ARTICLE IN PRESS
JSAMS-02980; No of Pages 4
Journal of Science and Medicine in Sport xxx (xxxx) xxx–xxx
Contents lists available at ScienceDirect
Journal of Science and Medicine in Sport
journal homepage: www.elsevier.com/locate/jsams

Brief report

# Relative pedaling forces are low during cycling

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ARTICLE INFO

*Article history:*
Received 2 December 2023
Received in revised form 22 April 2024
Accepted 16 May 2024
Available online xxxx

*Keywords:*
Torque
Cycling
Assessment
Biomechanics
Performance

ABSTRACT

We quantified and compared the mechanical force demands relative to the maximum dynamic force (MDF) of 11 cyclists when pedaling at different intensities (ventilatory threshold, maximum lactate steady state, respiratory compensation point, and maximal aerobic power), cadences (free, 40, 60 and 80 rpm), and all-out resisted sprints. Relative force demands (expressed as %MDF) progressively increased with higher intensities ($p < 0.001$) and lower cadences ($p < 0.001$). Notwithstanding, relative force demands were low (<54 % MDF) for all conditions, even during the so-called 'torque training'. These results might be useful when programming on-bike resistance training to improve torque production capacity.


**Practical implications**

- With the protocol described here, scientists and coaches might be able to assess MDF during cycling, which could open new applications.
- Assessment of relative pedaling forces might be useful for comparing and equalizing stimulus between on- and off-bike resistance sessions (e.g., training both modalities at 70 % MDF or 1RM, respectively).

## 1. Introduction

Given the importance of torque (force) production for cycling performance, training aimed at improving this ability is growing in popularity.[1] This is commonly referred to as 'torque' training, and usually consists of performing bouts of varying duration at low cadences (~60 rpm or less). Nevertheless, evidence examining the adaptations produced by these efforts, compared to medium/high-cadence ones, does not prove a clear superiority in favor of the former.[2–4] Indeed, it is completely unknown the actual force demands that torque training requires on the cyclist relative to his/her maximal dynamic pedaling force (MDF).[5] Expressing these force values relative to the MDF would be of great practical value because, as has widely been proven in off-bike resistance training, relative intensity (e.g., as a % of 1-repetition maximum [1RM] in resistance training exercises) is one of the main determinants of training adaptations.[6,7] Under this context, this study aimed to quantify the relative mechanical force demands of cyclists when pedaling at a wide range of intensities and cadences, including those used in widespread torque training.

## 2. Methods

The G*Power software (Universitat Kiel, Kiel, Germany) was used to calculate the required sample size. A minimum of 9 participants were needed to detect a medium effect size of 0.50 with alpha and power values of 0.05 and 90 %, respectively, assuming a conservative correlation coefficient of 0.50. Thus, eleven highly-trained male cyclists (age, mean ± SD = 29 ± 8 years; $VO_{2max}$ = 65.0 ± 6.9 mL·kg$^{-1}$·min$^{-1}$, training experience = 18 ± 7.3 years; height = 174 ± 5 cm; body mass = 71.9 ± 6.9 kg) participated in the study after providing written informed consent (ethical approval #4135/2022). They were instructed to maintain their normal diet and to refrain from

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https://doi.org/10.1016/j.jsams.2024.05.009
1440-2440/

Please cite this article as: D. Barranco-Gil, A. Hernández-Belmonte, J. Iriberri, et al., Relative pedaling forces are low during cycling, Journal of Science and Medicine in Sport, https://doi.org/10.1016/j.jsams.2024.05.009

performing strenuous training during the entire study period, as well as to avoid ingesting stimulants (e.g., caffeine) 48 h before testing.

