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JOURNAL OF SPORTS SCIENCES, 2016
http://dx.doi.org/10.1080/02640414.2016.1215490

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# Acute effects of small changes in crank length on gross efficiency and pedalling technique during submaximal cycling

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**ABSTRACT**

The main purpose of this study was to assess the acute effects of small changes in crank length (assumable by competitive cyclists) on metabolic cost and pedalling technique during submaximal cycling. Twelve amateur road cyclists performed three sets of submaximal pedalling (150, 200 and 250 W) at a constant cadence (91.3 ± 0.8 rpm) in a randomised order with three commonly used crank lengths, preferred (172.5–175 mm), +5 mm and −5 mm. Energy cost of pedalling, kinetic and kinematic variables were simultaneously registered. Changes in crank length had no significant effect on heart rate (144 ± 13, 145 ± 12 and 145 ± 13 bpm, respectively) and gross efficiency (GE) (20.4 ± 2.1, 20.1 ± 2.2 and 20.3 ± 2.4%, respectively). A longer crank induced a significant ($P < 0.05$) reduction of positive impulse proportion (PIP) (0.9–1.9%) due to a greater maximum (1.0–2.3 N · m) and minimum torque (1.0–2.2 N · m). At the same time, the maximum flexion and range of motion of the hip and knee joints were significantly increased (1.8–3.4° and $P < 0.05$), whereas the ankle joint was not affected. In conclusion, the biomechanical changes due to a longer crank did not alter the metabolic cost of pedalling, although they could have long-term adverse effects. Therefore, in case of doubt between two lengths, the shorter one might be recommended.

**ARTICLE HISTORY**
Accepted 15 July 2016

**KEYWORDS**
Cycling; crank length; biomechanics; energy expenditure

## Introduction

Previous studies have demonstrated the influence of biomechanical factors such as riding position (Garcia-Lopez et al., 2008) or saddle height (Ferrer-Roca et al., 2014; Price & Donne, 1997) on cycling performance. However, the influence of other factors such as crank length remains unclear (Macdermid & Edwards, 2010). While some studies have reported that this variable affects performance (Inbar, Dotan, Trousil, & Dvir, 1983; Klimt & Voigt, 1974; Martin & Spirduso, 2002; Too, 1990), others claim otherwise (Astrand, 1953; Barratt, Korff, Elmer, & Martin, 2011; Martin, Malina, & Spirduso, 2001; Morris & Londeree, 1997; Tomas, Ross, & Martin, 2010). Most of them have been performed in order to maximise short-term power output, with direct transference to track cycling, while only a few studies have been carried out during submaximal efforts, related to road cycling (Astrand, 1953; Klimt & Voigt, 1974; McDaniel et al; 2002; McDaniel et al; 2002; Morris & Londeree, 1997).

To date, seven experimental studies have analysed the effect of crank length on power output (supramaximal effort). Three of them pointed out that intermediate crank lengths (between 145 and 180 mm) produced higher power output compared with extreme crank lengths (<140 and >200 mm) (Inbar et al., 1983; Martin & Spirduso, 2002; Too & Landwer, 2000). Three other studies comparing cranks from 135 to 170 mm in children (Martin et al., 2001), from 120 to 220 mm (Tomas et al., 2010) and from 150 to 190 mm (Barratt et al., 2011) in well-trained cyclists did not find differences in power output. Another study was conducted with small crank length variations (170, 172.5 and 175 mm) in female cross-country mountain bikers. Crank length had no effect on maximum power output, whereas less time to reach maximum power was obtained with the shortest cranks (Macdermid & Edwards, 2010). Recent findings seem to agree that crank length does not affect maximum power output in cycling (Barratt et al., 2011; Macdermid & Edwards, 2010; Tomas et al., 2010), although they have highlighted the need to investigate small changes in crank length, assumable by experienced cyclists (Macdermid & Edwards, 2010).

From a biomechanical perspective, there is a discrepancy between the industry standard crank lengths (165, 170, 172.5 and 175 mm) and that recommended from a theoretical optimisation model, 145 mm for the average man (1.77-m height) (Hull & Gonzalez, 1988). To date, only four experimental studies analysed the influence of crank length on energy cost of cycling (Astrand, 1953; Klimt & Voigt, 1974; McDaniel, Durstine, Hand, & Martin, 2002; Morris & Londeree, 1997). One of them investigated the effect of pedalling with different crank lengths (165, 170 and 175 mm) in six well-trained cyclists (Morris & Londeree, 1997). Non-significant differences were found between the three crank lengths and the preferred length. Similar results were found on energy cost while pedalling with 160, 180

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and 200 mm crank lengths (Astrand, 1953) and riding with 145, 170 and 195 mm (McDaniel et al., 2002). Nevertheless, Klimt and Voigt (1974) found differences when comparing crank lengths from 100 to 200 mm. They recommended different optimal crank length for children of 6, 8 and 10 years old (140, 150 and 160 mm, respectively), probably due to the fact that lower limb height change with children's age. None of these four experimental studies took changes in pedalling technique (kinetic and kinematic profile) into account. This aspect could be critical because it might affect both the energy cost of cycling and lower limb muscular activity (Blake, Champoux, & Wakeling, 2012; Mileva & Turner, 2003; Theurel, Crepin, Foissac, & Temprado, 2012).

Therefore, the purpose of this study was to assess the acute effects of small changes in crank length (±5 mm) on the energy cost of cycling and pedalling technique (kinetic and kinematic profiles) during submaximal pedalling. Additionally, as a secondary purpose, the effect of the power output on these variables was analysed.

## Methods

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### *Subjects*

Twelve amateur road cyclists participated in the study (Table 1). Inclusion criteria were a minimum of 2 years competing in cycling and training volume of more than 3000 km before the study. Riders participated voluntarily and none reported any medical problem at the time of undertaking it. They were informed of the procedures, methods, benefits and possible risks involved, and written consent was obtained before starting the study. It was approved by the University Ethics Committee and met the requirements of the Declaration of Helsinki for research on human beings.

### Procedures

All cyclists were tested at the beginning of their competition season (February–March). The assessment protocol was performed in a one-day session under similar environmental conditions (20–25°C, 60–65% relative humidity). The cyclists arrived at the laboratory (800 m altitude) with their bikes after a 48-h period with no hard training. First, the cyclists' anthropometrical characteristics and bikes were measured. These measurements and the clipless pedals were matched in a cycle ergometer that allowed the crank length modification. Cyclists performed a 10-min warm-up period at a power output of 100 W, with a 5-min rest before starting the test. They used their own cycling shoes, to avoid the influence of this variable on energy cost of pedalling and the kinetic and kinematic analyses.

