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1. Introduction

Evaluating pedaling asymmetry in cycling is of major interest since it is often associated to lower efficiency, an increased risk of injury or premature fatigue. To quantify asymmetry, algebraic indices are commonly used to evaluate bilateral differences of discrete variables or through waveform analysis by comparing bilateral patterns (Pouliquen et al., 2018). Whereas some studies quantified bilateral muscle activations of lower limbs during straight and curved sections in track cycling (Watanabe et al., 2015), no data were reported concerning *in situ* kinematic asymmetry adjustments during a cycling time-trial (TT), especially considering women. Thus, the aim of this study was to assess the bilateral asymmetry of body-segment angular rates during a 4-km TT among female cyclists. In particular, the modifications in asymmetry all along the TT were investigated using lower limb mounted gyroscopes.

2. Methods

2.1 Experimental procedure

After a standardized warm-up, 7 high-level female cyclists, all right-leg-dominant, performed a self-paced 4-km TT on an outdoor velodrome. Angular rates of bilateral thigh, shank and foot were monitored all along the test using IMUs (Cometa MiniWave Infinity) at a sampling rate of 286 Hz with a full scale of ±2000 deg/sec.

2.2 Data analysis

Before the trial, an anatomical calibration procedure was performed in order to align IMU sensor frame to body segment frame following a method previously evaluated (Cordillet et al., 2019). Such a method allows to obtain angular rates in relation to the body segment frames. In order to perform cycle-to-cycle analysis, pedaling cycles were extracted from the medio-lateral angular rate of the thigh mounted IMU by identifying dead centers (crank arms at 12 o'clock and 6 o'clock). Medio-lateral component of angular rate for each body-segment was considered for analysis. In order to compare time delays between right and left patterns of angular rates during pedaling cycles, a normalized cross-correlation technique (Gouwanda and Senanayake, 2011) was used to identify similarities between the left and right waveforms as follows:

$$r_{\dot{\theta}_R\dot{\theta}_L}(k) = \frac{c_{\dot{\theta}_R\dot{\theta}_L}(k)}{\sqrt{\sum_{t=1}^{N}\left(\dot{\theta}_R(t)-\overline{\dot{\theta}_R}\right)^2 \sum_{t=1}^{N}\left(\dot{\theta}_L(t)-\overline{\dot{\theta}_L}\right)^2}}$$

Where $c_{\dot{\theta}_R\dot{\theta}_L}(k)$ is defined as:

$$c_{\dot{\theta}_R\dot{\theta}_L} = \begin{cases} \sum_{t=1}^{N-k}\left(\dot{\theta}_R(t)-\overline{\dot{\theta}_R}\right)\left(\dot{\theta}_L(t+k)-\overline{\dot{\theta}_L}\right) \\ + \\ \sum_{t=N-k+1}^{N}\left(\dot{\theta}_R(t)-\overline{\dot{\theta}_R}\right)\left(\dot{\theta}_L(t-N+k)-\overline{\dot{\theta}_L}\right), k \in [1, N] \\ \sum_{t=1}^{N-k}\left(\dot{\theta}_R(t)-\overline{\dot{\theta}_R}\right)\left(\dot{\theta}_L(t+k)-\overline{\dot{\theta}_L}\right), \quad k = 0 \end{cases}$$

$\overline{\dot{\theta}_R}$ and $\overline{\dot{\theta}_L}$ represent mean values for the right and left instantaneous rotations ($\dot{\theta}_R$ and $\dot{\theta}_L$). The left angular rates were shifted by 180° to synchronize the initial kinematic cycle at bottom dead center, for both legs. τ_{lag}, expressed as pedal angle lag, indicates the angle lag of the right pattern compared to the left pattern and corresponds to the value k for which the correlation coefficient $r_{\dot{\theta}_R\dot{\theta}_L}(k)$ is maximal. A positive τ_{lag} indicates that the right pattern is shifted forward in the crank cycle relative to the left pattern. For each body-segment, the maximal cross-correlation value (r_{max}) corresponding to the best overlap between the right and left limb angular rates was considered.

2.3 Statistics

A Shapiro-Wilk normality test was employed on τ_{lag} and r_{max}. A non-parametric Friedman test was used to determine the effect of distance (each 1-km interval was compared to the first one). Pairwise Wilcoxon test was employed for the multiple comparisons. Level of significance was set at $p<0.05$.

3. Results and discussion

	Sections	r_{max}	p	τ_{lag}	p
Foot	km 1	0.935	n/a	1.86	n/a
	km 2	0.929	n.s	2.45	n.s
	km 3	0.922	*	3.11	*
	km 4	0.920	*	3.19	*
Shank	km 1	0.951	n/a	9.29	n/a
	km 2	0.950	n.s	10.25	n.s
	km 3	0.948	n.s	10.76	*
	km 4	0.950	n.s	10.38	*
Thigh	km 1	0.887	n/a	0.22	n/a
	km 2	0.881	n.s	0.40	n.s
	km 3	0.877	n.s	0.59	n.s
	km 4	0.873	*	0.08	*

Table 1 Results of cross-correlations between right and left angular rates waveforms during the 4-km TT. Evolutions of angle lags (τ_{lag}) and maximal correlation coefficient (r_{max}) expressed in degrees. All values were compared with the first kilometer. * denoted significant differences with p value lower than 0.05 (n.s : non significant).

Results of cross-correlation between right and left angular rates waveforms during the 4-km TT are presented in Table 1. Lower correlation was obtained for the thigh. Indeed, while high pattern similarity was observed for the foot and the shank ($r_{max} > 0.9$), moderate similarity for thigh was highlighted ($r_{max} < 0.9$). Furthermore, the similarity between left and right pattern of the shank was not affected by the distance. However, in comparison with the first kilometer, the correlation coefficient for the foot was significantly lowered from the third kilometer. For the thigh, the similarity between bilateral waveforms was significantly lowered during the fourth kilometer. Concerning the angle lag between right and left patterns, a positive sign of τ_{lag} was overwhelmingly observed and can be associated to the right leg patterns mostly ahead of time compared to the left leg. More specifically, for the foot, absolute value of τ_{lag} increased from the third kilometer. For the shank, significant differences were also observed from the third kilometer, but with a decrease of τ_{lag}. Finally, concerning the thigh, a significant difference was quantified from the fourth kilometer. Despite some inter-individual differences, the observed kinematic adjustments, especially the reduction of similarity of side-to-side patterns may reflect a response to fatigue mechanisms that cause movement deterioration during the test (Pouliquen et al., 2018).

4. Conclusions

Considering the angular velocity patterns in the sagittal plane, the asymmetry in the thigh was less affected by the distance and thus by fatigue appearance. The foot demonstrated the highest differences in terms of bilateral pattern similarity but also in terms of angle lag between sides. However previous studies during exhaustive exercises in laboratory conditions demonstrated that the asymmetry of sagittal kinematics was less affected than out of sagittal planes (Pouliquen et al., 2018). Thus, an interesting prospect of this study would be to consider asymmetry analysis in frontal and transverse planes during time trials.

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