Participants attended our laboratory on 11 different days (1 test/day, 48–72 h of rest between tests) (Fig. 1). All the tests took place at the same time of day (±1 h) under constant laboratory environmental conditions (temperature = 22.0 ± 2.2 °C, relative humidity = 44.8 ± 8.9 %, wind cooled at 2.55 $m \cdot s^{-1}$). The first visit consisted of a graded exercise test — see below — and a complete medical examination (including ECG) to confirm normal cardiac function, together with familiarization with the different testing protocols. In the second visit, the participants performed the same graded exercise test again after a 10-minute warmup at 75 W (initial workload = 75 W, increases of 5 W every 12 s until volitional exhaustion) to determine the power output (PO) associated with well-established physiological/metabolic indicators, as explained elsewhere[8]: first ventilatory threshold (VT), respiratory compensation point (RCP) and maximum oxygen uptake ($VO_{2max}$). Gas exchange data were collected breath-by-breath (MetaLyzer 3B-R3, Cortex Biophysik GmbH; Leipzig, Germany). The maximal aerobic power (MAP) was also determined and defined as the lowest PO associated with the $VO_{2max}$. The participants visited the laboratory 3 more times to determine the PO associated with the maximal lactate steady state (MLSS) through 30-minute constant-workload tests.[8]

The cyclists attended the laboratory on 5 more days, during which they performed (in random order) different bouts (1 per day) at the PO corresponding to the 'classical' indicators VT, MLSS, RCP, or the MAP, respectively, or 3 all-out sprints of 10-second duration each. For the bouts at the PO of the 'classical' indicators, participants used a freely chosen cadence as well as fixed cadences of 80, 60, and 40 rpm (in random order, 1 min for each bout with a 5-minute rest between consecutive bouts). Average tangential force (i.e. component of force that is parallel to the direction of the crack motion, N), torque ($N \cdot m$, $N \cdot m \cdot kg^{-1}$), cadence (rpm), and PO (W) during the last 40 s of each bout were registered. On the other hand, the sprints started from a dead stop, were performed against varying resistances (1, 2 and 3 kp), and were interspersed by 5-minute rests.

All the aforementioned assessments were performed with the participants' own bicycles attached to a validated cycle-ergometer (CycleOps Hammer; Madison, WI)[9] using a hyperbolic mode (i.e., the work rate was imposed to the subjects with a constant load independent of the pedal cadence), except for the sprints — where a friction-loaded isoinertial ergometer (Monark© 874E; Varberg, Sweden) was used (pedal crank = 175 mm) and the position of the saddle (height and setback) and handlebars (reach and drop) was individually adjusted to replicate the participant's own bike.