**Table 1.** Characteristics (mean ± SD) of the cyclists and their bicycles.

| | | Mean ± SD | Range |
|---|---|---|---|
| Cyclists | Age (year) | 20.8 ± 2.8 | 18.0–27.0 |
| | Body mass (kg) | 68.5 ± 6.6 | 57.0–79.1 |
| | Height (cm) | 176.9 ± 6.4 | 166.5–182.4 |
| | Trochanteric height (cm) | 90.3 ± 3.7 | 84.0–96.5 |
| | Inseam length (cm) | 86.7 ± 4.5 | 78.5–95.7 |
| | Cycling experience (year) | 8.1 ± 3.4 | 3.0–11.0 |
| | Training volume (km) | 4063 ± 1595 | 3000–8000 |
| Bicycles | Saddle height (cm) | 76.1 ± 3.3 | 69.5–81.5 |
| | Saddle height (% IL) | 108.0 ± 2.8 | 103.4–113.7 |
| | Saddle back (cm) | 7.5 ± 1.5 | 4.7–10.2 |
| | Crank length (mm) | 173.3 ± 1.2 | 172.5–175.0 |
| | Handlebar-D (cm) | 55.9 ± 1.9 | 52.2–58.5 |
| | Handlebar-V (cm) | 9.0 ± 1.8 | 6.5–12.0 |

See Figure 1 for the main bike measurements. % IL, percentage of inseam length.

The cyclists performed three sets of three submaximal pedalling sets (150, 200 and 250 W) with different crank lengths (preferred, 5 mm shorter, 5 mm longer) in a randomised order. Both, physiological (energy cost of pedalling) and biomechanical variables (kinematic and kinetic profiles) were simultaneously recorded. Each repetition lasted 6 min with 5-min rest in between. The recovery period between sets was 10 min, sufficient to change the seat and handlebar height in order to maintain the same distance between the top of the seat and the pedal axis and the same vertical distance between the seat and the handlebar, respectively. The riding position was standardised with the cyclists' hands on the brakes in order to avoid changes on metabolic cost due to modification of the trunk angle (Heil, Derrick, & Whittlesey, 1997).

Three power output levels (150, 200 and 250 W) were selected because they are representative of the effort in a cycling stage (Vogt et al., 2007), and allow a respiratory exchange ratio (RER) lower than 1.00, indicating no significant anaerobic contribution (Rodriguez-Marroyo et al., 2009). Additionally, riders received continuous feedback on their cadence and were asked to keep it constant at 90 rpm to avoid any possible influence of cadence on the mechanical variables of pedalling (Neptune & Herzog, 1999). The selected cadence is representative of the seated pedalling cadence during flat stages (Rodriguez-Marroyo, Garcia-Lopez, Villa, & Cordova, 2008; Vogt et al., 2006).

## Anthropometric and bicycle measurements

An anthropometric tape (Holtain LTD; Crymych, UK) and a Harpenden anthropometer (CMS instruments, London, UK) were used to measure bicycle and anthropometric dimensions (height, trochanteric height and inseam length). Inseam length was the barefoot distance between the ground and the pubis (Ferrer-Roca et al., 2014). The same experimenter performed all the measurements. Next, the main bike measurements were recorded (Figure 1) (Korff, Fletcher, Brown, & Romer, 2011). Both relative saddle height and relative crank length (expressed in percentage) were calculated by dividing the saddle height and the crank length by the inseam length (Ferrer-Roca, Roig, Galilea, & Garcia-Lopez, 2012; Martin & Spirduso, 2002), respectively. AQ9

## Kinetic analysis

Kinetic analysis was performed on a validated electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode BV, Groningen, Netherlands) (Reiser, Meyer, Kindermann, & Daugs, 2000), which allowed the

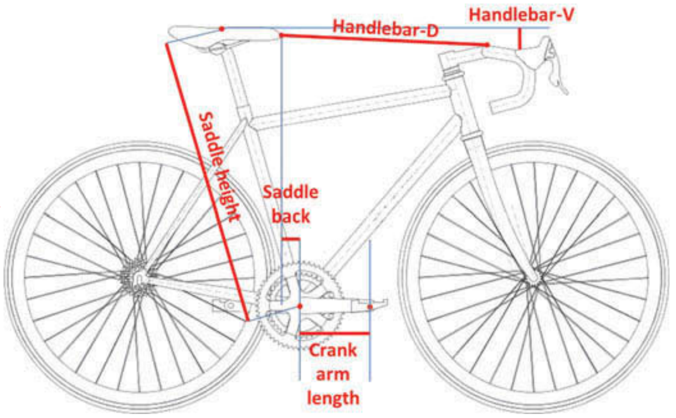

**Figure 1.** The main bike measurements: saddle height, saddle back, crank length, vertical distance between the top of the saddle and the handlebar's brake (Handlebar-V) and distance between the front of the saddle and the middle of the handlebars (Handlebar-D).

measurement of the torque exerted on the left and right cranks independently every 2° of a complete revolution (Dorel, Couturier, & Hug, 2009). Before starting the study, a dynamic calibration procedure was performed (Calibrator AQ10 2000, Lode BV, Groningen, Netherlands). The torque measurements showed a coefficient of variation of 0.96 ± 1.20% (95% of confidence interval (CI) between 0.72 and 1.19%), and an intraclass correlation coefficient of 0.999 ($P < 0.001$). Moreover, zero-offset calibration was done before each testing session. All complete 6-min intervals of the three sets of submaximal pedalling were recorded (LEM software, Lode BV, Groningen, Netherlands). For the kinetic analysis, the mean of □360 complete revolutions from minute 1 to minute 5 were selected, and values of right and left cranks were averaged (Figure 2). Pedalling rate, maximum torque and minimum torque were directly obtained from the software. Additionally, torque-time data and crank length were AQ11 exported to ASCI format to calculate the rest of the mechanical variables: positive impulse, negative impulse and the positive impulse proportion (PIP).

$$\mathrm{PIP}\ (\%) = \frac{\text{Positive Impulse}}{[\text{Positive Impulse} + |\text{Negative Impulse}|]} \times 1000$$

## Kinematic analysis

Kinematic analysis of the cyclists “right side was performed assuming symmetry of motion between left and right sides (Heil et al., 1997). Five reflective markers of 10 mm diameter were attached to the cyclists” skin (greater trochanter, lateral femoral epicondyle and lateral malleolus) and to the bikes (crank and pedal axes of rotation) (Bini, Diefenthaeler, & Mota, 2010; García-López, Díez-Leal, Ogueta-Alday, Larrazabal, & Rodríguez-Marroyo, 2015). A high-speed digital AQ12 video camera (Sony Handycam HDR-HC7, Sony Inc, Europe, 200 Hz and 720 × 576 pixels) and a floodlight were positioned 4 m away from the sagittal plane, where a calibration frame was placed (1.00 × 1.20 m). Automatic tracking, processing and analysing data were performed by a specific software (Kinescan-IBV, Version 2001, Institute of Biomechanics of Valencia, Valencia, Spain) (Garcia-Lopez et al., 2008). Six complete revolutions were analysed in minutes 2 and 4 of every trial as representative values. Sagittal hip, knee and ankle angles were determined following previous conventions (Ferrer-Roca et al., 2014). Angular position values were expressed as minimum and maximum flexion for the hip and knee joints, and plantarflexion and dorsiflexion for the ankle. The range of movement (ROM) was also determined.

