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Functional data analysis reveals asymmetrical crank torque during cycling performed at different exercise intensities

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ABSTRACT

Pedaling asymmetry is claimed as a factor of influence on injury and performance. However, the evidence is still controversial. Most previous studies determined peak torque asymmetries, which in our understanding does not consider the pattern of movement like torque profiles. Here we demonstrate that asymmetries in pedaling torque at different exercise intensities can be better described when the torque profiles are considered using functional analysis of variance than when only the peak values are analyzed. We compared peak torques and torque curves recorded while cyclists pedaled at submaximal intensities of 60%, 80%, and 95% of the maximal power output and compared data between the preferred and non-preferred legs. ANOVA showed symmetry or rather no difference in the amount of peak torque between legs, regardless of pedaling intensity. FANOVA, on the other hand, revealed significant asymmetries between legs, regardless of cycling intensity, apparently for different sections of the cycle, however, not for peak torque, either. We conclude that pedaling asymmetry cannot be quantified solely by peak torques and considering the analysis of the entire movement cycle can more accurately reflect the biomechanical movement pattern. Therefore, FANOVA data analysis could be an alternative to identify asymmetries. A novel approach as described here might be useful when combining kinetics assessment with other approaches like EMG and kinematics and help to better understand the role of pedaling asymmetries for performance and injury risks.

1. Introduction

Low to moderate power output is sustained most of the time in cycling competitions (Ebert et al., 2006). Nevertheless, the characteristic of cycling elicits variability in power output, and there are crucial high-intensity intervals in cycling, notably in tactical moves and sprint bunches. Power output depends on crank torque and pedaling cadence. Considering that trained cyclists show a consistent preferred pedaling cadence (Lucía, Hoyos & Chicharro, 2001), most changes in power output during a cycling trial will result from variations in crank torque.

Crank torque output influences the exercise intensity and metabolic demands during cycling (Carpes et al., 2007). This relationship between intensity and torque output is considered in the context of pedaling asymmetry, where there is considerable speculation on the effects of asymmetric pedaling on performance and injury risk. Furthermore, peak crank torque asymmetries were found during prolonged cycling at lower to moderate exercise intensities but not at higher intensities (Carpes et al., 2007), while in maximal tests, peak crank torque asymmetries were found at higher intensities (Trecroci et al., 2018). When peak torque, impulse, and sagittal kinematics were analyzed in cyclists with different levels of experience, asymmetries were found regardless of the intensity (García-López et al., 2015). Controversial results are evident in the specialized literature regarding asymmetries in pedal forces and torque. A common characteristic among the different studies is that conclusions rely on the analysis of mean or peak values. To the best of our knowledge, no previous study has

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presented a clear conclusion on the relationship between asymmetries and injury in cyclists, which we consider may also be resultant from the controversial results already mentioned.

There is no consensus regarding the best approach to analyze cycling asymmetries data. Discrete parameters, such as the maximum and minimum peak values obtained from temporal series, serve as standard descriptors of cycling asymmetry. In most previous studies, the detection of cycling asymmetry was restricted to bilateral differences in peak torque. Since this approach neglects temporal information in the torque waveforms, important information could be overlooked.

In this sense, quantitative analysis methods that consider the entire crank cycle, such as functional data analysis (FDA) (Ramsay and Silverman, 2005), could provide novel information. To perform FDA, the torque curve is represented by a mathematical function that spans the whole torque cycle and not only sets of points. Recently, statistical methods like the analysis of variance (ANOVA) have been adapted and extended to the FDA approach (Helwig et al., 2016); this process is referred to as functional analysis of variance (FANOVA). In FANOVA, the parameters of the dependent variable become functional, e.g., associated with continuous-time monitoring processes, whose final outputs are samples of functions (Laukaitis and Rackauskas, 2005), but the design matrix remains as in the classical general linear model (Andrade et al., 2014; Park et al., 2017). We consider that the FANOVA approach could help analyze cycling asymmetries with specific goals like to determine the influence of exercise intensity on pedaling asymmetries, which is a topic of great discussion in the literature.