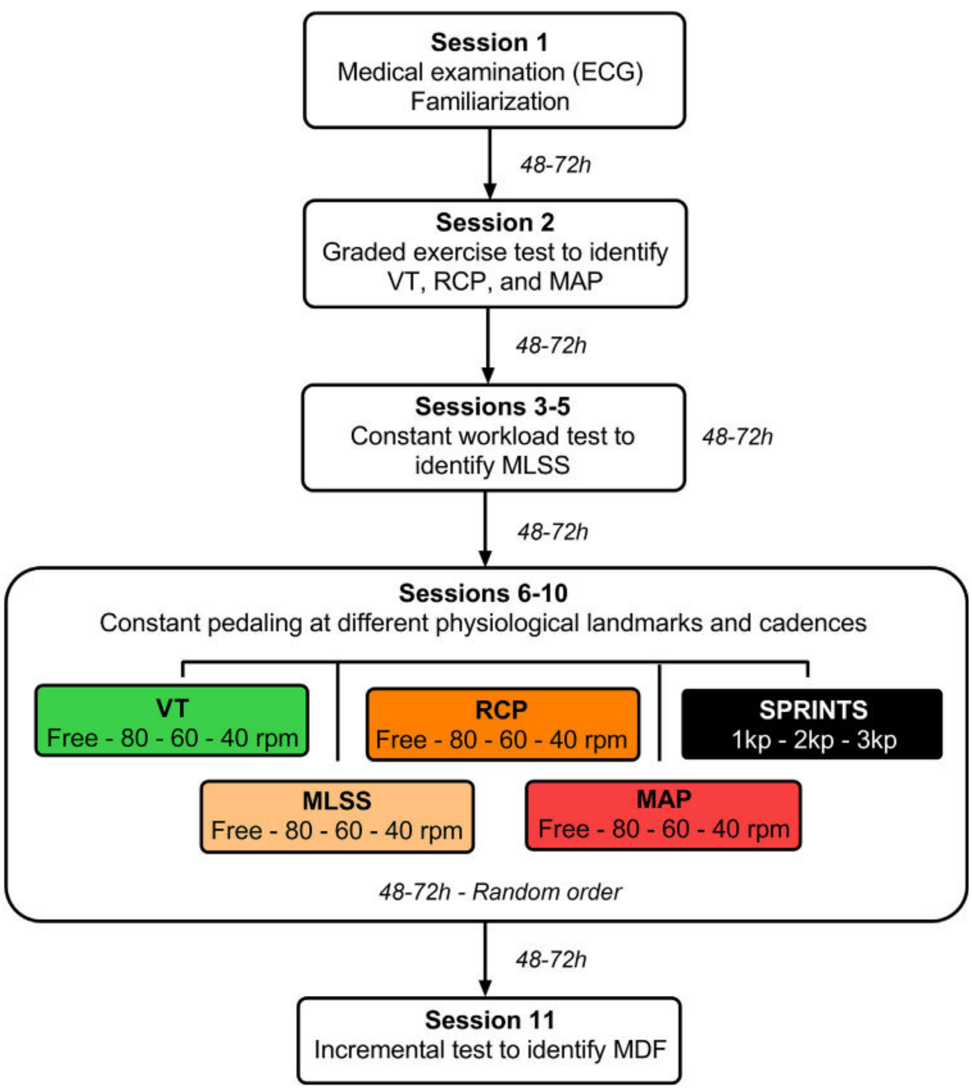


**Fig. 1.** Graphical representation of the study design. ECG, electrocardiogram; VT, ventilatory threshold; RCP, respiratory compensation point; MAP, maximal aerobic power; MLSS, maximal lactate steady state; MDF, maximal dynamic force.

On a final visit, participants attended our laboratory for MDF determination using the aforementioned isoinertial cycle-ergometer equipped with a validated power meter (Rotor 2INpower, Madrid, Spain) adapted to its bottom bracket, which allowed torque assessment.[10] The MDF was determined by progressively increasing pedaling resistance (starting at 2 kp, with 0.5–3.0 kp increases) through the addition of calibrated disks (Eleiko, Sport AB; Halmstad, Sweden). Participants were required to perform a 5-second all-out effort with each resistance (with 5-minute rests in-between) and the test continued until reaching the heaviest resistance above which the cyclist could no longer properly complete a whole — i.e., 360° with both legs — pedaling cycle (equivalent to 1RM; accuracy = 0.5 kp). Load increments were individualized, so that participants reached the 1RM in less than 8 attempts. The MDF was defined as the force (N) attained with the 1RM-load. The testing protocol of this progressive loading test up to the MDF, its feasibility, test–retest reliability and long-term stability data have been recently published elsewhere.[5]

Normality and homoscedasticity were verified with Shapiro–Wilk and Levene's tests, respectively. A repeated-measures ANOVA (within-subject factors, intensity and cadence) was used to examine the effect of these parameters on % of MDF. Bonferroni's post hoc adjustment was used when significant differences were detected. The significance level was set at 0.05. Relative forces were ranked as low (<60 % MDF) or high (≥60 % MDF) according to resistance training classifications.[6]

## 3. Results

The participants performed 7 ± 1 attempts until reaching their MDF, which was successfully determined in all of them. The load range during the incremental pedaling test was 2–22 kp, whereas mean cadences were 110 ± 14 rpm (whole incremental test), 153 ± 20 rpm (low % MDFs), and 45 ± 7 rpm (high %MDFs). Participants' 1RM was attained with a mean resistance and pedal cadence of 18.0 ± 1.2 kp and 22 ± 4 rpm, respectively, which corresponded to an MDF value of 980 ± 63 N (maximum torque = 171 ± 11 N·m or 2.4 ± 0.1 $N\cdot m\cdot kg^{-1}$).

