Citation for published version:
Sides, D & Wilson, C 2012, 'Intra-limb coordinative adaptations in cycling', *Sports Biomechanics*, vol. 11, no. 1, pp. 1-9. https://doi.org/10.1080/14763141.2011.637118

DOI:
10.1080/14763141.2011.637118

Publication date:
2012

Document Version
Peer reviewed version

Link to publication

Intra-limb Coordinative Adaptations in Cycling

Keywords: Cadence, Coordination, Cycling, Work Rate

Resubmission Date: 24 June 2011

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Abstract

This study aimed to establish the nature of lower extremity intra-limb coordination variability in cycling and investigate the coordinative adaptations that occur in response to changes in cadence and work rate. Six trained and six untrained males performed nine pedalling bouts on a cycle ergometer at various cadences and work rates (60,90,120 rpm at 120,210,300 W). Three dimensional kinematic data were collected and flexion/extension angles of the ankle, knee and hip were subsequently calculated. These data were used to determine two intra-limb joint couplings (hip flexion/extension-knee flexion/extension [HK], knee flexion/extension–ankle plantar-flexion/dorsi-flexion [KA]) which were analysed using continuous relative phase analysis. Trained participants displayed significantly ($p<0.05$) lower coordination variability (6.6±4.0°) than untrained participants (9.2±4.7°). For the trained subjects, the KA coupling displayed significantly more in phase motion in the 120 rpm (19.2±12.3°) than the 60 (30±7.4°) or 90 rpm (33.1±7.4°) trials and the HK coupling displayed significantly more in phase motion in the 90 (33.3±3.4°) and 120 rpm (27.9±13.6°) than in the 60 rpm trial (36.4±3.5°). The results of this study suggest that variability may be detrimental to performance and that a higher cadence is beneficial. However, further study of on-road cycling is necessary before any recommendations can be made.

Introduction

The majority of kinematic research in cycling has focused on individual lower extremity joints (e.g. Ericson, Nisell & Nemeth, 1988; Caldwell, Hagberg, McCole & Li, 1999). In a kinematic chain the motion of one segment subsequently influences the motion of an adjacent segment, and therefore the study of isolated joints does not effectively capture the complexity of the coordinated motion of components of the body (Bartlett, Wheat & Robins, 2007). The consideration of the coupling relationship between segments may therefore be crucial in the analysis of human movement and this was recently acknowledged in the field of cycling by Chapman, Vicenzino, Blanch and Hodges (2009). Quantifying the coupling relationships facilitates the analysis of joint coordination which has successfully been employed to gain insight into the movement strategies underlying performance in a variety of sporting disciplines such as walking and running (Li, van den Bogert, Caldwell, van Emmerik & Hamill, 1999) and triple jumping (Wilson, Simpson & Hamill, 2009).

A key component in the analysis of movement coordination is the role of variability within the system under investigation (Wilson, Simpson, van Emmerik & Hamill, 2008). Possessing movement variability is important in skills where the adaptability of complex motor patterns is necessary within dynamic performance environments (Button, Davids & Schollhorn, 2006). This adaptability enables athletes to adjust to both intrinsic and extrinsic factors (Bradshaw & Aisbett, 2006). However, in skills where tight task constraints are imposed or in closed kinetic chain activities, such as cycling, there is likely to be a reduced requirement for adaptability. This is despite the fact that there are many factors (intrinsic and extrinsic) which may need accommodating. Thus, any variability present in the system may be indicative of an inconsistent performance. It is often assumed that individuals share a common optimal pattern of movement in the belief that a single most efficient technique exists in the majority of the population (Brisson & Alain, 1996). This notion is evident in the cycling literature (Cannon, Kolkhorst & Cipriani, 2007; Ostler, Betts & Gore, 2008; Ettema & Loras, 2009) and may offer an explanation into the lack of research on movement variability in cycling.

A further area of research in coordination and its associated variability is the impact of control parameters. Changes in coordination occur when a specific control parameter (e.g. speed) is modified (Li et al., 1999). Two control parameters that can be manipulated by cyclists are cadence and work rate. In humans, the nature of the lower extremity coordination is affected by the inertial properties of the oscillatory segments (Haddad, van Emmerik, Whittlesey & Hamill, 2006). Li (2004) found that as cadence increases there is an added influence of the inertial properties of the limbs, which consequently affects coordination. There is conflict within the current cycling literature regarding the most economical cadence, defined in this study as that which is associated with the lowest metabolic cost at a given work rate. This is due in part to its work rate-dependent nature (Ansley & Cangley, 2009), which warrants the investigation of the two parameters simultaneously (Burke, 1996). Changes in the coordination patterns utilised by cyclists as a result of changes to the work rate and / or cadence may therefore have an effect on their economy.

The aim of this study was two-fold. Firstly to investigate how lower extremity intra-limb coordination variability varies in cyclists of differing experience, and secondly to investigate the intra-limb coordinative adaptations that occur in response to a change in cadence and work rate.

