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Original Article

Effects of saddle height on muscular pattern and interlimb coordination in cycling

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Abstract:
Purpose: In the face of empiricism prevailing to set an ideal position in cycling, the present study aims to find whether interlimb coordination and muscular activation patterns would provide relevant parameters to characterise an optimal saddle height. Methods: Eighteen experimented bikers were asked to pedal at a rate of 90 rpm under three randomized experimental conditions: Usual Saddle Height (USH), Saddle Height plus (SHP) (leg fully extended, pedal down, ankle in a neutral position) and Saddle Height minus (SHM) (same saddle height difference applied inversely). From the 3D coordinates, the kinematics of ankle, knee and hip were computed and the relative phase between the joints periodic motion was assessed through a Continuous Relative Phase (CRP) algorithm. Muscular activity was recorded through a surface EMG system. Results: While the hip, the knee, and the ankle range of motion were affected by saddle height changes, CRP highlights modifications in interjoint coordination, particularly between ankle and knee and ankle and hip, indicating significant tendency to an in-phase coordination for the experimental conditions compared to the USH condition. Conclusions: Whereas saddle height changes affect joint kinematics and muscular patterns, the freeing of neuro-muscular degrees of freedom in the USH condition allows motor output to adapt dynamically during its very execution. Results suggest that interjoint coordination is an integrative variable providing a relevant parameter to define a correct saddle height in cycling. To reach an ideal cycling position, it may help avoiding the deleterious and painful consequences of a cyclist's inadequate position.
KeyWords*:* saddle height; coordination; muscular pattern; cycling position

Introduction

The riding position is a key factor for performance (Faria, Parker, & Faria, 2005) and comfort while cycling(Ayachi, Dorey, & Guastavino, 2015). Any modification of the cycling position induces change in the trunk angle, hence, a change in the relation between body posture and the bicycle geometry which will affect physical performance (Fonda & Sarabon, 2010). Such postural changes may be reflected in the neuromuscular activation patterns (Chapman et al., 2008). For example, the subsequent modifications in length for muscles that span the hip joint influence the joint torque distribution and can require the recruitment of more distal muscles (Savelberg, Van de Port, & Willems, 2003).

Since body configuration impacts the efficiency of cycling (Duc, Bertucci, Pernin, & Grappe, 2008), it could also induce injuries due to overuse, particularly for the knee joint (Ferrer Roca, Roig, Galilea, & Garcia-Lopez, 2012).

Sitting height is critical for an adept configuration of the bicycle, hence of the riding position, and several methods have been proposed to set a proper saddle height, albeit without reaching unanimity (Peveler, Bishop, Smith, Richardson, & Whitehorn, 2005): While some authors use the crotch length, others refer to knee kinematics (Cavanagh & Sanderson, 1996). Even though saddle height modifications affect timing and kinematic variables, a certain empiricism still prevails in setting an ideal position, with the consequence of frequent muscle and joint chronic diseases(Callaghan, 2005). At any rate, an undisputed reference for an optimal cycling position is a non-fully extended knee.

Like any complex system, that is, an ensemble composed of innumerable components (Kelso, Southard, & Goodman, 1979), the human body is adept to exploit its redundancy in order to bring about an appropriate coordinative pattern in a given context.

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Studying movement in terms of interlimb coordination has been fruitful in the domain of sports science (Dedieu & Zanone, 2013), particularly in the field of cycling (Chapman, Vicenzino, Blanch, & Hodges, 2009; Sides & Wilson, 2012).Following the pioneering work of Bernstein (1937/1967) postulating that motor learning implies a reduction of the redundant degrees of freedom, numerous studies showed that practice gradually releases or “frees” some among all available degrees of freedom, so that they progressively “learn” to work together (Temprado, Della-Grasta, Farrell, & Laurent, 1997). Thus, the production of coordinated movements involves synergies which, with increasing practice, exploit redundancy in order to achieve coordination and flexibility.

In this context, the consideration of the timing relationship between segments is instrumental in the analysis of cycling movement, particularly in order to capture the complexity of the body coordinated motion. Since the motion of one segment influences the motion of adjacent segments (De Leo, Dierks, Ferber, & Davis, 2004), the study of isolated joints does not effectively capture the complexity of the coordinated motion of the bodily components (Bartlett, Wheat, & Robins, 2007). So, considering only the articulatory aspect to determine cycling position is bound to be insufficient, if not misleading.

