Modeling cycling performance: Effects of saddle position and cadence on cycle pedaling efficiency

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Abstract
The modeling method is an effective means of estimating causality as well as examining cycle pedaling efficiency. Pedaling efficiency can also be examined by an experimental method, but the experimental method can lead to contradictory results due to perturbation of the measured output parameters. Experimental studies generally yield realistic results, but it is difficult to control for all the variables of interest and to determine the causal relationships between them. The objective of this study is to investigate the pedaling efficiency and causality with considering saddle position and pedaling cadence as variables. Based on the mathematical pedaling modeling, the internal work calculation method was used to calculate the consumed mechanical energy and energy conservation percentage ($C_s$). The optimal saddle position with the lowest mechanical energy and the highest energy conservation percentage could be changed by the cadence. At the low cadence, the higher saddle position, and the shorter horizontal distance between the saddle and crankshaft led to higher pedaling efficiency ($h$: 0.95 m, $d$: 0.16 m, and knee angle: 28°). However, the highest pedaling efficiency was achieved at the high cadence with a saddle height ($h$) of 0.9 m and a horizontal distance between the saddle and the crankshaft ($d$) of 0.06 m (knee angle: 48°). The lowest cadence is the optimal cadence in terms of the consumed energy, but the optimal cadence was 90 r/min in terms of the energy conservation percentage. Compared to the energy consumption, the energy conservation percentage was demonstrated to influence the fatigue of a cycle rider more critically. The energy conservation percentage was highest at 90 r/min, and 90 r/min was close to the preferred cadence by the cyclist.

Keywords
Cycling, dynamical modeling, mechanical energy, pedaling efficiency, energy conservation percentage

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Introduction

A bicycle is driven forward via repetitive movement known as pedaling, and the energy efficiency of pedaling directly influences the cycling efficiency. Thus, to enhance the efficiency and ensure optimum performance, achieving energy optimization and ensuring a low risk of injury for the cyclist is important. In addition, pedaling efficiency is a key factor that influences muscle fatigue accumulation. Consequently, the factors related to pedaling have been extensively investigated.

Bini et al.\(^1\) experimentally analyzed the effect of the saddle height on the joint kinematics by calculating the pedal force and joint mechanical energy by using force sensors and reflective makers. They suggested that the saddle height did not particularly influence the single joint; however, mechanical work at the individual joint was likely balanced by the hip, knee, and ankle joints. This finding meant that energy exchange occurs at hip, knee, and ankle joints. Some researchers\(^2\)–\(^4\) have measured the oxygen uptake (\(VO_2\)), which is commonly used in mechanical energy analysis, to determine an optimal saddle position by minimizing the changes in \(VO_2\). The changes in \(VO_2\) were minimized when the pedal was located at the bottom dead center (6 o’clock position), the knee angle was between 25\(^\circ\) and 30\(^\circ\), and the saddle height was approximate 103%–104% of the leg length, yielding the highest efficiency. However, energy analysis using \(VO_2\) involves aerobic energy, making it difficult to measure the energy of pedaling alone, thereby leading to inaccurate results.

In terms of the saddle position, other studies have been focused on injury and safety instead of energy. Some researchers\(^5\),\(^6\) have suggested that 109% of the inseam distance (floor to ischium) may be the optimum distance from the pedal to the top of the saddle that is called the Hemley method, however, this method was not suitable for long inseam length (IL) groups (IL < 0.8 m), but rather only for medium and short ILs.\(^7\) Other researchers\(^8\),\(^9\) have suggested that the knee angle should be between 25\(^\circ\) and 35\(^\circ\) to reduce the risk of injury during cycling.

Among the assorted variables related to the saddle position, other researchers have analyzed the saddle position using variables other than those related to the joints and \(VO_2\). Kang et al.\(^10\) considered the vertical alignment of the knee and foot. Seo et al.\(^11\) examined the influence of the saddle height on the thigh muscle activities, and Dedieu et al.\(^12\) investigated the effects of the saddle height on the muscular activation patterns.

