Is a joint moment-based cost function associated with preferred cycling cadence?

Anthony P. Marsh\textsuperscript{a, \textastern}, Philip E. Martin\textsuperscript{b}, David J. Sanderson\textsuperscript{c}

\textsuperscript{a}Department of Health and Exercise Science, Wake Forest University, P.O. Box 7868, Reynolda Station, Winston-Salem, NC 27109-7868, USA  
\textsuperscript{b}Exercise and Sport Research Institute, Arizona State University, Tempe, AZ 85287-0404, USA  
\textsuperscript{c}School of Human Kinetics, University of British Columbia, Vancouver, Canada V6T 1Z1

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Abstract

Eight experienced male cyclists (C), eight well-trained male runners (R), and eight less-trained male noncyclists (LT) were tested under multiple cadence and power output conditions to determine: (1) if the cadence at which lower extremity net joint moments are minimized (cost function cadence) was associated with preferred pedaling cadence (PC), (2) if the cost function cadence increased with increases in power output, and (3) if the association is generalizable across groups differing in cycling experience and aerobic power. Net joint moments at the hip, knee, and ankle were computed from video records and pedal reaction force data using 2-D inverse dynamics. The sum of the average absolute hip, knee, and ankle joint moments defined a cost function at each power output and cadence and provided the basis for prediction of the cadence which minimized net joint moments for each subject at each power output. The cost function cadence was not statistically different from the PC at each power output in all groups. As power output increased, however, the cost function cadence increased for all three subject groups (86 rpm at 100 W, 93 rpm at 150 W, 98 rpm at 200 W, and 96 rpm at 250 W). PC showed little change (R) or a modest decline (C, LT) with increasing power output. Based upon the similarity in the mean data but different trends in the cost function cadence and PC in response to changes in power output as well as the lack of significant correlations between these two variables, it was concluded that minimizing net joint moments is a factor modestly associated with preferred cadence selection.

Keywords: Bicycling; Cadence; Joint moments; Optimization; Inverse dynamics

1. Introduction

Pedaling cadence is widely accepted as an important factor affecting cycling performance, although it is not clear how selected biomechanical factors may play a role in the determination of preferred cadence. Lower extremity net joint moments, assumed to be indirect markers of muscular effort, have been proposed as a biomechanical factor associated with preferred pedaling cadence (e.g., Hull and Jorge, 1985; Redfield and Hull, 1986; Kautz and Hull, 1995). Hull and colleagues (Redfield and Hull, 1986; Hull and Gonzalez, 1988; Hull et al., 1988) demonstrated that mechanical cost functions based on the sums of either the absolute or squared joint moments are minimized in the range of 90–105 rpm. Redfield and Hull (1986) speculated that the mechanical cost function would be minimized at higher cadences as power output increased. This was supported in a subsequent modeling study by Hull and Gonzalez (1988).

Although Hull and colleagues have suggested that minimization of mechanical factors (e.g., muscle moments, muscle stresses) is associated with preferred cadence, these associations have not been demonstrated empirically. McLean and LaFortune (1991) determined the cadences at which different combinations of the lower extremity net joint moments were minimized in 10 experienced cyclists and observed that a cost function based only on knee torque was minimized at a cadence not statistically different from the cadence at which gross mechanical efficiency (i.e., work accomplished/energy expended) was maximized (80.4 vs. 81.3 rpm, respectively). However, they did not measure preferred cadence nor vary power output in order to examine the consistency of the association as exercise intensity changed. Thus, no previous research has reported contrasts of
actual preferred cadences with experimentally-determined cadences that minimize a particular mechanical or muscular cost function at a range of power outputs.

In order to examine the utility and generalizability of a moment-based cost function as a possible determinant of preferred cadence, we examined the association between such a cost function and preferred cadences of three subject groups (experienced cyclists, highly fit runners, and less-trained noncyclists) differing substantially in cycling experience and fitness level. One might speculate that experienced cyclists pedal with lower muscular effort at a given power output, and display different cost function cadences and different preferred cadences compared to noncyclists. For example, Marsh and Martin (1995) reported lower average soleus and medial gastrocnemius EMG for experienced cyclists compared with noncyclists at fixed cadences and power output. Also we have recently shown that a group of less-fit individuals preferred lower cadences at the same absolute power output compared to high fit experienced cyclists and runners (Marsh and Martin, 1997). The purpose of our study was to test the hypotheses that: (1) preferred cadence matches the cadence at which the sum of the average absolute net hip, knee, and ankle joint moments is minimized (hereafter referred to as the cost function cadence), (2) the cost function cadence increases as power output increases, and (3) these observations are independent of cycling experience and fitness.