Therefore, in this study, we verify whether analysis of crank torque asymmetries considering the torque profiles using functional analysis of variance (FANOVA) can provide quantitative details for description and comparison of asymmetries. Such information can help discuss pedaling technique and performance than when only the peak values are analyzed considering discrete values (e.g., peak torque values in an ANOVA design). We also determine whether asymmetry is affected by exercise intensity. We hypothesize that FANOVA would reveal more information to detect asymmetry than ANOVA due to considering more data points to represent the movement and that lower intensities would elicit larger asymmetry than higher intensities.

2. Methods

2.1. Participants

To be included in the study, participants should be amateur cyclists older than 18 years and not presenting with previous injury or pathology that could influence cycling performance (for instance, low back pain or muscle injuries). Participants who did not complete the assessment were excluded from the analyses. The local institutional ethics committee approved all the procedures (CAAE 84968018.1.0000.5149). All participants provided written consent to participate in the experiments. In total, 20 amateur cyclists were recruited from the local community by a direct invitation to local cycling teams. The cyclists had an average (standard deviation) age of 34 (15) years, body mass of 73 (23) kg, height of 1.72 (0.10) m, average weekly volume of 212.5 (25.2) km, average speed of 28.5 (4.5) km/h in training sessions, and regularly participated in competitions. In the laboratory maximal test, they achieved a maximum power output (MPO) of 317.16 (33.75) W.

2.2. Procedures

Participants visited the laboratory on four occasions with at least a 48-h interval between visits and always during the same time (morning or afternoon). On the first day, participants answered an anamnesis questionnaire. Leg preference was determined by the preference to kick a ball. They completed an incremental maximal test to determine the MPO. Each participant used their cycling shoes and was individually adjusted to the cycle ergometer (Silberman et al., 2005). The participants' body positioning was the same for all tests. The MPO test started with a 5 min warm-up at 100 W, followed by progressive increments of 25 W every minute (Lucía et al., 2002) until the cyclists were no longer able to sustain exercise with a cadence above 75 rpm. The MPO was defined as the last workload stage completed. All participants received similar verbal encouragement to perform their best during the entire exercise. The rate of perceived effort and heart rate were monitored every minute throughout the test.

They performed submaximal tests at intensities of 60%, 80%, and 95% of the MPO on the three subsequent visits. The exercise intensities were tested in a randomized order. Submaximal tests started with a standardized warm-up of 10 min cycling at variable workloads (2 min at each workload of 50, 120, 60, 120, and 70 W) followed by an increase in workload to the target power output, which was sustained for five minutes. The pedaling cadence was requested to be 90 ± 5 rpm (García-López et al., 2015; Rossato et al., 2008). During all submaximal tests, the bilateral crank torque was recorded continuously with a rotational resolution of 2°. All tests and torque recordings were performed using a cycle ergometer (LODE Excalibur Sport, Groningen, The Netherlands) instrumented to measure the crank torque and cadence continuously during pedaling. Participants were instructed to remain seated on the saddle with their hands on the handlebars. The heart rate was recorded using a heart monitor (s810, Polar Electro Oy., Finland), and the rate of perceived effort was evaluated using the Borg scale (Borg, 1982).

2.3. Statistical analysis

Data were submitted to descriptive statistics with the normality of the distribution and homoscedasticity checked with Shapiro-Wilk and Levene tests, respectively. Pedaling torque was assessed during the third minute of exercise, to represent the middle of the session, considering 10 consecutive crank revolutions. The peak torque value was identified for each of the 10 crank revolutions and then averaged to compare the peaks between preferred and non-preferred leg by using a two-way analysis of variance (ANOVA) for repeated measures considering the factors leg (preferred vs. non-preferred) and intensity (60 vs. 80 vs. 95%). A Bonferroni post hoc was applied to identify differences between intensities when a main effect or interaction was found. Effect sizes were estimated by the eta squared (η^2) and classified as large when ≥ 0.14, medium for values between 0.139 and 0.06, and small for values between 0.059 and 0.01 (Fritz; Morris & Richler, 2012). ANOVA considered a significance level set at 0.05. Equation (1) showed the two factors in the ANOVA approach:

$$torque_{ijk} = \mu + \alpha_j + \beta_k + \alpha\beta_{jk} \tag{1}$$

where α is the factor leg with j levels (j = 2), β is the factor intensity with k levels (k = 3), $\alpha\beta$ is the interaction between these two factors, ε_{ijk} are the residuals, and μ is the overall mean.