Beyond the organisation of joints, a modification of the riding position can also tap into the neuromuscular system (Chapman et al., 2008). Changes in the muscle activation pattern may be viewed as a sign of the ongoing modification in the synergy, bringing together all the components at all levels in order to produce a specific coordinated motor output (Latash, 2008). Thus, it is beneficial, if not critical to analyse the synchronization between joints in association with the ongoing pattern of muscular activity, captured by ElectroMyoGraphy (EMG). This procedure may shed some light onto how the motor command issued by the Central Nervous System (CNS) to the muscles adapts following changes in the cycling position (Hamill, Haddad, & McDermott, 2000).

Notwithstanding the various existing methods based on joint kinematics devised to reach an optimal saddle height, the present study aims to find whether interlimb coordination and muscular pattern coordination could provide relevant parameters to characterise, on an individual basis, the riding position as a function to various height of saddle. Beyond a mere description of changes in the ongoing coordination pattern, this study may help setting standards for an ideal saddle height.

Material & methods

This study was done in accordance with the Helsinki Declaration and has been approved by the local ethics committee.

Participants

Eighteen experimented bikers participated in the study (males; age: 29.79 (SD 5.28) years; weight: 81.06 (SD 7.53) kg; height: 182.75 (SD 8.57) cm). They had 14.3 (SD 5.45) years of experience in cycling and were regular participants of competitive cycling events. Their average weekly training volume was 11.87 (SD 4.31) hours.All participants qualified as to be free of any type of pain and of any orthopaedic or neurological trouble in the lower extremities on the date of the experiment. They were informed of the procedures, methods, benefits and possible risks involved in the study. They volunteered to participate in the study and gave a written informed consent.

Procedure

Participants were asked to pedal on a home trainer with their own bike at a rate of 90 rpm monitored by a cadence sensor under three randomized experimental conditions: Usual Saddle Height (USH) calculated individually by every participant according to a standard method (Bini, Hume, & Croft, 2011), Saddle Height *plus* (SHP) (leg fully extended, pedal down, ankle in neutral position) and Saddle Height *minus* (SHM) (same height difference inversely applied). The mean height difference was +/- 2.09 % (SD = 0.43).

After an individual warm-up at freely chosen velocities, participants were asked to stabilize their cadence at a rate of 90 rpm in each experimental condition. In order to ensure measurements in a steady condition, data recording started at least 10 minutes after the ride onset at 90 rpm and lasted 1 minute

Data collection

The 3D coordinates of markers placed on body landmarks were recorded using a motion analysis system (Codamotion ™, Charnwood Dynamics Ltd, UK).

Muscular activity of *rectus femoris*, *vastus lateralis*, *vastus medialis,gluteus medius*, *biceps femoris*, *gastrocnemius medialis*, *gastrocnemius lateralis* and *tibialis anterior*was recorded through a surface EMG system (Trigno Wireless System ™, Delsys, Boston, MA).

Data processing

The raw 3D coordinates were smoothed through a two-way Butterworth low-pass filter with a cutoff at 6 Hz. The total cycle duration was calculated as the time between the moments when the pedal reached a 12 o’clock position on two consecutive times, that is, when the pedal marker reached its maximal value in the z-axis.

From the 3D coordinates, the kinematics of ankle, knee and hip were obtained, using the convention followed by Ferrer-Roca et al.(2014).

The relative phase value between ankle and knee, ankle and hip and knee and hip was assessed by a Continuous Relative Phase (CRP) algorithm, using a Hilbert transform within the range of $-180° \leq CRP \leq 180°$.

The EMG signal was band-pass filtered between 10 and 400 Hz. The linear envelope was obtained by low-pass filtering of the rectified signals at 6 Hz. Each linear envelope was normalized in time on 100 samples and in magnitude in reference to the highest peak of each pedal cycle. A muscle was considered to be active when the signal magnitude was above two standard deviations computed during relaxed upright standing. The start and duration of muscular activity were expressed as a percentage of the total cycle duration.

Statistical analyses

The mean values for the start, end and duration of muscle activity were compared through a repeated measures ANOVA.

The joint angular positions, the range of motion and CRP were averaged and analysed through a repeated measures ANOVA.

A k.Means Clustering Analysis was carried out using an average linkage method for CRP.

Effect size index was calculated.

The significance level for all analyses was set at $p < 0.05$.