Methods

Participants

Six trained (mean ± □SD; age 20.82 ± □1.27 years; body mass 72.77 ± 11.00 kg; height 1.78 ± 0.07 m) and six untrained males (mean ± □SD; age 21.24 ± □1.25 years; body mass 74.41 ± 5.90 kg; height 1.81 ± 0.06 m) were recruited to participate in the study. The selection criterion for trained participants was a minimum of five hours of cycling specific training per week (mean ± □SD; 9.6 ± 4.7 hours) and for untrained participants zero hours of cycling training per week. All participants were free of lower extremity injury at the time of the study. Ethical approval for the study was obtained from the University's ethics committee and each participant provided written informed consent before the onset of data collection.

Experimental set-up

The experimental set-up consisted of a two-scanner Cartesian Optoelectronic Dynamic Anthropometer (CODA) motion analysis system (Charwood Dynamics Ltd., UK), collecting 3D kinematic data at a sampling rate of 100 Hz. The experiment was conducted on a Monark braked cycloergometer (Monark, Sweden).

Protocol

To control for potential effects of footwear all participants wore their own sports trainers as opposed to cycling shoes with cleats. Participants set the seat to a comfortable height and undertook a self-directed warm up for a period of two minutes. Twenty-three active markers of 2-mm diameter were attached to the right lower limb and the pelvis. The markers were located on the following anatomical landmarks: 5th metatarsal head, 1st metatarsal head, lateral malleolus, medial malleolus, heel, medial and lateral knee epicondyles, greater trochanters, anterior superior iliac spines, iliac crests and posterior superior iliac spine. The remaining markers were attached to polystyrene plates which were placed on the distal thigh and shank. Each plate contained a cluster of 4 markers. An additional marker was placed on the pedal axis in order to identify individual revolutions.

Participants undertook nine pedalling bouts at three cadences and three work rates (60, 90, 120 rpm at 120, 210, 300 W) in a randomised order. Participants pedalled in an upright position with their hands on the hoods and their elbows extended, and maintained the same position across trials. In each condition participants were instructed to reach the required cadence (visual feedback provided via a digital RPM-meter) and maintain this for at least 10 s to establish a steady state. Data were subsequently recorded for a minimum of 20 s (30 s for trials at cadences of 60 RPM) to ensure that a minimum of 10 revolutions were recorded. Participants were instructed to maintain the required cadence until told by the recorder that they could stop. A minimum of a one-min recovery was given between trials.

Data processing

Three-dimensional (3-D) kinematic data were recorded for each trial. Raw coordinate data were smoothed using a fourth order Butterworth digital filter with a cut-off frequency of 8 Hz, selected using Winter's (1990) residual analysis technique. Visual 3D motion analysis software (C-motion, Inc., Rockville MD, USA) was used to calculate 3-D joint angles of the hip, knee and ankle according to the method outlined by Grood and Suntay (1983). Only the flexion/extension component of the 3-D angle was used for subsequent analysis. For each participant 10 consecutive revolutions within ±2 rpm of the required cadence were selected for further analysis. One revolution was identified as the time between the pedal reaching 12 o'clock on two consecutive occasions, defined when the pedal marker reached its maximal value in the z-axis. Monaghan, Delahunt and Caulfield (2006) concluded 10 trials were sufficient to maximise intra-rater reliability of kinematic data when using a CODA 3-D motion analysis system. The time series of each joint angular position and velocity was assessed on a revolution-by-revolution basis and interpolated to 100 data points using a cubic spline technique.

Data analysis

Many techniques exist to quantify joint coordination, each with advantages and limitations. Continuous relative phase (CRP) was used in the current study due to the cyclical nature of the movement and the inclusion of temporal data, which has been deemed to be more sensitive to changes in coordination (Davids, Bennett & Newell, 2006). Phase plots of the hip, knee and ankle were employed to compare lower limb motion. These joints were selected based on their significance in cycling (Ericson et al., 1988). Each phase plot was determined in raw units with angular displacement on the abscissa with its first derivative, angular velocity, on the ordinate (Scholz, 1990). The joint angle and angular velocity data were normalised to the maximum and minimum of each athlete-specific data set according to the procedure presented by Hamill, van Emmerik, Heiderscheit and Li (1999). This resulted in the angle data being normalised to between -1.0 to 1.0 and the angular velocity data being normalised to its greatest absolute value to maintain zero velocity at the origin. Phase angles were subsequently calculated from the normalised phase plot using the arctangent function of the normalised position and velocity time series (Kurz & Stergiou, 2002). CRP was assessed over two intra-limb couplings of interest; (i) knee flexion/extension - ankle plantar-flexion/dorsi-flexion (KA) and (ii) hip flexion/extension-knee flexion/extension (HK). CRP was defined as the difference between the normalised phase angles of the coupling throughout the revolution, measured in degrees (º). For each coupling the distal angle was subtracted from the proximal. A CRP of 0^{o} corresponds to in phase coupling, meaning the phase angles for the two motions are identical, and a potentially stable coupling pattern exists as they are behaving similarly (Dierks, Davis, Scholz & Hamill, 2006). As the CRP moves away from 0^{o} the two motions become more out of phase and are behaving in a less similar fashion until a CRP of 180º indicates an anti-phase coupling.