2. Methods

Eight experienced cyclists, eight well-trained runners with no cycling experience and eight less-trained noncyclists, all of whom were males, were selected based on a questionnaire and a bicycle VO2max test (Table 1). The VO2max test consisted of a 5 min warmup ride below 100 W, followed by 2 min at 100 W, after which power output increased by 50 W every 2 min until just prior to volitional exhaustion when increments of 25 W were used (Marsh and Martin, 1997). The VO2max criteria were < 50 ml.kg−1.min−1 for less-trained subjects and > 65 ml.kg−1.min−1 for trained subjects. Noncyclists were classified as individuals who did not use a bike as a training mode or for regular commuting purposes. All individuals provided written informed consent following guidelines outlined by Arizona State University’s Human Subjects Review Board prior to testing.

Preferred cadences were determined at power outputs of 100, 150, 200, and 250 W for trained subjects. For less-trained subjects, only the two lower power outputs were studied because of their lower fitness status and inability to sustain pedaling at the higher cadences. A Schwinn Velodyne ergometer was used to control power output in all tests. Subjects rode for 8 min at each randomly assigned power output while cadence was recorded every 15 s. To minimize fatigue effects each power output was followed by a brief rest period. The preferred cadence was calculated as the average cadence during the final 6 min at each power output.

Video and pedal force data were subsequently collected as cadence was manipulated under constant power output conditions (100, 150, 200, and 250 W for cyclists and runners and 100 and 150 W for less-trained subjects). Subjects pedaled at six randomly presented cadences (50, 65, 80, 95, 110 rpm, and their preferred cadence) under each randomly assigned power output. Video and force data collection were initiated when the subject was pedaling comfortably at the assigned cadence. The subject continued cycling until data collection at the six cadences was completed for a given power output, typically requiring 10 min of continuous pedaling. A 5 min rest period separated power output conditions to minimize fatigue effects. Sagittal plane motion was recorded using a Panasonic AG-450 camcorder (frame rate 60 Hz; exposure time 0.002 s) placed approximately 10 m from the subject. Retro-reflective markers were placed on the pedal spindle and anatomical landmarks of the greater trochanter, lateral femoral condyle, lateral malleolus, calcaneus and the head of the fifth metatarsal. Neptune and Hull (1995) reported that estimating the hip joint center using the greater trochanter landmark can lead to errors

Table 1
Subject characteristicsa

<table>
<thead>
<tr>
<th></th>
<th>Cyclists</th>
<th></th>
<th>Runners</th>
<th></th>
<th>Less-trained</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>24.82</td>
<td>3.63</td>
<td>27.10</td>
<td>5.69</td>
<td>25.39</td>
<td>4.85</td>
</tr>
<tr>
<td>Mass (kg)a</td>
<td>73.4</td>
<td>8.4</td>
<td>67.9</td>
<td>7.8</td>
<td>82.3</td>
<td>7.2</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.8</td>
<td>5.5</td>
<td>175.6</td>
<td>8.5</td>
<td>178.3</td>
<td>7.0</td>
</tr>
<tr>
<td>VO2max (ml.kg−1.min−1)b</td>
<td>70.1</td>
<td>4.0</td>
<td>72.9</td>
<td>2.3</td>
<td>45.4</td>
<td>2.5</td>
</tr>
<tr>
<td>VO2max (l.min−1)b</td>
<td>5.14</td>
<td>0.50</td>
<td>4.94</td>
<td>0.49</td>
<td>3.80</td>
<td>0.43</td>
</tr>
</tbody>
</table>

aNote. n = 8 for all groups.

bP < 0.05, Less-trained subjects significantly different from cyclists and runners.

cP < 0.05, Less-trained subjects significantly different from runners.
in hip moment estimates of up to 9%. Their data (Fig. 8, p. 432) further suggest, however, that for the majority of the crank cycle a reasonable estimate of the hip joint moment is generated using this surface landmark.