In addition to the research focused on the saddle position, several researchers\(^13\)–\(^16\) attempted to determine the optimal cadence, which is the angular velocity of the pedal, to attain the highest pedaling efficiency, primarily using experimental methods involving blood lactate and \(VO_2\) measurements. Although the findings of these studies have varied depending on the experimental conditions and adopted technique, the optimal cadence value ranged from 60 to 80 r/min, whereas the study participants, i.e. cyclists, preferred a cadence of 90 r/min.

These prior experimental studies produced reliable results because actual data are used. However, the results could be inaccurate as it is difficult to measure the experimental variables accurately, and it is not sufficient to clarify the cause-and-effect relationships between the results and variables. Several economic and environmental limitations also hinder experiments performed under conditions resembling real-life
situations. In addition, in the existing experimental investigations performed using the joint kinematic method, the energy conservation percentage \( C_s \) has not been determined, and the correlations among the kinetic energy (KE), potential energy (PE), and mechanical energy (ME), which considerably influence the pedaling process, have not been clarified.

To this end, we proposed a mathematical method with simple biomechanical modeling to analyze the pedaling efficiency by establishing the relationships among the ME, KE, and PE under various saddle positions and cadence values. Furthermore, the energy conservation percentage that previous studies barely treated was also investigated.

**Method**

During cycling, the muscles of the lower limb are subjected to gravity and inertial resistance depending on the posture of the cyclist, and these resistances affect the pedaling efficiency. These resistances are influenced by variables such as the relative positions of the thigh, shank, and pedal; pedaling cadence; vertical alignment of the knee and foot; and angle of the foot. These variables can be adjusted to minimize resistance, reducing the mechanical energy consumption (ME) and increasing the energy conservation percentage \( C_s \). The smallest value of the ME and the highest value of the \( C_s \) correspond to the highest pedaling efficiency and the optimized values of the above-mentioned variables influencing the resistances. The saddle position and cadence, which affect the lower limb kinematics the most among the variables, were set as the research objects in this study and examined using a biomechanical model (Figure 1). As most human motions during cycling primarily occur in the sagittal plane, the posture and cadence were considered as the independent variables in the sagittal plane. The weight, moment of inertia, and lengths of the thigh and shank were obtained from Vaughan et al.\(^{17}\). Vaughan et al. predicted the segment mass, a moment of inertia by using prediction equations of Chandler et al.\(^{18}\) and the measured anthropometric parameters of a normal male subject. Although the height is excluded from the anthropometric data of a normal male, it was able to be estimated to be 178 cm by using segment/stature ratio.\(^{19}\) In the moments of inertia table, the flexion/extension axis data representing the moments of inertia about the axis rotation in the sagittal plane were used in this study. The flexion/extension axis of thigh originates from the hip joint, and the flexion/extension axis of shank originates from the knee joint.

**Modeling of pedaling process**

The positions of the knee and foot can be obtained as follows:

\[
B = (l_1 \sin \theta_1, l_1 \cos \theta_1) \quad (1)
\]

\[
C = (l_1 \sin \theta_1 - l_2 \sin \theta_2, h - l_1 \cos \theta_1 - l_2 \cos \theta_2) \quad (2)
\]

The foot has been simplified to a point \((C)\) which is the end of the shank for simplification of the model. In addition, the foot position, in the context of the crank, can be expressed
as follows:

\[ C = (d + r \cos \theta_3, y - r \sin \theta_3) \]  

(3)

The crank arm length \((r)\) is set to 170 mm, which is a middle length of the common crank arm lengths (165, 170, and 175 mm).\(^{20}\) By solving the nonlinear equations (2) and (3), \(\theta_1\) and \(\theta_2\) with respect to \(\theta_3\) can be calculated, and the angular velocities \(\omega_1\) and \(\omega_2\) can be calculated by differentiating \(B\).

\[ l_1 \sin \theta_1 - l_2 \sin \theta_2 = d + r \cos \theta_3 \]  

(4a)

\[ h - l_1 \cos \theta_1 - l_2 \cos \theta_2 = y - r \sin \theta_3 \]  

(4b)
\[ l_1 \cos \theta_1 \dot{\theta}_1 - l_2 \cos \theta_2 \dot{\theta}_2 = -r \sin \theta_3 \dot{\theta}_3 \quad (5a) \]

\[ l_1 \sin \theta_1 \dot{\theta}_1 - l_2 \sin \theta_2 \dot{\theta}_2 = r \cos \theta_3 \dot{\theta}_3 \quad (5b) \]