## Energy cost of pedalling analysis

Oxygen uptake ($VO_2$) and RER (Medisoft Ergocard, Medisoft Group, Sorinnes, Belgium), and HR (Polar Team, Polar Electro Oy, Kempele, Finland) were continuously registered during the test, considering the average of the last 3-min period of each set as representative data (Hopker, Coleman, Jobson, & Passfield, 2012). Gross efficiency (GE) was calculated as the ratio of work accomplished (expressed in kcal · $\mathrm{min}^{-1}$) to

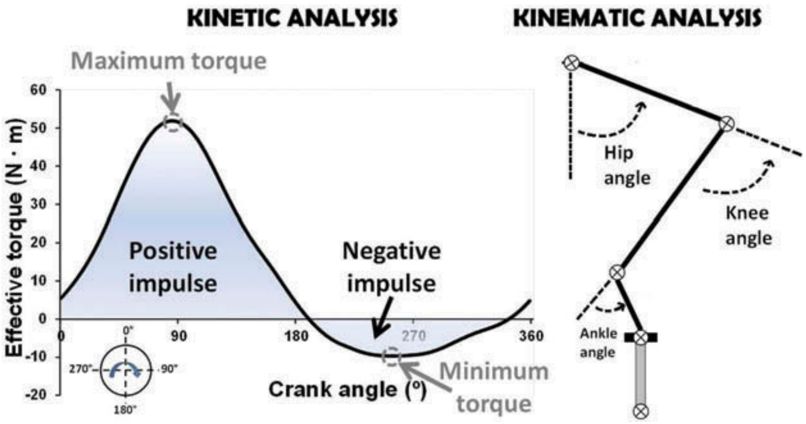

**Figure 2.** Biomechanical variables analysed during pedalling. Kinetic analysis: torque-angle profile of a complete revolution and main selected variables for analysis. Kinematic analysis: schematic illustration of reflective marker locations and definition of angles.

Table 2. Mean ± SD of the physiological variables at different power outputs (150, 200 and 250 W) and at different crank lengths (shorter, preferred and longer).

| | | Shorter crank | Preferred crank | Longer crank |
|---|---|---|---|---|
| 150 W | Cadence (rpm) | 91.4 ± 0.6 | 91.3 ± 0.7 | 91.3 ± 0.6 |
| | Heart Rate (bpm) | 129 ± 10 † ‡ | 128 ± 10 † ‡ | 128 ± 12 † ‡ |
| | Gross efficiency (%) | 18.6 ± 1.3 † ‡ | 18.4 ± 1.9 † ‡ | 18.7 ± 2.3 † ‡ |
| 200 W | Cadence (rpm) | 91.2 ± 0.9 | 91.3 ± 0.7 | 91.4 ± 0.8 |
| | Heart Rate (bpm) | 143 ± 13 † | 144 ± 13 † | 145 ± 14 † |
| | Gross efficiency (%) | 20.5 ± 1.8 † | 20.4 ± 2.0 † | 20.5 ± 2.5 † |
| 250 W | Cadence (rpm) | 91.4 ± 0.7 | 91.4 ± 1.0 | 91.4 ± 1.0 |
| | Heart Rate (bpm) | 161 ± 15 | 162 ± 13 | 162 ± 14 |
| | Gross efficiency (%) | 22.0 ± 1.9 | 21.5 ± 1.7 | 21.6 ± 1.8 |
| MEAN | Cadence (rpm) | 91.3 ± 0.7 | 91.4 ± 0.8 | 91.4 ± 0.9 |
| | Heart Rate (bpm) | 145 ± 18 | 145 ± 18 | 146 ± 19 |
| | Gross efficiency (%) | 20.8 ± 2.4 | 20.5 ± 2.3 | 20.7 ± 2.4 |

Significant difference ($P < 0.05$): Power (†150 *vs* 250 W, ‡ 150 *vs* 200 W).

Table 3. Mean ± SD of the kinetic variables at different power outputs (150, 200 and 250 W) and at different crank lengths (shorter, preferred and longer).

| | | Shorter crank | Preferred crank | Longer crank |
|---|---|---|---|---|
| 150 W | Maximum torque (N · m) | 37.2 ± 4.4 * † ‡ | 37.6 ± 4.5 † ‡ | 38.2 ± 4.5 † |
| | Minimum torque (N · m) | −13.3 ± 3.0 * † ‡ | −13.9 ± 3.4 † ‡ | −14.3 ± 3.2 † ‡ |
| | PIP (%) | 76.8 ± 3.2 * † ‡ | 76.3 ± 3.7 * † ‡ | 75.7 ± 3.5 † ‡ |
| 200 W | Maximum torque (N · m) | 44.0 ± 5.4 * # | 44.8 ± 5.3 * † | 45.7 ± 5.4 † |
| | Minimum torque (N · m) | −12.0 ± 2.9 * # † | −12.6 ± 3.1 * † | −13.1 ± 2.7 † |
| | PIP (%) | 81.4 ± 4.2 * † | 80.9 ± 4.0 † | 80.5 ± 3.7 † |
| 250 W | Maximum torque (N · m) | 49.8 ± 5.5 * | 50.4 ± 5.5 * | 52.1 ± 5.6 |
| | Minimum torque (N · m) | −9.2 ± 3.3 * # | −10.5 ± 2.3 * | −11.4 ± 2.5 |
| | PIP (%) | 86.5 ± 3.6 * # | 85.8 ± 3.3 * | 84.6 ± 3.5 |
| MEAN | Maximum torque (N · m) | 43.9 ± 7.2 * # | 44.5 ± 7.2 * | 45.5 ± 7.6 |
| | Minimum torque (N · m) | −11.4 ± 3.5 * # | −12.3 ± 3.2 * | −12.9 ± 3.0 |
| | PIP (%) | 81.7 ± 5.4 * # | 81.1 ± 5.3 * | 80.4 ± 5.0 |

PIP, positive impulse proportion. Significant difference ($P < 0.05$): crank (* with longer crank, # shorter crank *vs* preferred crank) and power (†with 250 W, ‡ 150 *vs* 200 W).

energy expended (kcal · min$^{-1}$) (Hopker et al., 2012; Rodriguez-Marroyo et al., 2009).