The right pedal of the bike was instrumented with two Kistler 9251 A piezoelectric load cells each measuring three components (normal to the pedal surface, anterior–posterior, and medial–lateral) of the resultant pedal force (Broker and Gregor, 1990). Outputs from the two load cells for each force component were summed prior to amplification. A potentiometer driven by a gear mounted to the crank was used to measure the angle of the pedal with respect to the crank. An optical encoder was used to determine the crank position in the laboratory reference frame. The analog signals of the optical encoder, potentiometer and three force amplifiers were sampled simultaneously at 120 Hz for 5 s. Crank, pedal, and force data and video records were synchronized using an LED that was illuminated in the camcorder field of view for the duration of analog sampling.

Video records were digitized for the motion corresponding to the full 5 s of force sampling. The raw vertical and horizontal coordinate data for each marker were smoothed separately with a fourth order, zero lag, recursive Butterworth digital filter using cutoff frequencies (4–5 Hz) determined from an analysis of residuals (Winter, 1990). Linear and angular kinematics of the cycling motion were computed from the smoothed coordinate data. Pedal force data were also filtered with a 10 Hz cutoff frequency that was selected according to results of a residual analysis. The normal and anterior–posterior forces acting on the pedal were transformed to the laboratory reference frame using pedal and crank position data. The kinematic and kinetic data were then combined to compute the net joint moments at the hip, knee, and ankle using inverse dynamics (Bressler and Frankel, 1950). The lower extremity was modeled as a planar, three-segment rigid body system. Segment mass and center of mass data were estimated according to Clauser et al. (1969) and Hinrichs (1990). Segment moments of inertia were predicted using data from Whittsett (1963) and personalized using the methods outlined by Dapena (1978). Axes of rotation were assumed to be coincident with marked joint centers, internal frictional forces were assumed negligible, and the changes in inertial parameters that would occur with redistributions of segment mass were ignored. The midpoint between the fifth metatarsal and the pedal spindle was used as the point of application of the pedal forces on the foot in the link segment model.

Hip, knee, and ankle net joint moments for each subject were normalized to percent of crank cycle and averaged across the total number of complete cycles of motion for a given cadence and power output. The absolute value for each average net joint moment profile was then computed and the resulting curve integrated to provide a single value that represented the average absolute joint moment. For each cadence/power combination, a moment-based cost function was defined as the sum of the average absolute joint moments at the hip, knee, and ankle.

To determine for each subject the cost function cadence (i.e., that cadence at which the moment-based cost function was minimized), values of the cost function for the five fixed cadences at a particular power output were fit with a second-order polynomial (Redfield and Hull, 1986). The polynomial function provided an excellent fit to the data; \( r \) values exceeded 0.95 in 80% of the cases and were less than 0.85 in only 6% of the cases. The polynomial was then differentiated and solved for the cadence at which the first derivative was equal to zero. In the rare case that the predicted cadence was above 110 rpm (6 cases out of 80 total assessments), 110 rpm was used as the optimal cadence to avoid any extrapolation errors.

The statistical package SPSS for Windows was used for all statistical procedures. Paired \( t \)-tests were used to contrast the average cost function cadence with the mean preferred cadence at each power output. Correlations were conducted to describe the association between preferred and cost function cadences. A 3 (group) \( \times \) 2 (power output) \( \times \) 5 (cadence) ANOVA with repeated measures on the last two factors was conducted to determine the influence of power output and cadence on the cost function cadence and to determine if the responses of the three subject groups differed. Because the two trained groups pedaled at four common power outputs, a 2 (group) \( \times \) 4 (power output) \( \times \) 5 (cadence) ANOVA with repeated measures on the last two factors was also conducted to compare the response of the cost function cadence to manipulations of cadence and power output for the cyclists and runners.

3. Results

The moment-based cost function was systematically affected by both cadence and power output (Fig. 1). Independent of cycling experience and fitness level, the moment-based cost function was highest at 50 rpm, declined and tended to plateau as cadence was increased to 110 rpm. Under some conditions, a subtle increase in the cost function was observed as cadence increased from 95 to 110 rpm.

In support of our first hypothesis, the average cost function cadence was not significantly different from the preferred cadence for any group at any power output, except for less-trained subjects at 150 W (Fig. 2). Contrary to our hypothesis, however, correlations between the cost function cadence and preferred cadences at each power output were generally nonsignificant or inverse in nature thereby indicating that these two cadences were
not tightly linked with one another (Table 2). In addition, dissimilar trends in the mean data responses of the cost function and preferred cadences to power output changes were apparent. The cost function cadence increased, whereas preferred cadence showed little change (cyclists, runners) or tended to decrease (less-trained, noncyclists) as power output increased.