To determine the asymmetries considering the temporal series considering all the values of the 10 torque curves recorded, a two-way FANOVA for repeated measures was applied, considering the factors legs (preferred vs. non-preferred) and intensity (60 vs. 80 vs. 95%). The timing normalization procedure across the 10 crank revolutions consisted of assigning time values from 0 to 100, where 0 corresponded to the start of the crank cycle phase and 100 the end of the crank cycle. To perform the FANOVA analysis, the first step was to convert the data to a functional form; i.e., the raw data for observation "i" was used to define the "x_i" function, which could be evaluated at all t values of crank torque cycle. The function was defined using B-splines that are considered more stable and computationally efficient basis than cubic splines, and any cubic spline basis can be represented with B-splines (Park et al., 2017). Using a least-square fitting technique, four B-splines were applied to obtain a smooth and accurate representation of the data, as previously adopted (Ramsay and Silverman, 2005). It means that each curve in the dataset is composed of the same four basis functions (weighted and added together), although the weights are allowed to vary from curve to curve. We also performed the curve registration before generating the average curve for each condition. As the time series of different attempts shows some variation in phase or amplitude, the average curve may not accurately represent the real behavior.

The purpose of aligning curves is to reduce the phase variability while preserving the curves' shape and amplitude. Registering a reference point is the more usual way to register a set of curves. A reference point is defined as an identifiable point on all curves. It can be a crossover of minimums, maximums, or zero. The reference point record aligns all the specified reference points, making the average curve representing faithfully the attempts made (Crane et al., 2011). In our study, the peak torque was used as the reference point. After curve registration, the mean function and their 95% confidence bands were defined by a pointwise approach that led to an average curve. The average curve represents the common structure with average dynamics and average intensity (Kneip and Gasser, 1992). Equation (2) describes the FANOVA approach (Zhang, 2013).

$$y_{ijk}(t) = \mu(t) + \alpha_j(t) + \beta_k(t) + \alpha\beta_{jk}(t) + \varepsilon_{ijk}(t) \quad (2)$$

where $\alpha(t)$ is the factor leg with 2 levels, $\beta(t)$ is the factor intensity with 3 levels, $\alpha\beta(t)$ is the interaction between these two factors with 6 levels, $\mu(t)$ is the overall mean, $\varepsilon_{ijk}(t)$ are the residuals of the model, and t is the time (percent of crank torque cycle, in this case).

Thus, the crank torque and each effect in the model are functions of time. We adopted the pointwise F-test and Bonferroni post-hoc analysis (Zhang, 2013) (Figs. 1 and 2). We plot our estimates of these pairwise comparison functions and 95% confidence bands to determine significance. FANOVA considered a significance level set at 0.05. If the p-values were less than the level of significance adopted, the result was considered significant, similar to traditional ANOVA interpretation. As a function of t, p(t) is continuous. Similarly, any p-value function computed from data is continuous (Cox and Lee, 2008). All the procedures of functional data analysis were implemented in Matlab 2017a (MathWorks, USA), according to (Ramsay et al., 2009).

3. Results

3.1. ANOVA results

Table 1 presents the two-way ANOVA results that considered the peak torques from the preferred and non-preferred legs at different intensities. No interaction was found between leg and intensity ($F_{1,2}$ = 2.0; p = 0.8; η^2 = 0.18). A main effect of intensity was found (F_2 = 34.3; p = 0.001; η^2 = 0.79), identifying higher peak torques at an intensity of 80% (55.76) compared to that of 60% (48.31) of the MPO regardless of leg preference.