Considering the ratio of the center of gravity of the thigh and shank (Figure 2), the potential energy of the thigh and shank were determined.

\[ U_{\text{thigh}} = m_1 g (h - 0.433 l_1 \cos \theta_1) \quad (6) \]

\[ U_{\text{shank}} = m_1 g [(h - 0.433 l_1 \cos \theta_1) - (0.433 l_2 \cos \theta_2)] \quad (7) \]

**Figure 2.** The center of mass of each segment of the body of an adult human male.\(^{21}\)
The kinetic energy of the thigh and shank can be expressed as follows:

\[
T_1 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} I_1 \omega_1^2
\]  
(8)

\[
T_2 = \frac{1}{2} m_2 v_2^2 + \frac{1}{2} I_2 \omega_2^2
\]  
(9)

**Energy calculation**

If the non-conservative force does not act on the object and only the conservative force is applied, the sum of the kinetic energy (KE, \(T\)) and potential energy (PE, \(U\)) of an object is always constant while the object is moving (law of conservation energy). However, when a non-conservative force is generated by the human body, such as the pedaling movement, this law does not hold, and the work done by the non-conservative force can be regarded as the ME.

\[
ME_n + T_n + U_n = T_{n+1} + U_{n+1}
\]  
(10)

Therefore, the total consumed ME during pedaling can be defined as

\[
\sum ME = \sum_{i=1}^{N} |(T_{i+1} - T_i) + (U_{i+1} - U_i)|
\]  
(11)

The energy calculation method using equation (11) is similar to the calculation of the body internal work by using equation (12), as reported by Winter.22

\[
W = \sum_{i=1}^{N} |\Delta E_i|
\]  
(12)

**Energy conservation percentage**

The energy conservation percentage (\(C_s\)) can be obtained by modifying equation (12).

\[
W_s = \sum_{i=1}^{N} |\Delta E_i|
\]  
(13)

Assuming no energy exchange occurs among any of the components, the work done by each segment is

\[
W_s' = \sum_{i=1}^{N} (|\Delta E_{pi}| + |\Delta E_{kli}| + |\Delta E_{kri}|)
\]  
(14)

The \(E_{pi}, E_{kli}, \) and \(E_{kri}\) represent the potential energy, the translational kinetic energy, and the rotational kinetic energy of the \(i\)th segment, respectively. The \(C_s\) can be obtained by using \(W_s'\) and \(W_s\).

\[
W_c = W_s' - W_s
\]  
(15)
\[ C_s = \frac{W_c}{W_s} \times 100\% \] (16)

**Data processing**

The pedaling efficiency was investigated based on the human body data in Table 1, considering the saddle position and cadence in a full revolution (360°) of the pedal. To investigate pedaling efficiency depending on the saddle position and the cadence, the saddle position values \((h\) and \(d\)) and the cadence value \((\omega_3)\) were set as variables. \(h\) is the saddle height in the \(y\)-axis, and \(d\) represents the saddle position in the \(x\)-axis. All outcome parameters were calculated at five different saddle heights \((h; 0.75, 0.80, 0.85, 0.90,\) and \(0.95\) m), five different values for the horizontal distance between the saddle and crankshaft \((d; 0.06, 0.11, 0.16, 0.21,\) and \(0.26\) m), and five different cadences \((\omega_3; 1, 2, 3, 4,\) and \(5\) \(\pi\) rad/s). The inseam length was excluded from the anthropometric data. Considering the saddle position in terms of the optimal knee angle \((25°–30°)\) instead of the inseam length \((h = \text{inseam length} \times 109\%)\), the \(h\) and \(d\) were set. The ranges of the saddle height \((h)\) and horizontal distance \((d)\) were set in consideration of the seat tube angle range from 70° to 80°, which was used in the previous studies.\(^{23,24}\) The seat tube angle is defined as the angle between the saddle-crankshaft line and a horizontal line. The cases where the saddle height \((h)\) was 0.95 m, and the horizontal distance \((d)\) was 0.21–0.26 m were excluded since the saddle-pedal distance becomes longer than the leg length. The total number of cases analyzed was 123 (i.e. \(5 \times 5 \times 5 - 2\)).

