JOINT KINEMATIC ASYMMETRY BASED ON SPATIOTEMPORAL PATTERN DEVIATION DURING AN INCREMENTAL TEST IN HIGH LEVEL CYCLING

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The aim of this study was to use two asymmetry indexes from a kinematical point of view in professional cyclists during an incremental test to exhaustion. Twelve professional cyclists were evaluated during the French Cycling Federation's protocol. Based on motion capture, asymmetry analysis was addressed by means of cross-correlation technique and a normalized symmetry index (NSI). Results pointed out that NSI could vary up to 18% throughout the pedaling cycle, with different behavior between upward and downward pedaling phases. Both methods exhibited low values of asymmetry especially for flexion/extension, but higher asymmetry values for other DOF. This study shows the complementarity of both NSI and cross-correlation methods. It enables to continuously evaluate changes during the crank cycle associated to skeletal movement.

KEY WORDS: cycling asymmetry, cross-correlation, normalized symmetry index.

INTRODUCTION: High level cycling may lead to important microtraumatic risks and overuse injuries. Although cycling is done in partial lower limbs discharge, repetitive high loadings for periods up to several hours may contribute to overuse injuries (Abt et al., 2007). The primary factors causing microtrauma to the musculoskeletal system are related to the interface between the rider and the bike, e.g., positioning of the foot on the pedals, seat height and fore-aft adjustment, crank length, trunk inclination etc. Secondary factors relate to individual pedaling technique, changes in anthropometric parameters, or asymmetries between left and right sides (Gregor, 2000). Thus the evaluation of pedaling asymmetry is of importance as it may be associated to better performance and reduce the risk of overuse injuries. Most common indices used to evaluate pedaling asymmetry are considered using dynamical or kinematical approaches. From a dynamical point of view, some studies used indices based on the force generated (ratio of maximum forces generated by the right leg and left leg), on the crank torque or on the external work (ratio of external works generated by the right and left leg) (Smak, Neptune & Hull, 1999). These indices appear to depend on the dominant limb but also on cycling cadence (Smak et al., 1999; Daly & Cavanagh, 1976; Sargeant & Davies, 1977). From a kinematical point of view, most approaches are based on global parameters using range of motions (see Carpes, Mota & Faria, 2010 for a review) but scarce of them consider instantaneous values of asymmetry index during a pedaling cycle. Thus, information about the shape of kinematic pattern (changing magnitude across crank cycle) is often ignored. To overcome this limitation, objective methods are needed for analyzing kinematic data taking into account both timing and shape of the joint angular position during cycling motion. It is argued that uncoupling or asymmetry between limbs manifests itself in characteristic delays (phase shift) between significant events in distinct time signals. Thus, the use of cross-correlation techniques (Li & Caldwell, 1999) is a well-established approach for comparing signals and assessing time and shape similarities between time series-data. Moreover, some authors recently proposed to quantify asymmetry in gait events by means of a normalized symmetry index (Gouwanda & Senanayake, 2011). This method was revealed to be reliable for gait clinical applications, but might also be applied to biomechanics for cyclic sport motions. The aim of this study was to characterize spatiotemporal deviation between right and left limb motion in high level cyclist when exhausted using two different approaches. Differences are quantified using pairwise cross-correlation functions applied to recorded 3D kinematic data and using a normalized symmetry index (NSI).

METHODS: Twelve professional UCI Continental cyclists took part in the study.

Protocol: Before their participation, all subjects were informed of the risks and stresses associated with the protocol and gave their written consent. Each cyclist performed an incremental test to exhaustion on an SRM indoor trainer. This protocol is used by the French Cycling Federation to estimate maximum aerobic power. The ergometer was customized with subject's own bicycle's measures and clipless pedals. A display on the handlebars was used to check their power and pedaling cadence. After a 4min warm up, the test was an incremental test during which the power output was increased every 2min from 100W by stages of 50W until cyclists' voluntary exhaustion or when they were unable to maintain pedaling cadence. Power output was measured using the SRM training system (Science version, precision 0,5°). Before the experimental procedure, the SRM were calibrated according to the manufacturer's recommendations. The present analysis focused on the last stage of the incremental test to exhaustion.

Motion capture data collection: Cyclists were equipped with a set of 43 markers placed on anatomical landmarks. One additional marker was positioned on each pedal in order to automatically determine top dead center (TDC) and bottom dead center (BDC). Twelve high-resolution cameras of 4 megapixels operating at a nominal frame rate of 100Hz were used. After the capture, 3D coordinates of the landmarks were reconstructed with Vicon Nexus 1.8.5 (Oxford, UK) with a residual error less than 1mm. The 3D coordinate data were smoothed using a 2nd order Butterworth low pass filter with a cut-off frequency of 10Hz. 3D hip, knee and ankle rotations were calculated according to ISB recommendations (Wu & Cavanagh, 1995, Wu et al. 2002), following the ZXY sequence. For each subject, kinematic data were averaged using 20 crank cycles. The Range Of Motion (ROM) has been computed for each leg, as the absolute value of difference between the minimal and the maximal value.