3.2. FANOVA results

The pointwise F-test showed intensity and leg's main effect, without significant interaction. The Bonferroni post-hoc analysis showed that the torque curves did not differ significantly between the intensities of 80% and 95%. Still, both intensities elicited higher torque profiles than 60% of the power output with p-values lower than the level of significance adopted (alpha = 5%) (Fig. 1). The Bonferroni post-hoc analysis identified significant asymmetries in the torque curve from 0° to 50°, 130° to 180°, and 320° to 330° of the crank cycle with p-values (p(t)) lower than the level of significance adopted (alpha = 5%) (Fig. 2).

4. Discussion

Here we set out to verify whether crank torque asymmetries outcomes analyzed considering the torque profiles using a FANOVA can provide more details of pedaling technique and performance than when only the peak torque values analyzed considering in an ANOVA design.

To achieve this goal, we proposed a data approach based on FANOVA to analyze crank torque curves using time-series data, focusing on bilateral comparisons between preferred and non-preferred legs during cycling at three different intensities. FANOVA analysis confirmed our initial hypothesis concerning asymmetries better described when the full torque curves are analyzed. We discuss this main outcome considering that an analysis of the torque curve profile allows a better understanding of the whole biomechanical movement pattern. Our secondary hypothesis concerning lower intensities eliciting larger asymmetry than higher intensities was not confirmed. Neither ANOVA nor FANOVA showed significant interactions between leg and intensity.

The influence of pedaling asymmetries on cycling performance is unclear. Previous reports have considered peak torque to address this question and found controversial results (Carpes et al., 2007; Bini et al., 2010; García-López et al., 2015). These previous studies shared the same approach to analyzing asymmetries, which was to only consider the peak torques. Although relevant to the knowledge of the pedaling characteristics, given that a higher peak torque elicits a higher peak power output, considering a single value to represent pedaling asymmetries neglects the variability of the mechanical degrees of freedom of the human movement system. Indeed, it is possible to start a movement from the same initial position and achieve an identical final position with different partial movements (Bersntein, 1967). In this sense, one aspect that may have contributed to the divergence of results between previous studies is that the reduction of crank torque output to a single point (peak torque) was summarized without considering the pedaling pattern leads to this value. One could argue that pedal forces are important to analyze. We agree, but in this specific study, we consider that crank torque is also important due to its direct relationship with power output. The approach we propose can be easily applied to analyzing force signals considering data from instrumented pedals.

We hypothesized that the analysis of torque curves throughout the crank revolution would provide a clearer understanding of torque production for each leg; to test this hypothesis we performed a FANOVA analysis. The main advantage of using FANOVA is that the raw data do not need to be reduced to a single summary value or group of values to accommodate statistical analyses. Furthermore, the implementation of FANOVA is relatively straightforward, requiring only basic functions that are freely available in the literature (Ramsay, Hooker & Graves, 2009). Here, FANOVA detected relevant practical information about asymmetry not identified by the ANOVA analysis. These findings agree with Røislien et al.