The results were obtained using MATLAB R2020a (MathWorks, Natick, Massachusetts, USA) with customized codes.

**Results**

The trajectories of the knee and foot were shown in Figure 3(a). Good qualitative and quantitative matching is observed between the predicted and actual trajectories. The values of \(\theta_1\) and \(\theta_2\) depending on \(\theta_3\) are shown in Figure 3(b).

As the saddle height \((h)\) increased, the ratio of the increase in the KE is greater than that of the increase in the PE; however, as the horizontal distance between the saddle

### Table 1. Body segment parameter data for lower extremities of a normal male.

| Segment number | 1       | 2       | 3       |
|----------------|---------|---------|---------|
| Segment name   | R. Thigh| R. Calf | R. Foot |
| Mass (kg)      | 6.886   | 3.28    | 0.77    |
| Center of gravity position (ratio proximal/distal length) | 0.39 | 0.42 | 0.44 |
| Moments of inertia (kg·m²·m) | 0.1238 | 0.0490 | 0.0035 |
| Flexion/extension axis | 0.1188 | 0.0504 | 0.0040 |
| Abduction/adduction axis | 0.0229 | 0.0037 | 0.0011 |
and the crankshaft \((d)\) increased, the ratio of the increase in the KE becomes less than that of the increase in the PE. In the case of the cadence \((\omega_3)\), as the position variables \((d, h)\) do not change, the PE does not change (Figure 4(f)); however, the KE increases by 4, 2.25, 1.78, and 1.56 times as the cadence \((\omega_3)\) increases by 1 \(\pi\) rad/s (Figure 4(e)). Figure 5 shows the energy changes in the thigh and shank depending on the \(\theta_3\).

The calculated ME during pedaling is shown in Figure 5(d). The pedaling movement consumed a total of 42.14 J when the saddle height \((h)\) was 0.85 m, the horizontal distance \((d)\) was 0.16 m, and the cadence \((\omega_3)\) was 2 \(\pi\) rad/s. The ME and energy conservation percentage \((C_s)\) values are presented in Figure 6.

When the cadence \((\omega_3)\) was 1–3 \(\pi\) rad/s, the ME decreased with the increasing saddle height \((h)\). However, when the cadence was higher than 3 \(\pi\) rad/s, the ME decreased as the saddle height \((h)\) increased up to 0.9 m, and then increased as the saddle height \((h)\) increased to 0.95 m. For the horizontal distance \((d)\), the ME decreased with the decreasing horizontal distance \((d)\) at the low cadences (1–3 \(\pi\) rad/s) when the saddle height \((h)\) ranged from 0.75 to 0.80 m, but the ME decreased with the increasing horizontal distance \((d)\) at high cadences (4–5 \(\pi\) rad/s). When the saddle height \((h)\) was 0.85 m, the ME decreased as the horizontal distance \((d)\) decreased, however, the change in the ME by the horizontal distance \((d)\) is decreased as the cadence becomes higher. When the saddle height \((h)\) was in the range of 0.85–0.95 m, the ME decreased with the decreasing horizontal distance \((d)\) regardless of the cadence. The change in the ME by the saddle height \((h)\) was larger than the change by the horizontal distance \((d)\).

There was a negative correlation between the energy conservation percentage \((C_s)\) and the ME. In other words, when the ME was low, the energy conservation...
percentage ($C_s$) was high, and when the ME was high, the energy conservation percentage ($C_s$) was low. The correlation coefficients were $-0.9239$, $-0.8967$, $-0.9056$, $-0.9012$, and $-0.8894$ (all $p$-values < 0.05) when the cadence was 1, 2, 3, 4, and 5 $\pi$rad/s, respectively.

Figure 4. The changes in the kinetic energy and potential energy depending on the pedal angle ($\theta_3$). (a) KE depending on $h$, (b) PE depending on $h$, (c) KE depending on $d$, (d) PE depending on $d$, (e) KE depending on $\omega_3$ and (f) PE depending on $\omega_3$.
ME: mechanical energy; KE: kinetic energy; PE: potential energy.
Figure 5. The changes in energy depending on the pedal angle ($\theta_3$). (a) Energy to move thigh, (b) energy to move calf, (c) change in mechanical energy with angle and (d) change in total mechanical energy with angle ($d = 0.16$ m, $h = 0.85$ m, and $\omega_3 = 2 \pi$ rad/s).