## Statistical analysis

The results are expressed as mean ± SD and CI 95%. SPSS+ V.17.0 statistical software was used (SPSS, Inc., Chicago, IL, USA). The Shapiro–Wilk normality test was used to assess normality. Two-way analysis of variance with repeated measures was used to analyse the effect of the crank length and power output on biomechanical and physiological variables. Newman–Keuls post hoc analysis was used to establish statistical differences between means. Effect sizes (ES) of the differences (Cohen's *d*) were also calculated. The magnitude of the differences were considered to be trivial (ES < 0.2), small (0.2 ≤ ES < 0.5), moderate (0.5 ≤ ES < 0.8), and large (ES ≥ 0.8). Values of $P < 0.05$ were considered statistically significant.

## Results

Table 1 illustrates the anthropometric and bicycle measurements of the participants. The relative preferred crank length AQ13 was 20.0 ± 1.0 % of the inseam length (IC 95% = 19.4–20.7%). Relative preferred saddle height was 108.0 ± 2.8 % of the AQ14 inseam length (IC 95% = 106.2–109.8%). The preferred crank length selected by two-third of the riders ($n$ = 8) was 172.5 mm, and the rest of the cyclists ($n$ = 4) chose a crank length of 175 mm.

Table 2 illustrates non-significant effects ($P > 0.05$) of crank length (shorter, preferred and longer) on pedalling cadence, heart rate and GE. Additionally, higher power output increased both heart rate (14–18 bpm each stage; ES = 7.00 and $P < 0.001$) and GE (1.5–1.9 % each stage; ES = 2.87 and $P < 0.001$).

Table 3 shows that a longer crank increased maximum torque (1.0–2.3 N · m, ES = 2.26 and $P < 0.001$) and decreased minimum torque (1.0–2.2 N · m, ES = 1.93 and $P < 0.001$) while PIP decreased (0.9–1.9 %, ES = 2.81 and $P < 0.001$). Additionally, higher power output increased both maximum torque (12.5–13.9 N · m, ES = 6.62 and $P < 0.001$) and PIP (8.9–9.7%, ES = 7.40 $P < 0.001$) while minimum torque increased (2.9–4.1 N · m, ES = 2.16 and $P < 0.001$).

Tables 4 and 5 illustrate that a longer crank increased both hip (1.8–2.5°, ES = 4.56 and $P < 0.001$) and knee maximum flexion (2.9–3.4°, ES = 12.21 and $P < 0.001$), while the minimum flexion were not affected ($P > 0.05$). Consequently, both hip (2.0–2.2°, ES = 4.48 and $P < 0.001$) and knee ROM increased (2.7–3.0°, ES = 7.09 and $P < 0.001$). Ankle joint kinematics was not affected by the crank length (Table 6). A high-power output decreased both hip (1.8–1.9°, ES = 2.29 and $P < 0.001$) and knee minimum flexion (2.7–3.3°, ES = 2.63 and $P < 0.001$), and, to a lesser extent, hip (1.2–1.6°, ES = 1.34 and $P < 0.01$) and knee maximum flexion decreased (0.6–0.8°, ES = 0.96 and $P < 0.05$). Consequently, both hip (0.3–0.7°, ES = 0.62 and $P < 0.05$) and knee ROM increased (2.1–2.4°, ES = 1.12 and $P < 0.001$) (Tables 4–5). A high-power output also increased ankle dorsiflexion

Table 4. Mean ± SD of the hip kinematic variables at different power outputs (150, 200 and 250 W) and at different crank lengths (shorter, preferred and longer).

| | Hip | Shorter crank | Preferred crank | Longer crank |
|---|---|---|---|---|
| 150 W | Minimum flexion (°) | 28.0 ± 3.1 † | 27.9 ± 2.8 † | 27.8 ± 2.6 † |
| | Maximum flexion (°) | 71.9 ± 2.2 * # † ‡ | 72.6 ± 2.2 * † | 73.7 ± 2.5 † |
| | ROM (°) | 43.9 ± 2.7 * # | 44.7 ± 2.6 * ‡ | 45.9 ± 2.7 |
| **200 W** | Minimum flexion (°) | 26.4 ± 2.8 † | 26.4 ± 3.2 † | 26.7 ± 3.3 † ‡ |
| | Maximum flexion (°) | 70.9 ± 2.4 * # † | 72.1 ± 2.4 * † | 73.4 ± 1.8 † |
| | ROM (°) | 44.5 ± 2.3 * # | 45.6 ± 2.8 * | 46.7 ± 2.6 |
| **250 W** | Minimum flexion (°) | 26.1 ± 3.1 | 26.0 ± 3.3 | 26.0 ± 3.0 |
| | Maximum Flexion (°) | 70.3 ± 2.2 * # | 71.4 ± 2.4 * | 72.4 ± 2.3 |
| | ROM (°) | 44.2 ± 2.7 * # | 45.4 ± 2.6 * | 46.3 ± 2.5 |
| **MEAN** | Minimum flexion (°) | 26.8 ± 3.0 | 26.8 ± 3.0 | 26.8 ± 3.0 |
| | Maximum flexion (°) | 71.0 ± 2.3 * # | 72.0 ± 2.3 * | 73.1 ± 2.2 |
| | ROM (°) | 44.2 ± 2.5 * # | 45.3 ± 2.6 * | 46.3 ± 2.6 |

ROM, range of movement. Significant difference ($P < 0.05$): crank (* with longer crank, # shorter crank *vs* preferred crank) and power († with 250 W, ‡ 150 *vs* 200 W)

Table 5. Mean ± SD of the knee kinematic variables at different power outputs (150, 200 and 250 W) and at different crank lengths (shorter, preferred and longer).

| | Knee | Shorter crank | Preferred crank | Longer crank |
|---|---|---|---|---|
| 150 W | Minimum flexion (°) | 36.9 ± 4.2 † ‡ | 37 ± 3.6 † ‡ | 36.8 ± 3.5 † ‡ |
| | Maximum flexion (°) | 109.5 ± 2.3 * # † | 110.8 ± 2.2 * † | 112.4 ± 2.2 |
| | ROM (°) | 72.6 ± 3.9 * # † ‡ | 73.8 ± 3.5 * † ‡ | 75.5 ± 3.6 † ‡ |
| **200 W** | Minimum flexion (°) | 34.6 ± 4.1 † | 34.8 ± 4.2 † | 35.0 ± 4.6 † |
| | Maximum flexion (°) | 108.6 ± 2.3 * # | 110.3 ± 2.1 * | 112.0 ± 2.0 |
| | ROM (°) | 74.0 ± 3.8 * # † | 75.5 ± 3.9 * | 77.0 ± 4.2 † |
| **250 W** | Minimum flexion (°) | 33.8 ± 4.7 | 33.7 ± 4.8 | 34.1 ± 4.2 |
| | Maximum flexion (°) | 108.7 ± 2.1 * # | 110.0 ± 2.2 * | 111.8 ± 2.3 |
| | ROM (°) | 74.9 ± 4.4 * # | 76.3 ± 4.5 * | 77.6 ± 4.5 |
| **MEAN** | Minimum flexion (°) | 35.1 ± 4.4 | 35.1 ± 4.4 | 35.3 ± 4.2 |
| | Maximum flexion (°) | 109.0 ± 2.2 * # | 110.3 ± 2.1 * | 112.0 ± 2.1 |
| | ROM (°) | 73.9 ± 4.0 * # | 75.3 ± 4.0 * | 76.7 ± 4.1 |