Results

Mean angle value (Table 1)

The mean angle value between SHP and SHM conditions was significantly lower in the hip (resp. 47.02° ± 2.94 and 52.27° ± 1.61), the knee (resp. 67.68° ± 2.06 and 73.07° ± 2.23) and the ankle (resp. 65.13° ± 2.49 and 70.89° ± 1.49) when the saddle was in higher position than, respectively, usual saddle height and SHM condition (resp. $d = 0.78$; $d = 2.32$; $d = 1.29$ and $d = 2.22$; $d = 2.51$; $d = 2.80$).

Table 1: Kinematics and range of motion mean values (SD) and [confidence intervals] for hip, knee and ankle and Continuous Relative Phase (CRP) mean value (SD) and [confidence intervals] between ankle and knee, ankle and hip and knee and hip under the three experimental conditions.

	Saddle height		
	Saddle Height *minus*	Usual Saddle Height	Saddle Height *plus*
Mean angle value of hip (°)	52.27 (1.61) [51.53 53.01] †	49.09 (2.26) [48.05 50.13]	47.02 (2.94) [45.66 48.38]
Mean angle value of knee (°)	73.07 (2.23) [72.04 74.10] †	72.14 (1.76) [71.33 72.95]	67.68 (2.06) [66.73 68.63] ‡
Mean angle value of ankle (°)	70.89 (1.49) [70.20 71.58] †‡	67.88 (1.64) [67.12 68.64]	65.13 (2.49) [63.98 66.28]
Range of motion of hip (°)	43.17 (1.71) [42.38 43.96] †	49.63 (1.91) [48.75 50.51]	45.92 (2.01) [44.99 46.85] ‡
Range of motion of knee (°)	73.87 (1.06) [73.38 74.36] †‡	77.68 (2.25) [76.64 78.72]	76.95 (1.98) [76.04 77.86]
Range of motion of ankle (°)	10.97 (1.62) [10.22 11.72] †	15.89 (1.35) [15.27 16.51]	12.29 (2.49) [11.14 13.44] ‡
CRP between ankle and knee (°)	-11.35 (6.75) [-14.47 -8.23] †‡	-77.19 (5.87) [-79.90 -74.48]	8.47 (5.32) [6.01 10.93] ‡
CRP between ankle and hip (°)	-18.42 (6.18) [-21.27 -15.56] ‡	-51.26 (6.31) [-54.17 -48.34]	-6.25 (8.24) [-10.06 -2.44] ‡
CRP between knee and hip (°)	-14.33 (3.18) [-15.80 -12.86] ‡	-23.16 (5.06) [-25.50 -20.82]	-17.42 (5.56) [-19.99 -14.85]

†: Significant difference between Saddle Height *minus* and Saddle Height *plus*($p < 0.05$)

‡: Significant difference with Usual Saddle Height ($p < 0.05$)

Range of Motion value (Table 1 and Figure 1)

The hip, the knee, and the ankle range of motion (Figure 1) increase between SHP and SHM conditions is about 14.96 %, 4.16 % and 44.84 % for each joint torque with $d = 1.47$; $d = 1.94$; $d = 0.63$, respectively.

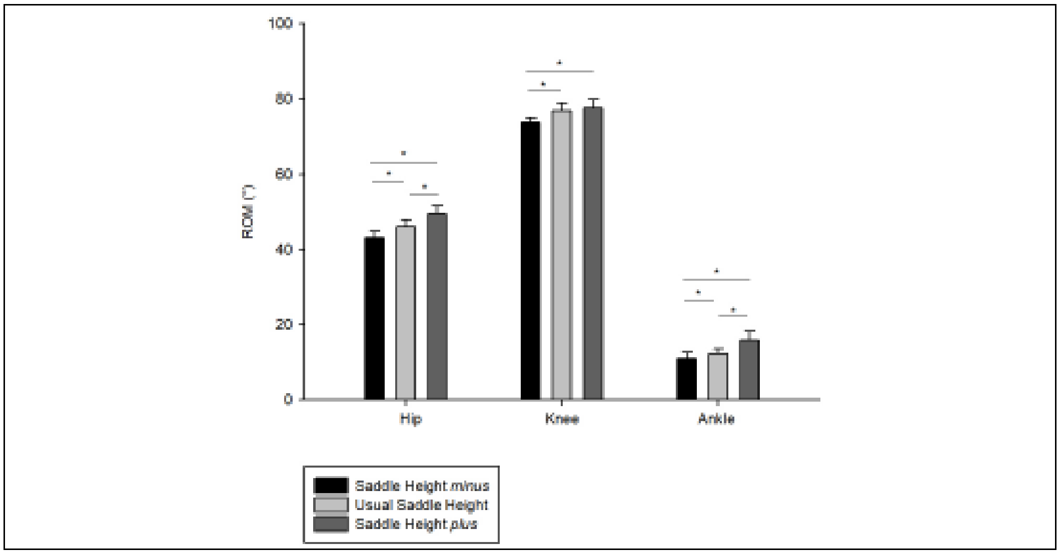

Figure 1: Range of Motion of hip, knee and ankle in all the three experimental conditions (* denotes significant differences)