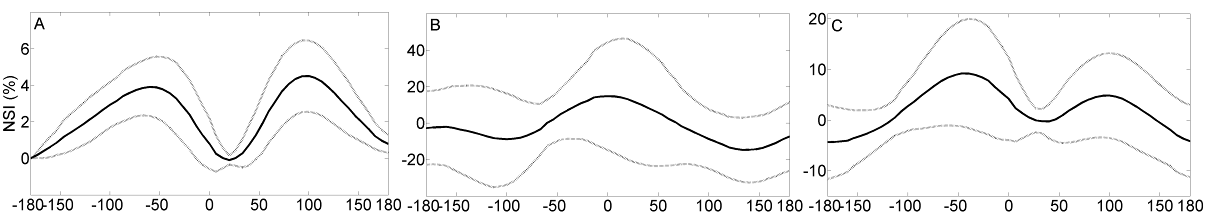
Kinematic asymmetry: In this study, two methods of assessing 3D joint asymmetries were used: instantaneous normalized symmetry index (NSI) and cross correlation technique. For each anatomical rotation (e.g., flexion/extension: fle./ext., abduction/adduction: abd./add., internal/external rotation: int./ext. rot.), θ_R and θ_L represent the joint angles for the right limb and left limb respectively. First, differences between right and left limb motion were assed using cross-correlation technique proposed by (Li & Caldwell, 1999): r_{max} corresponds to the correlation coefficient (CC) at the maximum of the cross-correlation function and gives an indication on the similarity of the right and left kinematic pattern for each Degree Of Freedom (DOF). τ_{lag} is the lag time (expressed as pedal angle lag) at the maximum of the cross-correlation function. Positive τ_{lag} indicates that θ_L leads θ_R and negative τ_{lag} implies that θ_L lags behind θ_R. Secondly, NSI was calculated for each time step following a method adapted from (Gouwanda & Senanayake, 2011):

$$\mathrm{NSI} = \frac{\theta_{N_R} - \theta_{N_L}}{(\theta_{N_L} + \theta_{N_R})/2} * 100$$

where

$$\theta_N = \frac{\theta - \theta_{min}}{\theta_{max} - \theta_{min}} + 1$$

In this equation, θ_R and $\theta_L$are normalized in θ_{N_R} and $\theta_{N_L}$to avoid negative value.



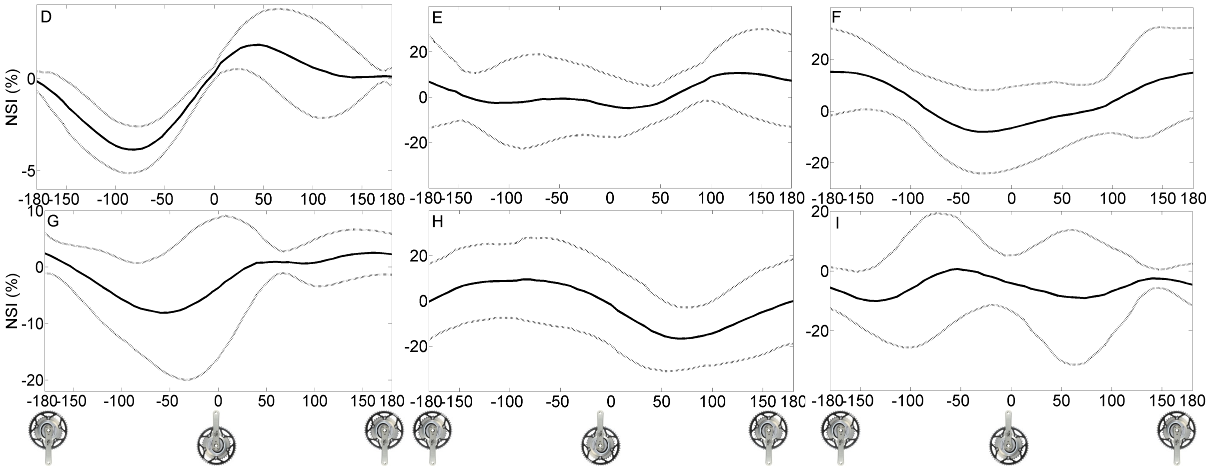


Figure 1: Mean (black line) and STD (grey line) of Normalized Symmetry Index for each DOF (A: hip fle./ext.; B: hip abd./add.; C: hip Int./ext. rot; D: knee fle./ext.; E: knee abd./add.; F: knee int./ext. rot; G: ankle pla./dor.; H: ankle inv./eve.; I: ankle int./ext. rot)