Torque and PO values, as well as the %MDF attained under each condition are shown in Table 1. Relative force demands progressively increased at higher intensities ($p < 0.001$) and lower cadences ($p < 0.001$) (Fig. 1, Supplementary Fig. 1). Except for the free-cadence versus 80 rpm comparison at VT ($p = 0.193$), relative pedaling forces (expressed as %MDF) were significantly different for all the pairwise intensity-cadence analyses ($p < 0.01$ to $p < 0.001$, see Supplementary Table 1). However, force demands were in all cases ≤54 % of MDF and ranged as follows: 25–52 N·m (14–30 % of MDF) at the VT; 29–63 N·m (17–37 % of MDF) at the MLSS; 33–74 N·m (20–44 % of MDF) at the RCP; 43–94 N·m (25–54 % of MDF) at the MAP; and 37–53 N·m (21–31 % of MDF) in the all-out sprints.

## 4. Discussion

Compared to MDF, the relative pedaling force demands across a wide range of metabolic (i.e., submaximal to supramaximal) intensities in competitive cyclists can be considered overall low (if not very low), even at peak intensities and/or at the lowest cadences associated with the so-called "torque training" (e.g., 54 % of MDF for the MAP with a pedal cadence of only 40 rpm).

Training loads during cycling training sessions or competitions are traditionally expressed relative to physiological indicators, such as the $VO_{2max}$[11] — for instance, it has been reported that professional cyclists spend most competition time at moderate-to-high intensities relative to their $VO_{2max}$, that is, ~75 % of total time above 50 % of $VO_{2max}$, or ~20–30 % and ~5–15 % above the VT and RCP, respectively.[12,13] However, the intensity of these efforts relative to the cyclists' MDF remains, to the best of our knowledge, unknown. Identification of the actual relative force demands during cycling might be of interest, as these demands have been shown to play a major role in the responses and adaptations induced by other training stimuli — notably during strength training. For instance, during resistance training, exercising with moderate-to-high relative loads (>60 % of 1RM, and particularly 80 % of 1RM) has been reported to result in greater gains of maximal strength compared to lower loads.[6,7,14]

Our results indicate that although low-cadence efforts increased force demands compared to normal-cadence ones (e.g., 40 rpm vs. Free-cadence = + 16 % at VT, + 20 % at MLSS, + 24 % at RCP, or + 29 % at MAP), relative forces compared to MDF were low even in situations that are usually expected to result in high force values —such as during the so-called 'torque training'.[2–4] In this effect, mixed evidence exists on the effectiveness of interventions aimed at improving torque production capacity in cyclists. Paton et al. reported that the inclusion of 30-second sprints performed at relatively low cadences (60–70 rpm) during 4 weeks yielded greater performance benefits — as assessed through sprint performance, peak power, and submaximal cycling