The cost function cadence increased as power output increased, supporting our second hypothesis. In addition, these increases were similar for all three subject groups, which supported our third hypothesis (Figs. 1 and 2). In the three group analysis, the cost function cadence was significantly higher at 150 W (93.3 ± 10.4 rpm) than at 100 W (86.3 ± 11.9 rpm) [$F(1, 21) = 11.89$, $p = 0.002$]. For the two-group ANOVA (cyclists vs. runners), the cost function cadence increased from 86.3 ± 10.2 to 94.0 ± 9.6 rpm and again to 98.5 ± 8.0 rpm and decreased slightly to 96.1 ± 7.3 rpm as power output increased from 100 to 250 W [$F(3, 42) = 8.18$, $p < 0.001$]. The cost function cadences of cyclists, runners, and less-trained noncyclists were not different [$F(2, 21) = 0.12$, $p = 0.891$] at the two power outputs common to all three groups (100 and 150 W). Similarly, there were no differences in cost function cadence between cyclists and runners across the four power outputs [$F(1,14) = 0.21$, $p = 0.657$]. Therefore, neither cycling experience nor fitness level influenced the cost function cadence, which was consistent with our third hypothesis.
Fig. 2. Mean (± SD) preferred and cost function cadences for highly fit and experienced cyclists (panel A), highly fit runners (panel B), and less-fit noncyclists (panel C) as a function of power output. The preferred and cost function cadences were not statistically different at any power output, except at 150 W for the less-fit noncyclists. Preferred cadence showed little change (cyclists, runners) or tended to decrease (less-fit noncyclists) with increases in power output, whereas the cost function cadence increased (except from 200 to 250 W for cyclists).
With respect to preferred cadence, the group by power output interaction was statistically significant \( F(2, 21) = 6.81, p = 0.005 \). Less-trained subjects selected lower preferred cadences at both 100 and 150 W compared to cyclists and runners and reduced cadence as power output increased. The cyclists and runners, in contrast, did not differ in preferred cadence \( F(1, 14) = 0.12, p = 0.735 \) and did not alter cadence as power output increased \( F(3, 42) = 0.87, p = 0.465 \).

### 4. Discussion

The purpose of this study was to examine if a mechanical variable suggested to be representative of muscular effort during cycling was associated with the preferred cadence. The question of interest was whether or not a composite of the net joint moments at the hip, knee, and ankle was minimized at the preferred cadence in a composite of the net joint moments at the hip, knee, and ankle was minimized at the preferred cadence. The cost function cadence at 200 W for cyclists and runners (101 and 96 rpm, respectively) agreed closely with previous modeling research by Redfield and Hull (1986) and Hull et al. (1988) who reported a cadence in the range of 90–105 rpm. The absence of statistically significant differences between the mean cost function and preferred cadences was also consistent with the notion that minimizing muscular effort is important in preferred cadence selection during submaximal steady-state cycling. However, the cost function and preferred cadences were not closely associated, as reflected in the weak or negative correlations, i.e., individuals with a high cost function cadence did not show a high preferred cadence and vice versa. The correlation analysis highlights the fact that there are additional factors contributing to preferred cadence selection.

Our prediction of an association between cost function and preferred cadences was based on earlier modeling efforts from Hull and colleagues (Redfield and Hull, 1986; Hull and Gonzalez, 1988; Hull et al., 1988). Using a dynamic optimization approach to assess cycling equipment setup issues, Kautz and Hull (1995) indicated that a net joint moment-based cost function has questionable physiological relevance and may be inadequate for

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>100 W</th>
<th>150 W</th>
<th>200 W</th>
<th>250 W</th>
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<tbody>
<tr>
<td><strong>C ((n = 8))</strong></td>
<td>0.17</td>
<td>0.27</td>
<td>0.08</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>0.68</td>
<td>0.52</td>
<td>0.85</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>R ((n = 8))</strong></td>
<td>0.14</td>
<td>0.43</td>
<td>0.04</td>
<td>0.73*</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>0.29</td>
<td>0.92</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>LT ((n = 8))</strong></td>
<td>0.68</td>
<td>0.85</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>0.02</td>
<td></td>
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\( ^* p < 0.05 \)
optimization studies of cycling. We would agree that if the goal is to equate muscular effort with physiological cost (as quantified by aerobic demand) then the net joint moment approach appears to be without a sound basis.