ROM, range of movement. Significant difference ($P < 0.05$): crank (* with longer crank, # shorter crank *vs* preferred crank) and power († with 250 W, ‡ 150 *vs* 200 W)

Table 6. Mean ± SD of the ankle kinematic variables at different power outputs (150, 200 and 250 W) and at different crank lengths (shorter, preferred and longer).

| | Ankle | Shorter crank | Preferred crank | Longer crank |
|---|---|---|---|---|
| 150 W | Plantar flexion (°) | 43.2 ± 5.8 | 43.2 ± 5.4 | 43.0 ± 4.9 |
| | Dorsiflexion (°) | 61.1 ± 7.0 † | 61.6 ± 7.0 † | 61.7 ± 7.8 |
| | ROM | 17.9 ± 4.1 † | 18.4 ± 4.0 | 18.8 ± 5.3 |
| **200 W** | Plantar flexion (°) | 44.4 ± 5.6 | 44.4 ± 6.5 | 44.3 ± 5.8 |
| | Dorsiflexion (°) | 62.1 ± 7.6 † | 62.2 ± 8.5 | 62.3 ± 6.9 |
| | ROM | 17.7 ± 4.0 | 17.9 ± 4.4 | 18.0 ± 3.6 |
| **250 W** | Plantar flexion (°) | 44.9 ± 5.0 | 44.9 ± 5.1 | 45.1 ± 5.4 |
| | Dorsiflexion (°) | 64.2 ± 6.8 | 64.2 ± 6.8 | 64.3 ± 7.5 |
| | ROM | 19.3 ± 3.8 | 19.3 ± 4.6 | 19.2 ± 4.8 |
| **MEAN** | Plantar flexion (°) | 44.2 ± 5.4 | 44.2 ± 5.6 | 44.1 ± 5.3 |
| | Dorsiflexion (°) | 62.5 ± 7.1 | 62.7 ± 7.3 | 62.8 ± 7.2 |
| | ROM | 18.3 ± 3.9 | 18.5 ± 4.2 | 18.7 ± 4.5 |

ROM, range of movement. Significant difference ($P < 0.05$): crank (* with longer crank, # shorter crank *vs* preferred crank) and power († with 250 W, ‡ 150 *vs* 200 W)

(2.6–3.1°, ES = 0.76 and $P < 0.05$) and ankle ROM (0.4–1.3°, ES = 0.57 and $P < 0.05$) (Table 6). No significant combined effects of crank length and power output were found.

## Discussion

The main outcome of this study was that small changes in crank length at submaximal intensity and at constant cadence did not produce significant changes in the energy cost of cycling, whereas significant changes on biomechanical variables (kinetics and kinematics) were obtained. A longer crank slightly increased positive torque during the downstroke and decreased negative torque during the upstroke, decreasing the PIP. Moreover, the maximum flexion and the range of motion of both hip and knee increased, while the ankle joint was not affected. These findings reinforce the idea that kinetic changes do not have to be associated with metabolic changes (Korff, Romer, Mayhew, & Martin, 2007). Furthermore, kinematic and kinetic changes due to a longer crank were not significant enough to alter the efficiency of energy consumption (Ferrer-Roca et al., 2014). However, further research should evaluate long-term effects of longer cranks on muscle coordinative pattern and overuse injuries.

The anthropometric characteristics (height and weight) and cycling experience (8.1 ± 3.4 years) of the riders (Table 1) were similar to those reported in previous studies involving amateur cyclists (Ferrer-Roca et al., 2012). Mean crank length (173.3 mm) was consistent with the optimum length (20% of the inseam length) described in previous studies (Martin & Spirduso, 2002).

## Effects of the changes in crank length

In the present study, changes in crank length had no significant effect on the physiological variables. The metabolic cost was similar when pedalling at the same cadence with the three crank lengths (Table 2). These results were consistent with three of the four previous submaximal studies, which did not find differences between crank lengths from 160 to 200 mm (Astrand, 1953), from 165 to 175 mm (Morris & Londeree, 1997) and from 145 to 195 mm (McDaniel et al., 2002), regardless of the commonly used crank length by the riders. On the other hand, the only study that pointed out differences in metabolic cost due to changes in crank lengths was performed with children from 6 to 10 years old (Klimt & Voigt, 1974). On the basis of the results obtained in the present research and the previous studies, the stronger scientific evidence is in favour of the non-influence of changes in crank length on energy cost of pedalling in trained adults.

Changes in crank length affected kinetic variables, increasing positive and decreasing negative torques and the PIP (Table 3). This might be due to the fact that the crank torque is negative between ~210 and 330° of the crank cycle during seated pedalling (Korff et al., 2007) and a longer crank length decreases the negative torque, which needs to be compensated with a greater positive torque in order to maintain the same power output. Furthermore, these differences had no effect on GE, which is consistent with other studies that demonstrated no correspondence between pedal force effectiveness and energy cost of pedalling (Korff et al., 2007; Mornieux, Stapelfeldt, Gollhofer, & Belli, 2008; Theurel et al., 2012). Nevertheless, these biomechanical changes should have important effects on muscle coordinative pattern. In fact, a previous study carried out with non-cyclists demonstrated that a longer crank (195 *vs* 155 mm) decreased significantly the EMG amplitude of the biceps femoris, while tibialis anterior and soleus increased, with no change in rectus femoris (Mileva & Turner, 2003). Moreover, other studies highlighted that muscle fatigue could be reduced by decreasing the activity of the main leg extensor muscles during downstroke (i.e., vastus lateralis and rectus femoris as knee extensor) and increasing the activity of the main leg flexor muscles during upstroke (i.e., rectus femoris as hip flexor, biceps femoris and tibialis anterior) (Mornieux et al., 2008; Takaishi, Yamamoto, Ono, Ito, & Moritani, 1998; Theurel et al., 2012). Further research should investigate modifications of the muscle coordinative patterns due to changes in crank length in trained cyclists, meanwhile pedalling at representative intensities and cadences (i.e., 200–300 W and ~90–100 rpm).