**Table 1**
Relative force, torque, and power output observed when pedaling at different intensities and cadences.

| | Target cadence | Relative force (% of MDF) | | | Cadence (rpm) | | | Torque (N·m) | | | Torque ($N\cdot m\cdot kg^{-1}$) | | | Power output (W) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | 95 % CI | Mean | SD | 95 % CI | Mean | SD | 95 % CI | Mean | SD | 95 % CI | Mean | SD | 95 % CI |
| VT | Free | 14 % | 3 % | 12 % – 16 % | 89 | 9 | 83 – 94 | 24.5 | 5.8 | 20.9 – 28.1 | 0.34 | 0.08 | 0.29 – 0.39 | 225 | 47 | 195 – 254 |
| | 40 rpm | 30 % | 6 % | 27 % – 34 % | 41 | 1 | 41 – 42 | 51.6 | 9.5 | 45.7 – 57.5 | 0.72 | 0.15 | 0.62 – 0.81 | 223 | 39 | 198 – 247 |
| | 60 rpm | 21 % | 4 % | 18 % – 23 % | 61 | 1 | 60 – 61 | 35.2 | 6.9 | 30.9 – 39.5 | 0.49 | 0.11 | 0.42 – 0.56 | 224 | 44 | 197 – 252 |
| | 80 rpm | 15 % | 3 % | 13 % – 17 % | 81 | 1 | 80 – 81 | 26.1 | 5.2 | 22.9 – 29.3 | 0.36 | 0.08 | 0.31 – 0.41 | 220 | 41 | 195 – 246 |
| MLSS | Free | 17 % | 4 % | 15 % – 19 % | 90 | 8 | 85 – 95 | 28.9 | 5.7 | 25.4 – 32.5 | 0.40 | 0.08 | 0.35 – 0.45 | 270 | 51 | 239 – 301 |
| | 40 rpm | 37 % | 7 % | 32 % – 41 % | 40 | 1 | 39 – 41 | 62.8 | 11.0 | 56.0 – 69.6 | 0.87 | 0.18 | 0.76 – 0.98 | 264 | 48 | 234 – 293 |
| | 60 rpm | 25 % | 5 % | 22 % – 28 % | 61 | 1 | 60 – 62 | 42.5 | 8.0 | 37.5 – 47.4 | 0.59 | 0.13 | 0.51 – 0.67 | 272 | 53 | 239 – 305 |
| | 80 rpm | 19 % | 4 % | 16 % – 21 % | 80 | 1 | 80 – 81 | 32.0 | 32.0 | 12.2 – 51.8 | 0.44 | 0.09 | 0.39 – 0.50 | 268 | 50 | 238 – 299 |
| RCP | Free | 20 % | 4 % | 17 % – 22 % | 91 | 7 | 87 – 95 | 33.3 | 5.8 | 29.7 – 36.9 | 0.46 | 0.09 | 0.41 – 0.52 | 317 | 55 | 283 – 351 |
| | 40 rpm | 44 % | 9 % | 38 % – 49 % | 42 | 1 | 41 – 43 | 74.1 | 12.9 | 66.1 – 82.1 | 1.03 | 0.22 | 0.90 – 1.16 | 329 | 58 | 293 – 365 |
| | 60 rpm | 29 % | 6 % | 25 % – 33 % | 61 | 1 | 60 – 62 | 49.7 | 9.4 | 43.9 – 55.6 | 0.69 | 0.15 | 0.60 – 0.79 | 319 | 64 | 279 – 358 |
| | 80 rpm | 22 % | 4 % | 20 % – 25 % | 80 | 1 | 79 – 80 | 37.9 | 6.6 | 33.8 – 42.0 | 0.53 | 0.11 | 0.46 – 0.59 | 317 | 54 | 284 – 351 |
| MAP | Free | 25 % | 4 % | 22 % – 28 % | 88 | 5 | 85 – 91 | 42.6 | 6.7 | 38.5 – 46.8 | 0.59 | 0.10 | 0.53 – 0.65 | 393 | 61 | 355 – 431 |
| | 40 rpm | 54 % | 9 % | 49 % – 60 % | 42 | 1 | 41 – 43 | 93.5 | 15.3 | 84.0 – 103.0 | 1.29 | 0.24 | 1.15 – 1.44 | 413 | 70 | 369 – 456 |
| | 60 rpm | 36 % | 6 % | 32 % – 40 % | 60 | 1 | 60 – 61 | 61.1 | 8.6 | 55.7 – 66.4 | 0.85 | 0.15 | 0.75 – 0.94 | 389 | 58 | 353 – 425 |
| | 80 rpm | 27 % | 5 % | 24 % – 30 % | 80 | 1 | 80 – 81 | 46.1 | 6.9 | 41.9 – 50.4 | 0.64 | 0.11 | 0.57 – 0.71 | 388 | 57 | 353 – 423 |
| Sprint | 1 kp | 21 % | 2 % | 20 % – 23 % | 177 | 15 | 167 – 186 | 36.6 | 4.2 | 34.1 – 39.2 | 0.51 | 0.07 | 0.47 – 0.55 | 555 | 85 | 502 – 608 |
| | 2 kp | 26 % | 3 % | 25 % – 28 % | 166 | 16 | 157 – 176 | 44.7 | 4.2 | 42.1 – 47.3 | 0.62 | 0.08 | 0.57 – 0.67 | 669 | 77 | 621 – 716 |
| | 3 kp | 31 % | 3 % | 29 % – 33 % | 156 | 13 | 148 – 164 | 53.4 | 3.9 | 50.9 – 55.8 | 0.74 | 0.08 | 0.69 – 0.78 | 778 | 86 | 724 – 831 |