Interjoint coordination (Table 1 and Figure 2)

The mean knee-hip CRP (Figure 2) was negative in all experimental conditions. It indicated that the hip was temporally ahead of the knee. On both sides of Usual Saddle Height (USH), the mean knee-hip CRP was close to 0 degree, which indicates that both joints tend to an *in-phase* coordination. The mean ankle-knee CRP (Figure 2) was also close to 0 degree on both sides of Usual Saddle Height (USH). Its value is negative in USH condition. This indicates that the ankle was temporally behind of the hipin USH condition. The mean ankle-hip CRP (Figure 2) was negative for all experimental conditions. This indicates that the hip was temporally ahead of the ankle. Its value indicates also there is a gap between both joints, significantly higher in USH condition. Moreover, compared to USH the saddle, theankle and hip were more *in-phase* for SHP and SHM.

The k.Means Clustering Analysis identified two clusters respectively without saddle height change (USH condition) and with saddle height change (SHP and SHM conditions). The correlation analysis between clusters and experimental conditions showed a significant correlation (ρ = 0.82).

Start and duration of muscular activity (Figure 3)

Duration and offset of *vastii, rectus femoris, gastrocnemii* and *soleus* were affected by saddle height changes. In both SHP and SHM conditions, the duration was longer than USH condition and the offset was delayed (Figure 3). Moreover, duration and onset of *biceps femoris* were also affected. In SHP condition, the start of activation was ahead, and duration was longer than the others experimental conditions (Figure 3).

A notable inter-subject variability, notwithstanding, prevents describing a uniform muscular pattern across participants.

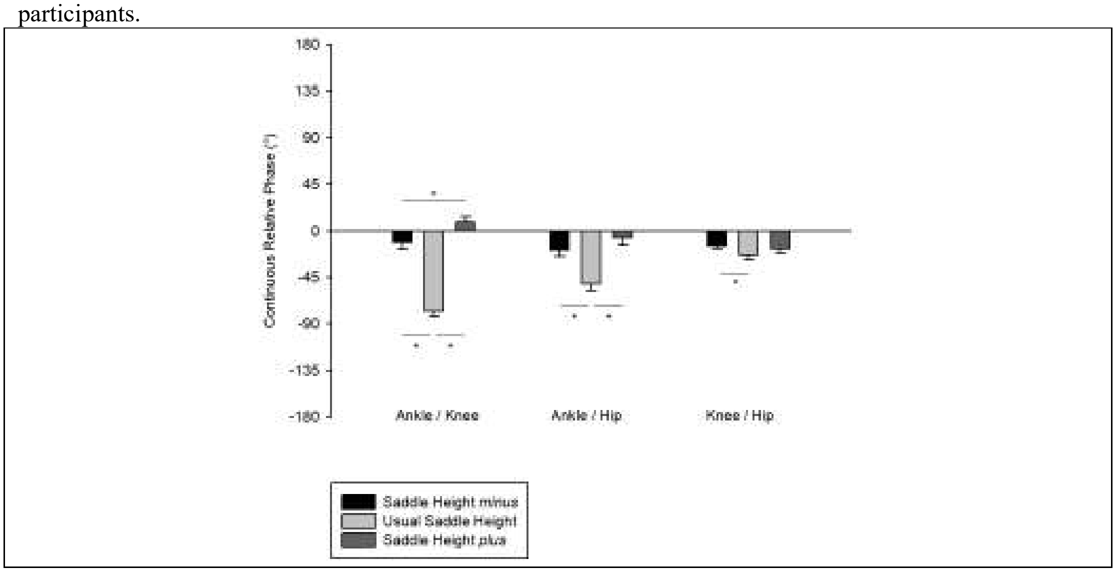

Figure 2: Continuous Relative Phase between Ankle/Knee, Ankle/Hip and Knee/Hip joints (* denotes significant differences)