Furthermore, the minimum flexion angle of the hip, knee and ankle joints were similar when pedalling with the different crank lengths (Table 4), which was probably due to the modification of the saddle height in order to maintain the same seat–pedal distance at the bottom point of the pedalling cycle (Barratt et al., 2011). This setting was not considered in some previous studies, and could be the reason why they found a decrease in the minimum knee flexion due to a longer crank (Mileva & Turner, 2003). In the present study, crank lengthening resulted in an increase of the maximum flexion and the ROM at hip and knee joints, whereas the ankle joint was not affected. These results are entirely consistent with those observed in previous studies on supramaximal pedalling (Barratt et al., 2011; Too & Landwer, 2000). However, kinematic changes were not significant enough to alter the energy cost of pedalling, possibly because these changes were smaller (1.8–3.4°) compared with those reported in other studies with wider crank length modifications (4–14° every ~35 mm of crank length) (Too & Landwer, 2000). Moreover, crank lengthening resulted in a greater maximum flexion of hip (lower than 20°) and knee (lower than 70°) than those obtained in earlier studies (Carpes, Dagnese, Mota, & Stefanyshyn, 2009; Ferrer-Roca et al., 2012; García-López et al., 2015; Price & Donne, 1997), and was opposite to the natural behaviour of these joints when pedalling power increases (as it is explained below). The increase in knee flexion has been related to patellofemoral compression force (Bini, Tamborindeguy, & Mota, 2010), and pedalling with cranks that are too long has been associated with anterior knee pain (Asplund & Pierre, 2004) which is one of the most prevalent overuse injuries and causes loss of training time (Clarsen, Krosshaug, & Bahr, 2010). Further studies should evaluate the long-term effect of pedalling with excessive crank length in relation to overuse injuries.

## Effects of the power output increase

Logically, the power output increased the metabolic cost and heart rate (Table 2). In line with previous studies performed with amateur cyclists, GE also increased from 18.4–18.7% at 150 W to 21.5–22.0% at 250 W (Chavarren & Calbet, 1999). More recently, studies have showed that GE increases up to 50% of the maximum aerobic power in an incremental test, and is unchanged from this point on (de Koning, Noordhof, Lucia, & Foster, 2012). Unfortunately, the present study did not measure the maximum aerobic power of the cyclists. Nevertheless, 10 of the 12 riders were able to perform a pedalling exercise at 300 W (with the three crank lengths), obtaining similar results ($P > 0.05$) to 250 W (21.8–22.3% *vs* 21.5–22.0%, respectively). These data were not finally included in the analysis because two cyclists were not able to finish the set at 300 W, and another four cyclists showed a RER higher than 1.0 (i.e., GE should not be calculated from this value).

The increase in power output also affected biomechanical variables (Tables 3–6). The maximum torque during downstroke increased while the torque values during upstroke were less negative, causing better PIP as power output increased (Table 3). These results were in line with previous studies where the main effect of increasing power output at constant cadence was an increase in maximum torque during the downstroke (Sanderson, 1991; Sanderson, Hennig, & Black, 2000) and a reduction in minimum torque during the upstroke (Rossato, Bini, Carpes, Diefenthaeler, & Moro, 2008). In fact, "the capacity to produce propulsive torque during the recovery phase reflects the ability of the cyclists at least to support the contralateral segment weight during the recovery phase" (Rossato et al., 2008). This effect has recently been described as a strategy to delay fatigue in the knee extensor muscles, implying greater activation of the knee flexor muscles in the contralateral lower limb (Theurel et al., 2012). In the present study, the natural behaviour of the upstroke forces when power output increased was contrary to the effects of a longest crank, especially at 250 W, possibly because riders performed their best potential (Sanderson et al., 2000), as well as the best GE.

The kinematic variables were also affected by the power increase (Tables 4–6). In line with early studies, the minimum flexion at hip and knee joints decreased (Bini & Diefenthaeler, 2010), whereas the maximum flexion did not decrease proportionally, so their ROM also increased. This kinematic profile has been described as an adaptation of professional cyclists developing higher power output than amateur ones (García-López et al., 2015). Furthermore, in the present study, the range of motion of the ankle was always less than 20°, whereas in early studies, elite cyclists showed values higher than 20°, considering the ankle kinematics as a critical factor between cyclists of different level (Chapman, Vicenzino, Blanch, & Hodges, 2009). In a previous study, changes in crank length were followed by specific adaptation of the activity of the muscles of the knee and ankle joints (Mileva & Turner, 2003). Maybe, the kinematic changes of the present study come from the activation of the tibialis anterior to keep the ankle dorsiflexed across the top dead centre. This could provide a more stable platform to transfer power to the pedal and a greater activation of the gluteus maximus (hip extensor), which is considered one of the main factors in reaching a higher power output (Blake et al., 2012). Further EMG studies should confirm this hypothesis.

The main limitation of the present study was not having performed an incremental maximal test on a separate day. For this reason, the workout of the riders at different power outputs (150, 200 and 250 W) could not be characterised in terms of relative intensity of $VO_{2max}$. However, previous studies highlighted that biomechanical variables should be analysed at the same absolute power output (e.g., 200 W) instead of the relative one (e.g., 70% of $VO_{2max}$ or $3\ W \cdot kg^{-1}$) in order to properly understand their behaviour (García-López et al., 2015; Leirdal & Ettema, 2011). Another limitation of the study was the small number of cyclists who participated. A larger sample would have allowed us to calculate the correlations between biomechanical and physiological variables. Similarly, if riders of different competitive levels had been analysed, it would have been possible to investigate the possible influence of this factor together with the crank length on the physiological and biomechanical variables. Further studies should address these limitations.

## Conclusions

This is the first study to simultaneously analyse the effects that small changes in crank length (±5 mm) have on biomechanical and physiological variables during submaximal pedalling. These small changes have no effect on energy cost of pedalling, which is consistent with most previous studies with major changes in crank length. However, changes on the pedalling biomechanics were observed due to the increase of the crank length, and several of them were opposite to the natural behaviour when pedalling power increased. A longer crank length causes loss of PIP due to a high positive crank torque applied during the downstroke in order to compensate the high negative crank torque applied during the upstroke. Furthermore, crank lengthening resulted in an increase of the flexion and the ROM at hip and knee joints, which could have long-term effects related with patellofemoral compression forces and changes on muscle coordinative pattern during distance events. Due to the fact that manufacturers offer a narrow range of crank lengths (i.e., 165, 170, 172.5 and 175 mm), in case of doubt between two lengths, the shorter one might be recommended. Further studies should analyse long-term effects of different crank lengths on muscle coordinative pattern in trained cyclists and their relationship with overuse injuries.