Abbreviations: CI, confidence interval; MAP, maximal aerobic power; MDF, maximal dynamic force; RCP, respiratory compensation point; VT, ventilatory threshold. Except for the free-cadence versus 80 rpm comparison at VT ($p = 0.193$), relative force values were significantly different for all the pairwise intensity-cadence analyses ($p < 0.01$ to $p < 0.001$, see Supplementary Table 1).

performance — than the same sprints performed at higher cadences (110–120 rpm).[2] According to the present findings, however, the relative force demands of such sprint tasks would be low (i.e., ≤30 % of MDF). Other authors have analyzed the effects of longer bouts (usually 4–6 min) at lower (submaximal) intensities and cadences (~60 rpm), and reported mixed effects compared with the bouts performed at high (~100–120 rpm) or free cadences.[3,4,15,16] Of note, attending to the present results, in the aforementioned stydies[2–4] the relative force demands might have also been overall low (i.e., <50 % of the participants' MDF in the low-cadence group). Thus, although more research is needed,[17,18] it is possible that increasing relative force demands during the so-called 'torque training' sessions might be needed to maximize its benefits, particularly when compared with strength training. Moreover, research is warranted to elucidate whether increasing cyclists' MDF (and consequently reducing relative force requirements for the same exercise) leads to an increased performance during actual racing.

This study is not without limitations. First, we analyzed force values during sprints performed on a friction-loaded isoinertial ergometer against relatively low resistances (1, 2 and 3 kp) from a dead stop, and future studies should therefore identify the force values that cyclists produce in the field during a 'real world' sprint. Moreover, future studies should incorporate force measurement devices that allow a proper discrimination between radial and tangential applied forces, which would ensure a more accurate identification of the relative force demands during cycling.

## 5. Conclusions

Although low-cadence efforts increased relative force demands (%MDF) compared to normal-cadence ones, cyclists' relative force demands during the wide range of physiological intensities assessed could be considered overall low, typically representing <50 % of MDF.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2024.05.009.

## Funding information

AHB is supported by a predoctoral contract granted by the Spanish Ministry of Science (Grant No. FPU19/03258). Research by PLV is supported by a Sara Borrell postdoctoral contract granted by Instituto de Salud Carlos III (CD21/00138). DB-G and AL are funded by the Spanish Ministry of Economy and Competitiveness and Fondos Feder (Alejandro Lucia, Grant No. PI18/00139).

## Confirmation of ethical compliance

The study adhered to the declaration of Helsinki. Participants provided written informed consent and the study was approved by the Institutional Review Board (ethical approval #4135/2022).

## CRediT authorship contribution statement

Conception and design: DBG, AHB, JI, AL, PLV, and JGP. Acquisition of data: DBG, AHB, AMC, ABR, LBA, VRR, IRSR, and RP. Analysis and interpretation of data: AHB, JI, AL, PLV, and JGP. Drafting the article or revising it critically for important intellectual content: DBG, AHB, AL, PLV, and JG. Final approval of the version to be published and agreement to be accountable for all aspects of the work: DG, AHB, JI, AMC, ABR, LDA, VRR, IRSR, RP, AL, PLV, and JGP.

## Declaration of interest statement

The authors declare no conflicts of interest.

## Acknowledgments

The authors sincerely thank all the participants.

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