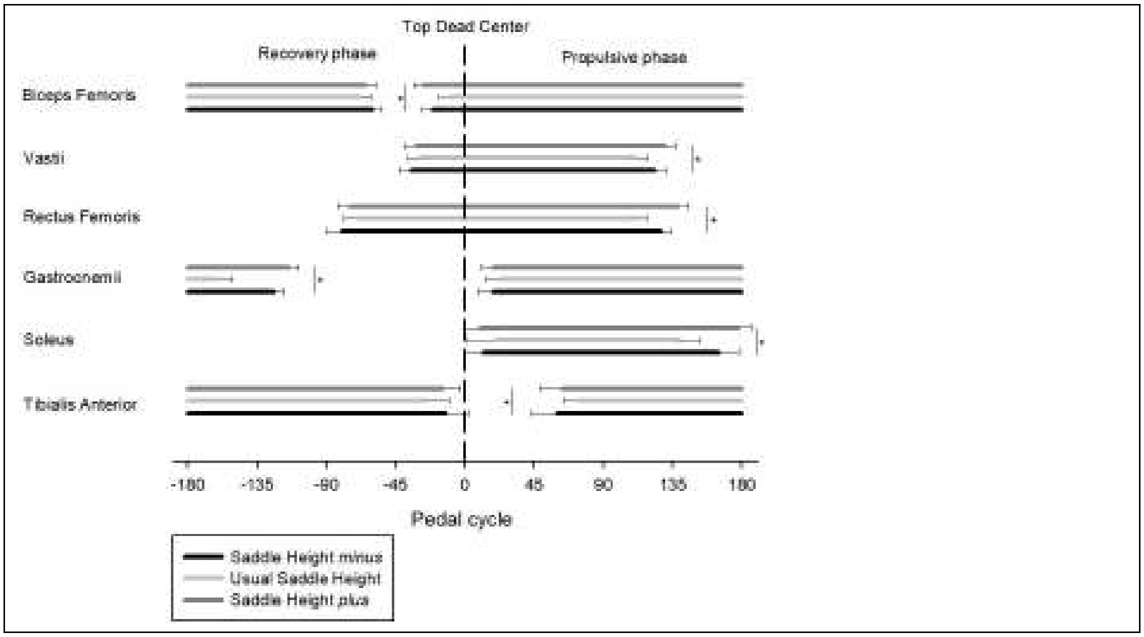

Figure 3:Start and duration of muscular activity during pedal cycle in all the three experimental conditions (* denotes significant differences)

Discussion

The aim of the present study was to explore whether interlimb coordination could be a relevant parameter to characterise the individual riding position by comparing the effects of imposing various heights of saddle.

As expected, a vertical change in the saddle height entailed changes the joints mean angle values and in t range of motion. The lower the saddle is, the more flexed the joints are. However, if the hip, the knee and the ankle ranges of motion increased between the extreme positions, their mean values were lower than in the usual position. When changes in saddle height cause joint flexion, an overload pain may follow particularly on the patellofemoral joints. Callaghan (Callaghan, 2005)indicated that such pain could be exacerbated by lowering the saddle height. McLean and Blanch (1993) pointed out that an inappropriate saddle height (particularly higher saddle) decreased the extensor torque at the knee, because the amount of knee flexion was lower. Moreover, saddle heightaffected *vastii*and *rectus femoris* activation patterns. All these alterations can contribute to the patellofemoral joints pain. The delayed offset of the activation of *rectus femoris* and *vastii* muscles in the SHPcondition could be an attempt for correcting the patellofemoral joints functional instability.

Beyond the articular changes, as shown by the mean joint angle that evolves in opposite directions in the SHM and SHP conditions (increase and decrease, respectively), the inter-joint coordination tends to 0° of CRP, that is, an in-phase coordination in both SHM and SHP conditions. This state of coordination represents a strong degree of joint linkage and a stable coordination motor pattern that can be maintained despite perturbations of the system (Kelso, Buchanan, & Wallace, 1991). Our results corroborate this assertion, particularly the EMG pattern in both SHM and SHP conditions. The start, end and duration of the muscular activity express a higher coactivation of the agonist/antagonist muscular groups, inducing a stronger joint linkage (Bini, Carpes, Diefenthaeler, Mota, & Guimaraes, 2008).