## Acknowledgements

The authors would like to thank the cyclists who participated in this study for their collaboration. We are indebted to Raúl Pernía, José Alberto Caveda and Alejandro Bartol for their aid during the study. This work has been supported by the Spanish Council of Sports (CSD) (12/UPB10/07), Spain. Thanks also to the Basque Government for supporting this research project with a predoctoral grant (2011–14). The authors have no conflicts of interest to disclose. AQ16

## Disclosure statement

No potential conflict of interest was reported by the authors. AQ17

## Funding

This work was supported by the Spanish Council of Sports (CSD); [12/UPB10/07].

## References

Asplund, C., & Pierre, P. S. (2004). Knee pain and bicycling. *The Physician and Sportsmedicine*, *32*(4), 23–30. doi:10.3810/psm.2004.04.201 AQ18

Astrand, P. O. (1953). Study of bicycle modifications using a motor driven treadmill-bicycle ergometer. *Arbeitsphysiologie*, *15*(1), 23–32.

Barratt, P. R., Korff, T., Elmer, S. J., & Martin, J. C. (2011). Effect of crank length on joint-specific power during maximal cycling. *Medicine and Science in Sports and Exercise*, *43*(9), 1689–1697. doi:10.1249/MSS.0b013e3182125e96

Bini, R., Diefenthaeler, F., & Mota, C. (2010). Fatigue effects on the coordinative pattern during cycling: Kinetics and kinematics evaluation. *Journal of Electromyography & Kinesiology*, *20*(1), 102–107. doi:10.1016/j.jelekin.2008.10.003

Bini, R., Tamborindeguy, A., & Mota, C. (2010). Effects of saddle height, pedaling cadence, and workload on joint kinetics and kinematics during cycling. *Journal of Sport Rehabilitation*, *19*(3), 301–314.

Bini, R. R., & Diefenthaeler, F. (2010). Kinetics and kinematics analysis of incremental cycling to exhaustion. *Sports Biomechanics*, *9*(4), 223–235. doi:10.1080/14763141.2010.540672

Blake, O. M., Champoux, Y., & Wakeling, J. M. (2012). Muscle coordination patterns for efficient cycling. *Medicine and Science in Sports and Exercises*, *44*(5), 926–938. doi:10.1249/MSS.0b013e3182404d4b

Carpes, F. P., Dagnese, F., Mota, C. B., & Stefanyshyn, D. J. (2009). Cycling with noncircular chainring system changes the three-dimensional kinematics of the lower limbs. *Sports Biomechanics*, *8*(4), 275–283. doi:10.1080/14763140903414409

Chapman, A., Vicenzino, B., Blanch, P., & Hodges, P. (2009). Do differences in muscle recruitment between novice and elite cyclists reflect different movement patterns or less skilled muscle recruitment? *Journal of Science and Medicine in Sport*, *12*(1), 31–34. doi:10.1016/j.jsams.2007.08.012

Chavarren, J., & Calbet, J. A. (1999). Cycling efficiency and pedalling frequency in road cyclists. *European Journal of Applied Physiology & Occupational Physiology*, *80*(6), 555–563. doi:10.1007/s004210050634

Clarsen, B., Krosshaug, T., & Bahr, R. (2010). Overuse injuries in professional road cyclists. *The American Journal of Sports Medicine*, *38*(12), 2494–2501. doi:10.1177/0363546510376816

de Koning, J. J., Noordhof, D. A., Lucia, A., & Foster, C. (2012). Factors affecting gross efficiency in cycling. *International Journal of Sports Medicine*, *33*(11), 880–885. doi:10.1055/s-00000028

Dorel, S., Couturier, A., & Hug, F. (2009). Influence of different racing positions on mechanical and electromyographic patterns during pedalling. *Scandinavian Journal of Medicine & Science in Sports*, *19*(1), 44–54. doi:10.1111/j.1600-0838.2007.00765.x

Ferrer-Roca, V., Bescos, R., Roig, A., Galilea, P., Valero, O., & Garcia-Lopez, J. (2014). Acute effects of small changes in bicycle saddle height on gross efficiency and lower limb kinematics. *The Journal of Strength and Conditioning Research*, *28*(3), 784–791. doi:10.1519/JSC.0b013e3182a1f1a9

Ferrer-Roca, V., Roig, A., Galilea, P., & Garcia-Lopez, J. (2012). Influence of saddle height on lower limb kinematics in well-trained cyclists: Static vs. Dynamic evaluation in bike fitting. *The Journal of Strength and Conditioning Research*, *26*(11), 3025–3029. doi:10.1519/JSC.0b013e318245c09d

García-López, J., Díez-Leal, S., Ogueta-Alday, A., Larrazabal, J., & Rodríguez-Marroyo, J. A. (2015). Mechanical efficiency between cyclists of different competition level. *Journal of Sports Sciences*, *24*, 1–8.

Garcia-Lopez, J., Rodriguez-Marroyo, J. A., Juneau, C. E., Peleteiro, J., Martinez, A. C., & Villa, J. G. (2008). Reference values and improvement of aerodynamic drag in professional cyclists. *Journal of Sports Sciences*, *26*(3), 277–286. doi:10.1080/02640410701501697

Heil, D. P., Derrick, T. R., & Whittlesey, S. (1997). The relationship between preferred and optimal positioning during submaximal cycle ergometry. *European Journal of Applied Physiology and Occupational Physiology*, *75*(2), 160–165. doi:10.1007/s004210050141

Hopker, J., Coleman, D., Jobson, S. A., & Passfield, L. (2012). Inverse relationship between VO2max and gross efficiency. *International Journal of Sports Medicine*, *33*(10), 789–794. doi:10.1055/s-0032-1304640

Hull, M. L., & Gonzalez, H. (1988). Bivariate optimization of pedalling rate and crank arm length in cycling. *Journal of Biomechanics*, *21*(10), 839–849. doi:10.1016/0021-9290(88)90016-4

Inbar, O., Dotan, R., Trousil, T., & Dvir, Z. (1983). The effect of bicycle crank-length variation upon power performance. *Ergonomics*, *26*(12), 1139–1146. doi:10.1080/00140138308963449

Klimt, F., & Voigt, G. B. (1974). Studies for the standardisations of the pedal frequency and the crank length at the work on the bicycle-ergometer in children between 6 and 10 years of age. *European Journal of Applied Physiology*, *33*(4), 315–326. doi:10.1007/BF00430239

Korff, T., Fletcher, G., Brown, D., & Romer, L. M. (2011). Effect of "Pose" cycling on efficiency and pedaling mechanics. *European Journal of Applied Physiology*, *111*(6), 1177–1186. doi:10.1007/s00421-010-1745-7