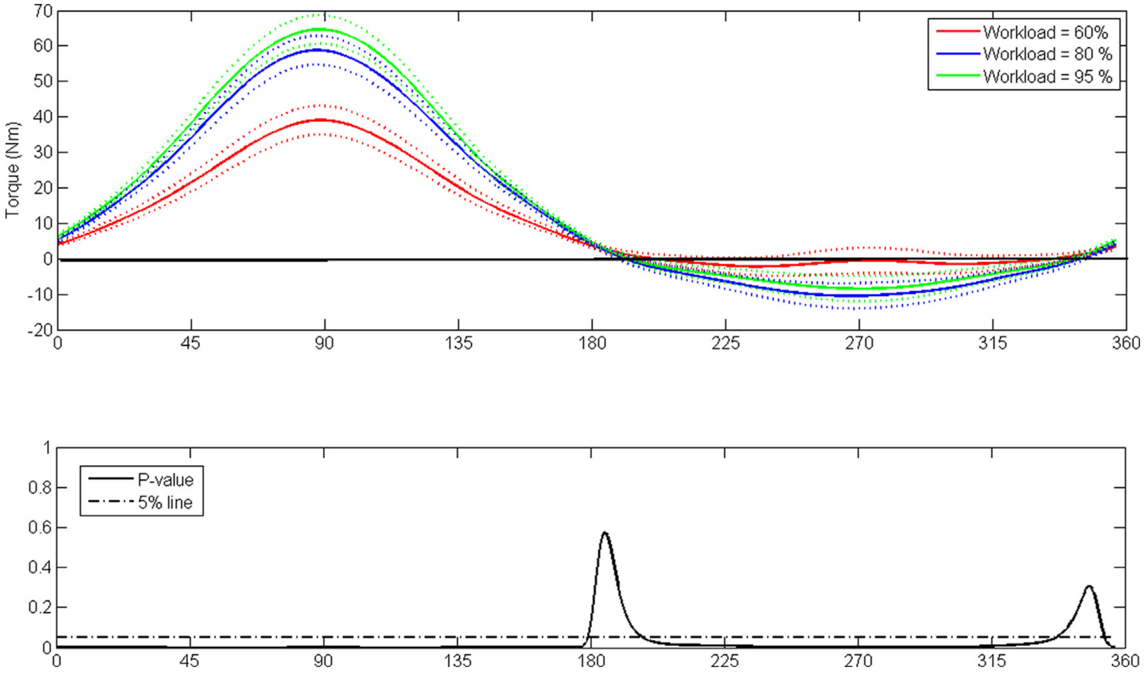

Fig. 1. The curves represent the mean and 95% confidence intervals of the torque profiles (Nm) in the three exercise intensities (upper panel). The pointwise F-test showed a main effect of exercise intensity. The Bonferroni post-hoc analysis showed that the torque curves did not differ significantly between the intensities of 80% and 95%. Still, both intensities elicited higher torque profiles than 60% of the power output, with p-values lower than the significance level adopted (the dotted horizontal line indicates a significance level set at 0.05 in the bottom panel). Nm: Newton-meter.

