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Prediction of energy efficient pedal forces in cycling using musculoskeletal simulation models

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Abstract

A biomechanical simulation model was developed to analyze energy efficient pedal forces in cycling. With a genetic optimisation algorithm muscle activation has been optimized in order to minimize metabolic energy consumption. Results show that the established mechanical definition of the Index of Efficiency is not appropriate to quantify pedaling technique, because it is not in agreement with metabolic efficiency of the biomechanical system.

Keywords: cycling efficiency, hill type muscle model, genetic optimisation algorithm , multi body system, Index of Efficiency

1. Introduction

To improve the transfer of human power to cycling performance, technical solutions such as elliptic chain rings, pedal-crank systems with varying lengths or independent crank arms have been developed. Since the effects of these systems are small [6, 8, 11], the present mechanism with fixed crank length and circular chain rings are most commonly used in cycling. In addition to optimise the equipment it is also possible to improve the athlete's pedalling technique. The task for athlete is hereby to maximize the motive efficiency, defined as the ratio between propulsive tangential force and the total force applied to the crank shown in Fig. 1.

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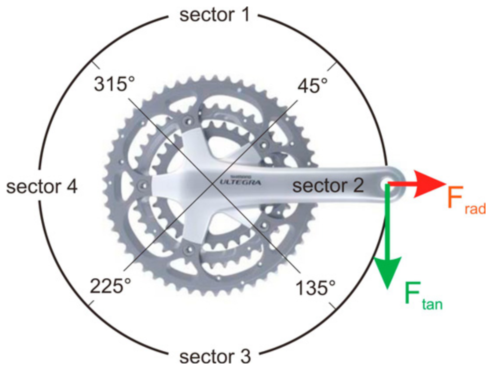

Fig. 1: Tangential and radial forces applied on the right pedal, used for the calculation of Index of Efficiency

For this purpose Davis and Hull [4] developed the Index of Efficiency (IE) to quantify the quality of pedalling technique.

$$IE = \frac{\int F_{\tan} d\varphi}{\int \sqrt{F_{\tan}{}^2 + F_{rad}{}^2} d\varphi} \quad (1)$$

It has been shown that applying optimal oriented forces to the pedal during cycling enhances power output for comparable load magnitudes [4]. However, studies on groups on high performance and recreational cyclists did not show any correlation between power output and Index of Efficiency [3, 7]. Therefore, the purpose of this study was to demonstrate that the above mechanical definition of Index of Efficiency is not in agreement with the metabolic efficiency of the biomechanical system. In particular we want to show that radial forces, even though not being effective for propulsion are important to realize efficient transfer of muscle power to cycling performance.

2. Methods

The human body model used in the simulation consists of 7 rigid bodies connected by the hip, knee, and ankle joints with one rotational degree of freedom in the sagittal plane. Segment masses, moments of inertia, and joint and center of mass locations were calculated based on regression equations [9]. The model represents a male subject with body weight and standing height of 78 kg and 183 cm. The mechanical model was driven by 8 Hill-type muscles [2] for each leg (Gluteus maximus, Illiopsoas, Vastus, Soleus and Tibialis Anterior, Hamstrings, Rectus Femoris and Gastrocnemius).

The bicycle rider system was implemented in MatLab Simulink/ Simmechanics 3.0. (Mathworks Inc, Natic, US). Muscle activation for each muscle was defined as a function of crank angle by a set of 8 control nodes per 360° interpolated with sinusoidal function [2]. This model results in 64 design parameters for optimisation. A genetic algorithm strategy (MatLab, genetic algorithm and direct search toolbox 2.4) was used to optimize muscle activation functions in order to minimize the metabolic energy consumption of all muscles. The metabolic energy consumption was calculated according to [1]. To generate constant cycling movement a few constraints had to be added. The mean crank frequency should remain with an accepted tolerance of 0.01 rad/min, while the maximum divergence from the crank frequency target should stay within borders of 0.2 rad/s.

The optimisation was carried out for a driving speed of 35 km/h, which corresponds to a driving resistance of 280 W, at a cadence of 90 U/min. The optimisation evaluated 20 generations of 750 individuals which took about 6 days CPU time on a dual-core 2200 MHz windows PC.