was applied to approximation for the downstroke

\[ \gamma_1, \gamma_2 \] : Constant parameters for each subject

\[ \gamma \] : Ankle angle

\[ f_n \] : Normal force in the rotation direction of a bicycle crank
Modeling of lower-limb motion

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Modeling of lower-limb motion

These figure showed that this relationship was not significantly affected by pedaling output and cadence in downstrokes.

\[ \gamma = \gamma_1 f_n + \gamma_2 \]

- Two variables used in the approximation method were determined by using relationship

<table>
<thead>
<tr>
<th>Subject</th>
<th>( \gamma_1 )</th>
<th>( \gamma_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0486</td>
<td>102.070</td>
</tr>
<tr>
<td>B</td>
<td>0.0695</td>
<td>107.712</td>
</tr>
<tr>
<td>C</td>
<td>0.0264</td>
<td>109.870</td>
</tr>
<tr>
<td>D</td>
<td>0.0615</td>
<td>97.832</td>
</tr>
<tr>
<td>E</td>
<td>0.0516</td>
<td>100.470</td>
</tr>
</tbody>
</table>
Construction of evaluation system

Calculation method for joint torque

Joint torque is the resistive force acting on the body due to the influence of external forces.

Cyclists are able to recognize their lower limbs behavior objectively.

Joint torque was calculated by using free body diagram. The free body diagram separates the lower limb into three segments (thigh, lower leg and foot).

- Positive joint torque: Extension torque
- Negative joint torque: Flexion torque

Equation of motion for each segment:

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

\[ I_k \ddot{\omega}_k = \vec{P}_{k,cgP} \vec{f}_{k,P} - \vec{P}_{k,cgD} \vec{f}_{k,D} - T_{k,P} + T_{k,D} \]
Construction of evaluation system

Calculation method for joint torque power

Joint torque power ($P_t$) is a calculated value based on joint torque ($JT$) and joint angular velocity ($JAV$)

Cyclists are able to estimate the action of virtual muscles

Joint torque ($JT$) was calculated by the free body diagram
Joint angular velocity ($JAV$) was calculated by differentiating the joint angle based on the link mechanism

$$P_t = JT \cdot JAV$$

Definition of joint torque power

<table>
<thead>
<tr>
<th>Joint torque</th>
<th>Joint angular velocity</th>
<th>Joint torque power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension torque (+)</td>
<td>Extension (+)</td>
<td>Positive power (+)</td>
</tr>
<tr>
<td></td>
<td>Flexion (−)</td>
<td>Negative power (−)</td>
</tr>
<tr>
<td>Flexion torque (−)</td>
<td>Extension (+)</td>
<td>Negative power (−)</td>
</tr>
<tr>
<td></td>
<td>Flexion (−)</td>
<td>Positive power (+)</td>
</tr>
</tbody>
</table>
Performance test

Test condition

- Subjects: 5 amateur male cyclists
- Applied bicycle: Wattbike (Wattbike Corp.)

In tests, subjects were ordered following condition
- Pedaling output: 200 W
- Cadence: 90 rpm
- Pedaling in 30 sec
Test result (knee joint torque)

- Knee joint torque in each subject
  - The difference is remarkable from 90° to 180°
  - Flexion torque was exerted
    - at about 100° of crank angle by subject D
    - at about 130° of crank angle by subject B, C and E
    - at about 160° of crank angle by subject A

- Knee joint torque

![Graph showing knee joint torque vs. crank angle for different subjects.](attachment:image.png)
Test result (knee joint torque)

- Knee joint torque in each subject
  - The difference is remarkable from 90° to 180°
  - Flexion torque was exerted
    - at about 100° of crank angle by subject D
    - at about 130° of crank angle by subject B, C and E
    - at about 160° of crank angle by subject A
Test result (knee joint torque)

- Knee joint torque in each subject
  - In previous research, trained cyclist exerted flexion knee joint torque at about 135° of crank angle
  - Subject B, C and E were pedaling well in downstrokes
Test result (joint torque power)

- Maximum joint torque power in each subject

Evaluation of maximum joint torque power allows us to estimate the action of muscles of lower limbs in bicycle pedaling.

Positive joint torque power means concentric working of muscle.

- 5 subjects were classified into 3 groups
  - A, B and C were classified into maximum knee joint torque power group
  - D was classified into maximum ankle joint torque power group
  - E was classified into maximum hip joint torque power group
Test result of subject A, B and C

- Maximum joint torque power in each subject

- Subject A, B and C were worked to advantage the positive joint torque power in the knee joint

- The maximum knee joint torque power was generated at about 90° or 180° of crank angle
  - A and C were worked maximum extension torque power at about 90° of crank angle
  - B was worked maximum flexion torque power at about 180° of crank angle
Test result of subject D

- Maximum joint torque power in each subject

- Subject D was worked to advantage the positive ankle joint torque power

- The maximum ankle joint torque power was generated at about 130° of crank angle

- Maximum extension torque power of ankle joint was exerted because subject D tends to move the ankle joint mainly
Test result of subject E

- Maximum joint torque power in each subject

Subject E was worked to advantage the positive hip joint torque power

- The maximum hip joint torque power was generated at about 130° of crank angle

- Maximum extension torque power of hip joint was exerted because subject E was generated maximum hip joint torque and hip joint angular velocity at the same time
Conclusion

- Performance tests with 5 armature cyclists were conducted using developed bicycle pedaling system with small biaxial load cells.
- Dynamic behavior of ankles in pedaling were analyzed by high speed camera system. From the results, a linear relationship between ankle angle and normal force of crank was proposed:
  \[ \gamma = \gamma_1 f_n + \gamma_2 \]
  - This relationship was applied to approximation of relationships between ankle angle and nominal force in downstrokes, especially.
- Joint torque power of each subjects in performance test were calculated and we investigate how each subject use their muscles of lower limbs in bicycle pedaling.
  - Three subjects (A,B,C) showed same tendency of pedaling This might means that they are pushing down or pulling up the bicycle pedal using a peripheral muscle group of knee joint.
  - Two subjects are different from the other subjects, this might means that they are pushing down using a peripheral muscle of ankle or hip joint.
Thank you for your attention