In-phase coordination is considered to be more stable due to a strong tendency to activate equivalent muscular groups simultaneously, that is, in cycling, to coordinate joint extensors vs. flexors. Moreover, such in-phase coordination proved to require less attention than out-of-phase pattern (Temprado, Zanone, Monno, & Laurent, 1999). Following Bernstein’s seminal hypotheses (1937/1967), it appears that, in order to control the relationship between joints in extreme saddle heights conditions, the CNS treats lower-limb joints as a single unit, by “freezing” kinematics degrees of freedom. On the contrary, in a USH condition, the observed discrepancy with the other height conditions suggests a reduction in the joint linkage. This loss of linkage could correspond to the release of degrees of freedom in the motor system, so-called "freeing" of degrees of freedom in Bernstein’s parlance.

The mean values of CRP are slightly higher in the present experimental conditions than those reported obtained by Sides and Wilson (2012) on a cyclo-ergometer. These values are different from the value of 0° typical of an in-phase coordination, which is considered to be a stable coordinative pattern (Kelso et al., 1979) and to require a low metabolic and attentional cost to be maintained (Zanone, Monno, Temprado, & Laurent, 2001). However, despite this apparent loss of stability, such coordinated behaviour has been reported in

numerous novice/expert comparison studies (Temprado et al., 1997): Freeing neuro-muscular degrees of freedom allows to adapt motor output dynamically throughout its very execution.
These coordination patterns could pertain to the observed differences in muscular activity. The *gastrocnemii* and the *soleus* muscles onset and offset are respectively ahead and delayed when the saddle height is in its extreme positions rather than in the usual position, so that duration of activity of the *gastrocnemii* and the *soleus* muscles is longer. From a biomechanical point of view, the *gastrocnemii*, by their multi-articular function, link both the ankle and knee joints (Sasaki & Neptune, 2006). Whereas Neptune and Herzog (2000) suggested that pedalling at rate of 90 rpm could be close to optimal for producing muscle power during sub-maximal pedalling, muscles onset and offset are delayed in SHP condition, particularly the knee extensors, perhaps in order to avoid knee instability in the a frontal plane.

Although the CRP modifications do not express the existence of a new coordination pattern, our results reveal an interjoint adaptation as a function to changes in the cycling position. The existence of multiple articular solutions contributes to the task complexity, so that one of the major difficulties encountered by the CNS in controlling and coordinating limbs is to harness such complexity.Whereas the riding position, imposing to sit on the saddle with the feet clipped on the pedals, does not offer a large number of combinations to bring the joints together in order to realize pedalling motion, the observed differences of CRP indicates that the CNS pick up every possibility of coordination to face changes in position. First, lower limb motion in cycling itself is constrained by the circular trajectory of the pedals and is therefore subject to practically no external influence. Second, only the ankle joint is susceptible to modify its movement. In turn, a usual seat height amounts to strengthening a coordination pattern between ankle and knee and ankle and hip that exists intrinsically, rather than creating a completely new pattern. These results are in accordance with expert vs. novice paradigms (e.g., Temprado et al., 1997(16)). The difference observed in the type of coordination took the form of changing the type of relationship between the ankle, knee and hip, and a reduction in strength of the relationships, which can be viewed as a freeing of degrees of freedom (Bernstein, 1937/1967).

These results support to the idea that in the face of changing constraints, the CNS can modify interjoint coordination while still preserving the same basic synergy (St-Onge & Feldman, 2003). Amongst numerous criteria adept to define a correct saddle height in cycling, the pattern of interlimb coordination appears to be a pertinent integrative variable. It could provide a means to reach an ideal cycling position and thus to avoid the painful consequences of an inadequate position for the cyclist. Interestingly, the various methods adopted to reach an optimal saddle height may reveal the emergence of an optimal solution for each individual. Facing the necessity to set an adept riding position, every single rider chooses to personalise one among the multiple possible coordinative solutions offered, rather than to adopt a common standard method. Notwithstanding these multiple solutions, the USH conditions gives rise to a single interjoint pattern of coordination, as shown by the reliability of the specific motion of every joint. On the other hand, a change in saddle height is also reflected by an increase of muscles co-contraction lading to an interjoint coordination closer to in-phase.

Conclusions

Beyond the focus on cycling, the present work proposes two complementary views on interlimb motion: the joint linkage defined at the physiological and anatomical level and the time relationship between the limbs at a coordinative level. If this dual approach to human movement somehow still bears on a distinction between the structural and functional aspects of movement, respectively, it offers a means to capture movement in its complexity. Going further than the mere analysis of isolated joints motion, the approach we adopted exposes the dynamical relationship between body segments.

Conflicts of interest Every author does not have any conflicts of interest to declare.

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