Figure 6. Mechanical energy (ME) and energy conservation percentage ($C_s$) as a function of variables ($h$, $d$ and $C_s$). (a)–(e) ME depending on the saddle position variables at 1, 2, 3, 4, and 5 $\pi$ rad/s. (f)–(j) $C_s$ depending on the saddle position variables at 1, 2, 3, 4, and 5 $\pi$ rad/s.
In addition, the energy conservation percentage ($C_s$) and the ME were more affected by the cadence than the saddle position (Figure 7). That is, the change in the energy conservation percentage and the ME by the saddle position was smaller than the change by the cadence. The ME increased as the cadence accelerated. The energy conservation percentage of thigh increased as the cadence ($\omega_3$) increased up to $2\pi$ rad/s, and then decreased. The energy conservation percentage of shank increased as the cadence ($\omega_3$) increased, and the total energy conservation percentage increased as the cadence ($\omega_3$) increased up to $3\pi$ rad/s, and then decreased slightly.

By changing the saddle height ($h$) and the horizontal distance ($d$) variables, the knee angle can be changed from $21^\circ$ to $83^\circ$. The knee angle decreased with the increased saddle height ($h$) and the horizontal distance ($d$). The change in the knee angle by the saddle height ($h$) was larger than by the horizontal distance ($d$).

**Discussion**

To ensure high cycling performance, setting the saddle appropriately is necessary. The objective of this study was to investigate the pedaling efficiency depending on the saddle position ($h$ and $d$) and the cadence ($\omega_3$) in terms of the ME and energy conservation percentage ($C_s$). To this end, a biomechanical model of pedaling was used to obtain the KE, PE, ME, and the energy conservation percentage ($C_s$). Using the pedaling model, it is possible to investigate the pedaling efficiency depending on the saddle position with two degrees of freedom rather than the limited saddle position due to the designed bicycle geometry. To investigate the pedaling efficiency, the saddle position ($h$ and $d$) and the cadence ($\omega_3$) were set as variables of interest. $h$ is the saddle height in the $y$-axis, and $d$ represents the saddle position in the $x$-axis.

In this study, it was observed that there was no optimal saddle position that covers all cadences. For the low cadence ($1–3\pi$ rad/s), the ME was small when the saddle height ($h$) is high, and the horizontal distance between the saddle and crankshaft ($d$) is short. Based
on the KE and PE values obtained from the developed model, the reason that the ME decreases as the saddle height \( h \) increases is that the negative work decreases. As the saddle height \( h \) increased, the ratio of increase in the KE was larger than the increase ratio of the PE, thus the negative work and ME decreased (Figure 4(a) and (b)). The ME decreased as the horizontal distance \( d \) decreased because the ratio of the decrease in the PE is greater than that of the decrease in the KE, thus the negative work and the ME decreased (Figure 4(c) and (d)). However, at the higher cadences (4–5 \( \pi \) rad/s), the relationship between the ME and the position variables was not linear. The ME showed a U-shaped as the saddle height \( h \) increased regardless of the horizontal distance \( d \). When the saddle height \( h \) was low, the ME increased as the horizontal distance \( d \) decreased, and when the saddle height \( h \) was high, the ME decreased as the horizontal distance \( d \) decreased. For the high cadence (over 3 \( \pi \) rad/s), the ME was lowest at the saddle height \( h \) of 0.9 m and the horizontal distance \( d \) of 0.06 m. Since the change in the KE with the pedal angle \( \theta_3 \) is greater than for the low cadences, the relationship between the ME and the position variables became more complex than for the low cadence (Figure 4(c)). Both the saddle height \( h \) and the horizontal distance \( d \) affect the ME, but the effect of the saddle height \( h \) on the ME was larger than the effect of the horizontal distance \( d \), as shown by Hazrati et al.\(^\text{25}\)

The effect of the cadence on the ME was larger than the effect of the saddle position (Figure 7(b)). The pedaling efficiency was high at the low cadence because of the decreased ME. There was a slight change in the ME between the cadences of 1 and 2 \( \pi \) rad/s, however, over 2 \( \pi \) rad/s of the cadence, the change in the ME by the cadence increased exponentially. Based on the KE and PE values obtained from the developed model, the ME increased as the cadence \( (\omega_3) \) increased since the KE increased by 4, 2.25, 1.78, and 1.56 times with no change in the PE (Figure 4(e) and (f)). These findings are in line with previous studies\(^\text{26,27}\) which suggested that the scenario with the lowest pedaling cadence was the most effective since the consumed energy was lowest.