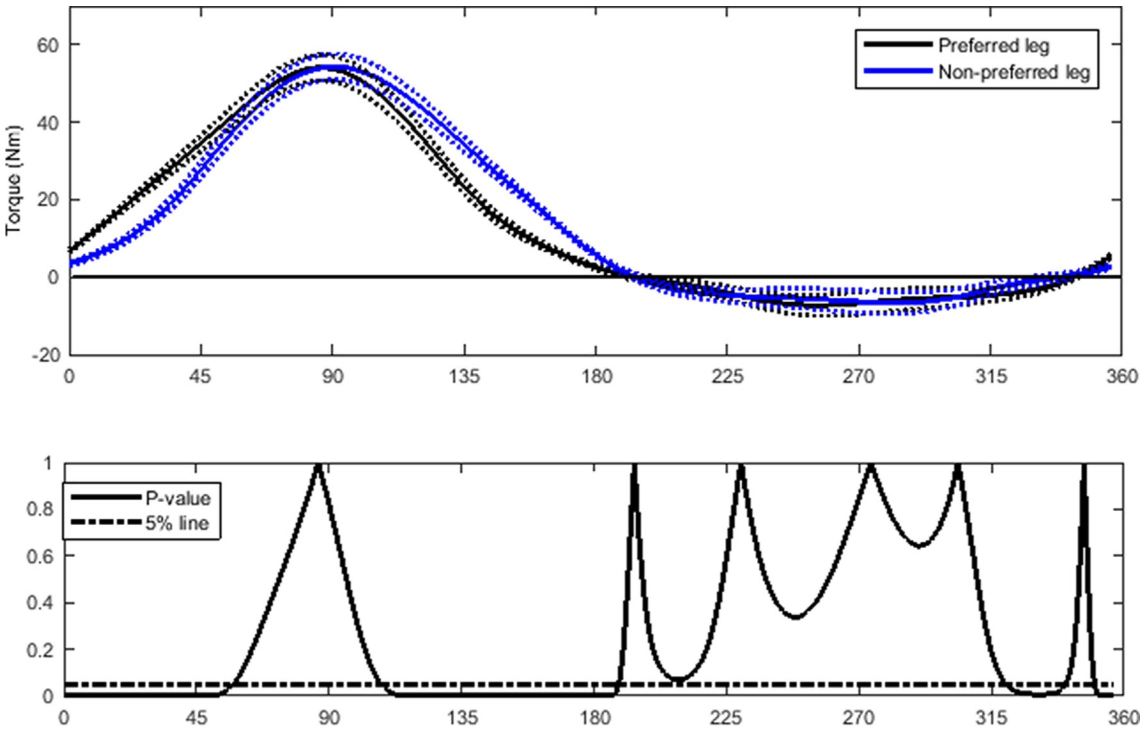

Fig. 2. The curves represent the mean and 95% confidence intervals of the torque profiles (Nm) between the preferred and non-preferred legs (upper panel). The pointwise F-test showed a main effect of the leg. The Bonferroni post-hoc analysis identified significant asymmetries in the torque curve from 0° to 50°, 130° to 180°, and 320° to 330° of the crank cycle, with p-values lower than the significance level adopted (the dotted horizontal line indicates a significance level set at 0.05 in the bottom panel). Nm: Newton-meter.

(2009), who stated that univariate methods are often insufficient, and Schöllhorn et al. (2002), who proposed that a continuous-time data approach adds relevant information for movement analyses. Furthermore, FANOVA analysis routines are easily implemented and the computational cost is low (Ramsay, Hooker, & Graves, 2009).

Asymmetries are very individual and high variability is observed when athletes or conditions, in this case, three different

Table 1
Peak torque determined for the preferred and non-preferred legs at the three intensities. Data are presented as mean (standard deviation). Intensities are described as percentage of the individual maximal power output (MPO). N.m: Newton-meter.

Intensities (MPO)	Preferred (N.m)	Non-preferred (N.m)
60%	48.17 (9.8)	48.45 (10.7)
80%	58.04 (7.4) *	57.67 (7.8) *
95%	55.80 (21.6)	(21.3)

* $p < 0.05$ A main effect of intensity was found by ANOVA identifying higher peak torques at an intensity of 80% compared to 60% of the MPO.

intensities, are grouped (Daly & Cavanagh, 1976; Carpes et al., 2007; Bini et al., 2016); therefore, asymmetry could be considered as an athlete "signature" that is consistent across different intensities (main effect). A similar observation was found previously when similar asymmetric peak torques were found for cyclists pedaling at different saddles heights (Diefenthaeler et al., 2016). When we compared the peak values using the common ANOVA approach, no pedaling asymmetries were identified. On the other hand, the FANOVA identified asymmetries for specific portions of the propulsion phase (0° to 180° of crank revolution). This result indicates the limitation of a single-moment analysis to describe cycling asymmetries. Differences in peak torque between the intensities, as depicted by the ANOVA and FANOVA analysis, are expected considering that higher power output requires larger torque, and peak torques are coincident with the crank's horizontal position arm at 90°, which favors the application of effective force. Therefore, we consider that FANOVA was able to show differences that were more related to the pedaling technique, which means the way cyclists apply force to the crank.

An interaction between intensity and asymmetry was not observed in the current study. In previous studies that suggested such an interaction, athletes performed simulated time trials in which the power output and cadence were variable (Carpes et al., 2007; Bini et al., 2010). We hypothesize that the constant workload and cadence may lead to a more stable force application pattern and, therefore, minimize asymmetries in peak values. We also avoided analysis of pedaling asymmetry in a state of fatigue that may significantly affect patterns of pedal force application (Diefenthaeler et al., 2012).

5. Conclusions

We conclude that considering the entire movement cycle analysis can more accurately identify torque asymmetry in cycling, regardless of the exercise intensity. Therefore, applying FANOVA permits better identification of asymmetries in amateur cyclists' torque profile. The possibility of using FANOVA to identify regions or sections of the movement influenced by a particular experimental condition, training level, or fatigue level in a statistically rigorous manner may provide a significant contribution to the analysis and understanding of asymmetry in sports biomechanics. Furthermore, it permits the combination of kinetics assessment with other approaches like EMG and kinematics.

Declaration of Competing Interest

The author declare that there is no conflict of interest.

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