Apparent efficiency in the evaluation of internal work rate in cycling

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Introduction
Internal work rate (IWR) due to energy changes of body segments has been estimated based on kinematic models (Wells R et al., 1986, Widrick JJ et al., 1992, Willems PA et al., 1995, Winter DA, 1979), and in cycling has been reported to increase with increasing pedal rate (Wells R et al., 1986, Widrick JJ et al., 1992) (Figure 1). It is essential to know the size of the total work rate (external work rate (EWR)+IWR), to be able to estimate mechanical efficiency. EWR is relatively simple to measure during cycling. However, IWR is more complicated to estimate, and criteria for estimation of IWR are debated. Alternatively, muscular efficiency may be estimated as apparent efficiency and subsequently be used in evaluation of IWR estimated from various kinematic models.

Methods
Sixteen males (73.7±8.2 kg, 1.77±0.05 m) cycled with pedal rates of 61, 88, and 115 rpm on a racing bicycle placed on a motorized Woodway ELG 70 treadmill (Woodway GmbH, Weil am Rhein, Germany) at work rates resulting in workloads of 40 and 70% of the maximum oxygen uptake (VO2max) when performed at 80 rpm. EWR was adjusted by changing the mass of a weight magazine, that was connected to a wire, running over a pulley - placed behind the treadmill, and tied to the back of the bicycle. VO2 and EWR were measured with the Douglass bag technique and a SRM crank dynamometer (Schoberer Rad Messtechnich, Jülich, Germany), respectively. IWR was estimated based on 2D kinematics according to Model 1 (Willems PA et al., 1995), Model 2 (Wells R et al., 1986), Model 3 (Widrick JJ et al., 1992), and Model 4 (Winter DA, 1979), models 1 and 4 including only positive summed energy changes. Additionally, IWR was estimated from the following equation:

\[
\text{EWR+IWR} = (\text{exercise–resting} \, \text{VO2} \cdot \text{OE} \cdot \text{DE})
\]

(Equation 1)

VO2 is oxygen uptake in l•s⁻¹. Resting VO2 was set to 0.004 l•s⁻¹. OE is the oxygen energy equivalent in J•l⁻¹, determined from the respiratory exchange ratios. DE is delta efficiency, or apparent efficiency, in percent. DE was taken to express muscular efficiency for the specific type of work performed (e.g. for different contraction velocities) and was calculated as the difference in EWR at 40 and 70% VO2max divided by the corresponding increase in rate of energy expenditure.

Results & Discussion
DE was 25.0±3.3, 26.5±2.4, and 26.3±2.7% at 61, 88, and 115 rpm, respectively, and not significantly different between pedal rates. Differences in IWR between 40 and 70% VO2max with 61, 88, and 115 rpm, respectively, were within 10% for all kinematic models used as well as for Equation 1. The mean values of IWR at the two workloads are presented in Table 1 and Figure 1.
Table 1: Mean values (±standard deviation) of internal work rate (IWR) presented in W, estimated from four different kinematic models and Equation 1.

<table>
<thead>
<tr>
<th>Pedal rate (rpm)</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Equation 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>26±4</td>
<td>15±4</td>
<td>101±12</td>
<td>8±2</td>
<td>15±24</td>
</tr>
<tr>
<td>88</td>
<td>59±10</td>
<td>59±11</td>
<td>149±19</td>
<td>29±5</td>
<td>41±20</td>
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<tr>
<td>115</td>
<td>121±23</td>
<td>159±30</td>
<td>238±38</td>
<td>80±15</td>
<td>91±46</td>
</tr>
</tbody>
</table>

Figure 1: Mean values of internal work rate (IWR) presented as a function of pedal rate during cycling. The standard deviations are not shown for clarification. Note that there is a good agreement between IWR estimated from Model 2 and 3 and IWR reported by the authors initially using these kinematic models (Wells R et al., 1986 and Widrick JJ et al., 1992, respectively). Further, note that IWR estimated from Equation 1 is close to IWR estimated from Model 4 and therefore particularly supports the use of this kinematic model to estimate IWR during cycling.

There was a good agreement between IWR estimated from Model 2 and 3 and IWR reported by the authors initially using these kinematic models (Wells R et al., 1986 and Widrick JJ et al., 1992, respectively) (Figure 1). It is a novel approach to use apparent efficiency in evaluation of estimates of IWR during cycling obtained from kinematic models. This approach supports the kinematic models including only positive summed energy changes (Model 1 and 4). Model 4 assumes total energy transfer (i.e. also between legs), results in the lowest IWR, compared with Model 1-3, and comes closest to IWR estimated from Equation 1. The reason could be that eccentric muscular work during cycling is negligible, and that energy is transferred between legs via the pedals and the crank.

References