For the energy conservation percentage \( (C_s) \) depending on the saddle position variables, there was a negative correlation \( (p\text{-values} < 0.05) \) between the energy conservation percentage \( (C_s) \) and the ME regardless of the cadence (Figure 6). That is, the ME was low when the energy conservation percentage \( (C_s) \) was high (Figure 8). The correlation coefficients between the ME and the energy conservation percentage \( (C_s) \) at each cadence were \(-0.9239, -0.8967, -0.9056, -0.9012, \text{ and } -0.8894\), respectively. The high energy conservation percentage \( (C_s) \) means that the energy transfer between the segments is easy, which is in line with the study\(^\text{28}\) that indicated that the higher saddle position at 60 r/min of the cadence, the smaller the load on the knee. The research on the energy conservation percentage \( (C_s) \) is not sufficient to support this explanation as it is not clear whether the ME is negatively correlated with the energy conservation percentage \( (C_s) \) in all movements or only in the pedaling movement. However, according to the definition of the energy conservation percentage \( (C_s) \) (equation (16)), the ME and energy conservation percentage \( (C_s) \) must have a negative correlation, validating the proposed approach.

The energy conservation percentage \( (C_s) \) was also more affected by the cadence than the saddle position (Figure 7). The total energy conservation percentage \( (C_s) \) increased as the cadence \( (\omega_3) \) increased up to 3 \( \pi \) rad/s, and then decreased slightly. The energy conservation percentage was the highest when the cadence was 3 \( \pi \) rad/s (i.e. 90 r/min). Over 90 r/min,
there was a trade-off between the thigh and shank. The energy conservation percentage of the thigh decreased, however, the energy conservation percentage \( (C_s) \) of the shank increased. The energy conservation percentage \( (C_s) \) depending on the cadence did not correlate with the ME \( (p\text{-value} > 0.4) \). This result, contrary to the relationship between the ME and the energy conservation percentage \( (C_s) \) depending on the saddle position, could be explained considering the negative work. When the cadence is high, the PE is rapidly converted to the KE, thus little negative work occurs because of the rapid energy conversion. However, at the low cadence, the energy conservation percentage \( (C_s) \) was high since the considerable negative work occurs during the energy conversion process. In other studies\(^{14-16} \) which have focused on the optimal cadence, the optimal cadence was not the low cadence but between 60 and 90 r/min. The results of our study are also in line with the studies,\(^{14-16} \) suggesting that the energetically optimal cadence is not the one that was arbitrarily selected by the athletes (90 r/min). At 3 \( \pi \text{rad/s} \) (i.e. 90 r/min), the total energy conservation percentage \( (C_s) \) was higher than that under other cadence values (Figure 7(c)), which is likely why athletes preferred this cadence.

The estimated optimal saddle position in terms of the knee angle in this study was in line with the previous studies\(^{2-4} \) at the low cadence (1–3 \( \pi \text{rad/s} \)), however, not at the high cadence (4–5 \( \pi \text{rad/s} \)). They suggested that the saddle should be positioned such that the knee angle ranged from 25° to 30° since the group with that range produced a significantly lower \( VO_2 \) compared to other knee angle comparison groups.\(^{2-4} \) At the low cadence, the lowest ME position was where the saddle height \( (h) \) was 0.95 m, and the horizontal distance \( (d) \) was 0.06 m, and the knee angle was 28.85°, which was in the range from 25° to 30°. In contrast to low cadence, the lowest ME position at the high cadence (4–5 \( \pi \text{rad/s} \)) was 0.9 m for the saddle height \( (h) \), 0.06 m for the horizontal distance \( (d) \), and 48° for the knee angle. These results suggested that the optimal saddle position could be changed by the cadence. Slightly lowering the saddle position for higher cadence can increase pedaling efficiency. Since the experiment in the previous studies

\[ \text{Figure 8. Change in knee angle depending on the saddle position variables.} \]
was performed at 60–90 r/min, the pedaling efficiency was highest when the knee angle was between 25° and 30°.