RESULTS: Results of cross correlation method are presented in Table 1. For each joint, the highest values of CC (r_{max}>0.95) correspond to fle./ext. indicating a high symmetry for this DOF. Moreover, low phase shifts are reported for fle./ext. associated with low τ_{lag} values (-0.55° for hip, 1.71° for knee and -3.13° for ankle joints. On another hand, the lowest CC values depicting the most asymmetric patterns correspond to the hip abd./add. (r_{max}=0.45) and ankle abd./add. (r_{max}=0.64). These latter joints are associated to the largest values of τ_{lag} (τ_{lag} = -23.99° and -7.72° respectively) which confirms a lowest synchronicity expressed by means of negative phase shifts. Finally, internal/external rotations exhibit values of 0.94 (hip), 0.80 (knee) and 0.82 (ankle). Figure 1 represents mean (±STD) NSI evolution for each DOF during the crank cycle. It can be observed that mean NSI fluctuates between 18% (for int./ext. knee rotation) and -15% (for ankle inv./eversion). Whatever the joint involved in the cycling motion, flexion/extension is the less affected DOF (absolute fluctuations lower than 8%). It can also be noticed that magnitude of NSI continuously changes during the crank cycle. Regardless of the DOF, NSI exhibited different behavior between upward (from -180° to 0° on fig. 1) and downward (from 0 to 180° on fig. 1) phases.

Table 1: Cross correlation coefficient, lag angle, NSI and ROM for both legs.

Joint	DOF	Cross correlation		NSI (%)	ROM±STD (°)	
		r_{max}	τ_{lag} (°)	Mean±STD	Right Leg	Left Leg
Hip	Flexion/Extension	0.99	-0.55	2.28±1.29	58.83±4.09	47.37±5.16
	Abduction/Adduction	0.45	-23.99	-1.72±21.91	10.90±5.64	9.78±5.50
	Internal/External Rotation	0.94	2.98	2.08±6.97	18.78±4.97	22.30±6.59
Knee	Flexion/Extension	0.99	1.71	-0.70±1.35	85.62±3.74	74.03±4.31
	Abduction/Adduction	0.75	-15.29	1.78±14.89	11.63±2.92	12.57±4.22
	Internal/External Rotation	0.80	-12.59	3.46±14.63	11.91±3.61	9.95±4.09
Ankle	Plantarflexion/Dorsiflexion	0.95	-3.13	-1.71±6.52	19.03±4.97	19.84±5.36
	Inversion/Eversion	0.64	-7.72	-1.89±17.06	10.88±4.63	10.90±6.79
	Internal/External Rotation	0.82	-3.76	-5.23±13.14	9.84±4.61	13.99±3.91

DISCUSSION: This study showed asymmetry between legs for all joints during the last stage of an incremental test. For the cross correlation method, τ_{lag} had negative value for six of the nine rotations, which means that the right leg is mostly ahead of time with respect to the left leg. An interesting prospect to this study could therefore be the leg dominance evaluation. NSI is used to provide the timing and magnitude of the movement deviations between left and right limbs in each cycling cycle. The main asset of this method lies in the possibility to associate NSI values with posture. Experiments conducted on high level cyclists indicated that NSI could vary up to 18% throughout the pedaling cycle. Indeed, conversely to classical symmetry indices for which the examiner has to choose few discrete time points to evaluate asymmetry, NSI method allows to account for instantaneous evolution of asymmetry during different phases of the crank cycle. For these reasons, NSI is a valid indicator of cycling asymmetry at any time of the cycle, but it requires analysis all along the trial and do not take into account for time shifts between legs. On another hand, the cross-correlation method provides a single value indicator that evaluates the movement patterns (shape and time delay) of the right and left limb to define joint asymmetry during cycling. The combination of the two methods is very useful, the first one to quantify the temporal shift and to find which side is ahead of the other and the second one to give an objective value for the asymmetry based on kinematical data. The present study showed that both methods exhibited low values of asymmetry for high level cyclists, especially for flex./ext. However this study quantified higher asymmetry for other DOF. This could be partly explained by larger relative standard deviations (as compared to mean values) presented in Table 1 for some DOF. It should also be noted that motion capture methods implies more variability in the transverse and frontal planes than in the sagittal plane (Nigg, Vienneau, Maurer & Nigg 2013; Sayers, Tweddle, Every & Wiegand, 2012).

CONCLUSION: This study analyzed anatomical rotations of the lower limb and asymmetry between legs during the last stage of an incremental test and pointed out the complementarity of both NSI and cross-correlation methods. It enables to continuously evaluate changes during the crank cycle associated to skeletal movement.

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