Recently, Neptune and Hull (1998) have developed a forward dynamic simulation of steady-state submaximal cycling and included the net joint moments as one of the performance criteria. Interestingly, they found that including experimentally derived EMG data in addition to the joint moments, crank torques and pedal angle in the performance criterion reduced the amount of negative muscle work in the downstroke and improved the match between the experimental EMG and the simulation muscle excitations. They suggested that minimizing negative muscle work may be another factor that should be considered important in endurance cycling.

While our results suggest that minimizing muscular effort is probably one of the determinants of the preferred cadence, the question remains as to what other factors play a role in the process. Chapman (1985) suggested that the function of bicycle gearing is to allow the lower extremity muscles to function at a velocity that maximizes muscle power output at any given external power. Chapman and Sanderson (1990) expanded this idea stating that “regardless of the length (of a muscle), or rather assuming that length change remains within the middle of the force–length relationship, the FV (force–velocity) relationship dictates the most desirable rate” (p. 616). They contended that the optimal rate of movement is one that globally maximizes power output from the musculature.

Clearly the cadence, force output required from the muscle, and the resulting pattern of muscle fiber recruitment are intertwined. Sargeant (1994) suggested that our ability to perform prolonged submaximal activities is closely linked to the different properties of “slow” and “fast” twitch muscle fibers and that rate selection may be associated with maintaining a reserve in power output capacity of the muscle so as to increase the time to fatigue. He suggested that the “optimal” cadence may be one at which the required power output is produced with as small a contribution as possible from fatiguable muscle fibers while maintaining a reserve in the power output capability of the muscle. It seems reasonable to speculate that at higher cadences muscle forces are lower (Hull et al., 1988; Patterson and Moreno, 1990) and fewer fatiguable muscle fibers are recruited (Ahlquist et al., 1992). Therefore, a performance advantage may exist in selecting higher cadences (~ 90 rpm) for submaximal cycling over a prolonged duration. Data from Takaishi et al. (1996) support this notion. Using the slope of the integrated EMG (iEMG) over time as a marker of neuromuscular fatigue, they examined the effect of cadence on vastus lateralis activation during moderate intensity (75% VO2max) pedaling at cadences ranging from 50 to 100 rpm. iEMG slope reflected a quadratic relationship with cadence and was minimized at 80–90 rpm. Takaishi et al. (1996,1998) concluded that preferred cadences of cyclists are closely associated with the minimization of neuromuscular fatigue and not with the minimization of the metabolic energy cost of pedaling. They further suggested that higher pedaling rates, coupled with lower pedaling forces and shortened activation times, lead to improvements in performance because of improvements in muscle blood flow and recruitment of fewer fast twitch muscle fibers. In support of this speculation, Gotshall et al. (1996) showed that a – VO2 difference and vascular resistance decreased as cadence increased from 70–110 rpm during 200 W cycling. Recently, Nickleberry and Brooks (1996) have shown that recreational cyclists rode 43% longer (20 vs. 14 min) and competitive cyclists 30% longer (35 vs. 27 min) when pedaling at 80 rpm compared to 50 rpm. These studies all support the notion that muscular effort, neuromuscular fatigue, and preferred rate of movement are related.

This paper has shown empirically that there is a modest association between the net joint moment-based cost function cadence and preferred cadence regardless of fitness or cycling experience. The cadences which minimized the cost function increased as power output increased, supporting the second hypothesis, whereas preferred cadences of the three groups remained relatively constant or declined with increases in power output. Since the net joint moment was used as a reflection of muscle effort it appears that minimizing muscle effort is important in preferred cadence selection. However, the weak correlations and differences in the trends of the cost function and preferred cadences suggest that there are other variables important in the process of cadence selection. It is probably not surprising that we did not find a close link between the preferred and cost function cadence since muscle properties were not included in this analysis. Therefore, we conclude that minimizing net joint moments is a factor associated with preferred cadence selection but that there are other intrinsic muscle properties, both mechanical and physiological, that influence the selection of the preferred cadence.

References