This study involved some limitations. In previous experimental studies, the foot and ankle angles were considered, and thus, the energy consumption pertaining to the ankle could be calculated. In this study, the foot and ankle were not considered to simplify the model. Analyzing the pedaling process without considering the foot excludes the joint moment generated by ankle, and thus the energy used to move the foot could not be obtained. However, the energy consumption pertaining to the ankle is small and thus does not considerably influence the overall energy efficiency. The muscle power of the ankle during cycling is smaller than those of the hip and knee. Furthermore, the crank load due to the frictional load between the wheels and the ground, was not considered. In other studies, the crank load was considered as a variable, however, the changes in the energy consumption (VO₂) depending on the crank load was only in the form of ratios, and no significant crank torque changes were noted with a change in the crank load during steady-state pedaling. Therefore, when the pedaling efficiency is investigated in terms of the saddle position and cadence, the crank load does not considerably influence the pedaling efficiency.

**Conclusion**

In this study, the ME and energy conservation percentage (Cₜ) were quantified based on a pedaling model to investigate the pedaling efficiency. The effects of the saddle position and the cadence on pedaling efficiency were investigated by considering the relation among the ME, KE, PE, and energy conservation percentage (Cₜ).

The optimal saddle position could vary depending on the cadence. At the low cadence (1–3 π rad/s), the higher saddle position (h) and the shorter horizontal distance between the saddle and crankshaft (d) corresponded to higher pedaling efficiency due to the reduced ME and increased energy conservation percentage (Cₜ). The ME was lowest when the knee angle was 28°. At the high cadence (4–5 π rad/s), the pedaling efficiency was highest when the knee angle was 48° instead of 28°.

From the point of view of the total consumed energy, the pedaling efficiency was highest at a cadence of 2 π rad/s since the ME was low at 1 and 2 π rad/s and, since the change in the ME between 1 and 2 π rad/s was not significant (0.60 J). However, in terms of endurance and muscle fatigue, the pedaling efficiency was highest at the 90 r/min (i.e. 3 π rad/s) of the cadence since the energy conservation percentage (Cₜ) was highest at the 90 r/min of the cadence.

This study has limitations in that the ankle angle, the crank load, and reaction forces are not considered. For simplification of the model, the ankle joint was not considered, but the muscle power generated by the ankle is smaller than other joints and thus the ankle joint does not considerably influence the overall energy efficiency. The crank load was a less important variable in this study since the crank inertia load only changes the ratio of the consumed energy depending on the saddle position and cadence with little change in the crank torque. However, as the force and moment generated in each joint were not considered, the risk of injury was not considered.
It is expected that adjusting the saddle position in order to set the knee angle to $25^{\circ}$–$30^{\circ}$ at the low cadence, and lowering the saddle height slightly at the high cadence could increase pedaling efficiency. In addition, by maintaining the cadence at 90 r/min, the inertia load on the lower body is minimized, thereby increasing pedaling efficiency compared to other cadence.

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**Appendix 1**

**Notation**

A  hip position
B  knee position
\( C \) foot position
\( l_1 \) thigh length (0.46 m)
\( l_2 \) calf length (0.43 m)
\( \theta_1 \) thigh angle
\( \theta_2 \) knee angle
\( \theta_3 \) pedal angle
\( \omega_3 \) Pedal angular velocity, cadence
\( r \) crank arm length (0.17 m)
\( h \) height of the saddle
\( d \) horizontal distance between the crankshaft and the saddle
\( y \) height of the crankshaft (0.26 m)
\( g \) gravitational acceleration
\( \text{ME} \) mechanical energy
\( \text{KE}, T \) kinetic energy
\( \text{PE}, U \) potential energy
\( C_s \) energy conservation percentage
\( W_s \) sum of the absolute energy changes
\( W_s' \) sum of the energy changes assumed that no energy exchange occurs among any of the components

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