Korff, T., Romer, L. M., Mayhew, I., & Martin, J. C. (2007). Effect of pedaling technique on mechanical effectiveness and efficiency in cyclists. *Medicine and Science in Sports and Exercises*, *39*(6), 991–995. doi:10.1249/mss.0b013e318043a235

Leirdal, S., & Ettema, G. (2011). Pedaling technique and energy cost in cycling. *Medicine and Science in Sports and Exercises*, *43*(4), 701–705. doi:10.1249/MSS.0b013e3181f6b7ea

Macdermid, P. W., & Edwards, A. M. (2010). Influence of crank length on cycle ergometry performance of well-trained female cross-country mountain bike athletes. *European Journal Of Applied Physiology*, *108*(1), 177–182. doi:10.1007/s00421-009-1197-0

Martin, J. C., Malina, R. M., & Spirduso, W. W. (2001). Effects of crank length on maximal cycling power and optimal pedaling rate of boys aged 8-11 years. *European Journal of Applied Physiology*, *86*(3), 215–217. doi:10.1007/s00421-001-0525-9

Martin, J. C., & Spirduso, W. W. (2002). Determinants of maximal cycling power: Crank length, pedaling rate and pedal speed. *European Journal of Applied Physiology*, *84*(5), 413–418. doi:10.1007/s004210100400

McDaniel, J., Durstine, J. L., Hand, G. A., & Martin, J. C. (2002). Determinants of metabolic cost during submaximal cycling. *Journal of Applied Physiology*, *93*(3), 823–828. doi:10.1152/japplphysiol.00982.2001

Mileva, K., & Turner, D. (2003). Neuromuscular and biomechanical coupling in human cycling: Adaptations to changes in crank length. *Experimental Brain Research*, *152*(3), 393–403. doi:10.1007/s00221-003-1561-y

Mornieux, G., Stapelfeldt, B., Gollhofer, A., & Belli, A. (2008). Effects of pedal type and pull-up action during cycling. *International Journal of Sports Medicine*, *29*(10), 817–822. doi:10.1055/s-2008-1038374

Morris, D. M., & Londeree, B. R. (1997). The effects of bicycle crank arm length on oxygen consumption. *Canadian Journal of Applied Physiology*, *22*(5), 429–438. doi:10.1139/h97-027

Neptune, R. R., & Herzog, W. (1999). The association between negative muscle work and pedaling rate. *Journal of Biomechanics*, *32*(10), 1021–1026. doi:10.1016/S0021-9290(99)00100-1

Price, D., & Donne, B. (1997). Effect of variation in seat tube angle at different seat heights on submaximal cycling performance in man. *Journal of Sports Sciences*, *15*(4), 395–402. doi:10.1080/026404197367182

Reiser, M., Meyer, T., Kindermann, W., & Daugs, R. (2000). Transferability of workload measurements between three different types of ergometer. *European Journal Of Applied Physiology*, *82*(3), 245–249. doi:10.1007/s004210050678

Rodriguez-Marroyo, J. A., Garcia Lopez, J., Avila, C., Jimenez, F., Cordova, A., & Villa Vicente, J. G. (2003). Intensity of exercise according to topography in professional cyclists. *Medicine and Science in Sports Exercise*, *35*(7), 1209–1215. doi:10.1249/01.MSS.0000074562.64053.4F AQ19

Rodriguez-Marroyo, J. A., Garcia-Lopez, J., Chamari, K., Cordova, A., Hue, O., & Villa, J. G. (2009). The rotor pedaling system improves anaerobic but not aerobic cycling performance in professional cyclists. *European Journal of Applied Physiology*, *106*(1), 87–94. doi:10.1007/s00421-009-0993-x

Rodriguez-Marroyo, J. A., Garcia-Lopez, J., Villa, J. G., & Cordova, A. (2008). Adaptation of pedaling rate of professional cyclist in mountain passes. *European Journal of Applied Physiology*, *103*(5), 515–522. doi:10.1007/s00421-008-0745-3

Rossato, M., Bini, R. R., Carpes, F. P., Diefenthaeler, F., & Moro, A. R. P. (2008). Cadence and workload effects on pedaling technique of well-trained cyclists. *International Journal of Sports Medicine*, *29*(9), 746–752. doi:10.1055/s-2008-1038375

Sanderson, D. J. (1991). The influence of cadence and power output on the biomechanics of force application during steady-rate cycling in competitive and recreational cyclists. *Journal of Sports Sciences*, *9*(2), 191–203. doi:10.1080/02640419108729880

Sanderson, D. J., Hennig, E. M., & Black, A. H. (2000). The influence of cadence and power output on force application and in-shoe pressure distribution during cycling by competitive and recreational cyclists. *Journal of Sports Sciences*, *18*(3), 173–181. doi:10.1080/026404100365072

Takaishi, T., Yamamoto, T., Ono, T., Ito, T., & Moritani, T. (1998). Neuromuscular, metabolic, and kinetic adaptations for skilled pedaling performance in cyclists. *Medicine & Science in Sports & Exercise*, *30*(3), 442–449. doi:10.1097/00005768-199803000-00016

Theurel, J., Crepin, M., Foissac, M., & Temprado, J. J. (2012). Effects of different pedalling techniques on muscle fatigue and mechanical efficiency during prolonged cycling. *Scandinavian Journal of Medicine and Science in Sports*, *22*(6), 714–721. doi:10.1111/j.1600-0838.2011.01313.x

Tomas, A., Ross, E. Z., & Martin, J. C. (2010). Fatigue during maximal sprint cycling: Unique role of cumulative contraction cycles. *Medicine and Science in Sports and Exercices*, *42*(7), 1364–1369. doi:10.1249/MSS.0b013e3181cae2ce

Too, D. (1990). Biomechanics of cycling and factors affecting performance. *Sports Medicine*, *10*(5), 286–302. doi:10.2165/00007256-199010050-00002

Too, D. (1991). The effect of hip position/configuration on anaerobic power and capacity in cycling. *International Journal of Sport Biomechanics*, *7*(4), 359–370. AQ20

Too, D., & Landwer, G. E. (2000). The effect of pedal crank arm length on joint angle and power production in upright cycle ergometry. *Journal of Sports Sciences*, *18*(3), 153–161. doi:10.1080/026404100365054

Vogt, S., Heinrich, L., Schumacher, Y., Blum, A., Roecker, K., Dickhuth, H. H., & Schmid, A. (2006). Power output during stage racing in professional road cycling. *Medicine & Science in Sports & Exercise*, *38*(1), 147–153. doi:10.1249/01.mss.0000183196.63081.6a

Vogt, S., Schumacher, Y. O., Roecker, K., Dickhuth, -H.-H., Schoberer, U., Schmid, A., & Heinrich, L. (2007). Power output during the Tour de France. *International Journal of Sports Medicine*, *28*(9), 756–761. doi:10.1055/s-2007-964982