Coordination variability (CRPv) was calculated as the standard deviation at each time point across the 10 resolutions for each condition for each participant. An average was then taken for all time points and reported at each condition (each cadence and work rate) for each coupling. The individual values for each condition were then also averaged across participants.

To provide a more sensitive analysis of CRPv and CRP, each revolution was divided into two phases. Consequently, 12 o'clock to 6 o'clock represented the propulsive phase and 6 o'clock to 12 o'clock represented the recovery phase.

Statistical analysis

Data were tested for normality using a Shapiro-Wilk test and all comparisons were normally distributed apart from the comparison of CRP and CRPv between the propulsive and recovery phases for the knee-ankle (KA) and hip-knee (HK) couplings.

An independent samples *t*-test was conducted to compare CRPv between trained and untrained participants. All further analysis was conducted on the data from trained participants only (n=6). A Wilcoxon Signed Ranked test was used to compare CRP and CRPv for the KA and HK couplings between the two phases of the revolution (propulsive and recovery). For all further analyses the two phases were considered separately. For each coupling, the main effects of cadence and work rate (and the subsequent interaction effects) on CRP and CRPv were tested using a two-way repeated measures analysis of variance (ANOVA). The assumption of sphericity was violated for all comparisons and therefore a Greenhouse-Geisser correction was applied. Where significant effects were identified, step-wise Bonferroni analysis was used to locate significant differences. A significance level of $p < 0.05$ was set for all statistical tests. All statistical analyses were conducted with SPSS (Version 16, Chicago, IL). No order effects were identified using a one-way ANOVA.

Results

The average CRPv values for the trained and untrained groups for each coupling are displayed in Table 1. For both the knee-ankle (KA) and hip-knee (HK) coupling the trained participants displayed significantly lower CRPv than untrained participants (for KA, $p < 0.001$; for HK, $p < 0.001$).

** Insert Table 1 here **

All further results are based on data from the trained subjects only (n=6). Significant differences in CRP were found between the propulsive and recovery phases for both couplings with a more in phase motion being displayed during the propulsive phase (propulsive *vs* recovery; KA, 27.4º ± 8.9 *vs* 48.5º ± 20.5, $p < 0.001$; HK, 22.5 º ± 6.7

vs 32.5º ± 6.8, $p < 0.001$). Significant differences in CRPv were also found between the recovery and propulsive phases for the KA coupling with a higher CRPv displayed during the recovery phase (propulsive *vs* recovery; 8.6º ± 2.9 *vs* 12.4º ± 6.9, $p < 0.001$), however no significant differences were found for the HK coupling.

No significant differences in either CRP or CRPv were found between work rate conditions for either the KA or HK couplings.

Significant differences in CRP were found between the cadences for the HK coupling during the recovery phase with the 60 RPM trial displaying more out of phase motion than either the 90 RPM or 120 RPM trials (main effect of cadence, $p<0.05$; post-hoc test results, 36.4º ± 3.5 for 60 RPM *vs* 33.3º ± 3.4 for 90 RPM, $p = 0.030$ and 27.9º ± 13.6 for 120 RPM, $p = 0.026$; Figure 1). Differences in CRP for the KA coupling were found during the propulsive phase only with the 120 RPM trials displaying significantly more in phase motion than either the 60 RPM or the 90 RPM trials (main effect of cadence, $p<0.05$; post-hoc test results, 19.2º ± 12.3 for 120 RPM *vs* 30.0º ± 7.1 for 60 RPM, $p = 0.011$ and 33.1º ± 7.4 for 90 RPM, $p = 0.024$; Figure 1).

** Insert Figure 1 here **

There were no differences in CRPv across the cadence conditions for the HK coupling however in the KA coupling a significantly higher CRPv was displayed during the recovery phase in the 60 RPM trials compared to either the 90 RPM or 120 RPM trials (main effect of cadence, $p<0.05$; post-hoc test results, 16.6º ± 7.6 for 60 RPM *vs* 11.6º ± 6.5 for 90 RPM, $p = 0.005$ and 8.9º ± 4.1 for 120 RPM, $p = 0.003$; Figure 2).

** Insert Figure 2 here **

Discussion

The purpose of the current study was to investigate the nature of lower extremity intra-limb coordination variability in cycling, and as a result hypothesise whether variability present in the human system is likely to be a functional element in cycling performance or an indicator of a reduction in performance. In addition, the intra-limb coordinative adaptations that occur in response to a change in cadence and work rate were also investigated.

A comparison of athletes with differing skill level has previously been used to establish the role of within participant intra-limb coupling variability in sports such as the triple jump (Wilson et al., 2008) and football (Ford, Hodges, Huys & Williams, 2006). In the current study it was the level of experience which was investigated and this was defined in terms of the number of hours of cycling specific training per week. The results showed that the trained group displayed the lowest within participant CRPv. This is in accordance with the findings of Chapman et al. (2009) who reported a greater inter-joint consistency in elite cyclists compared with novice cyclists.

The higher CRPv of the untrained participants can be explained from a traditional motor learning perspective. The theory of Fitts and Posner (1967) states that during the initial cognitive stage of learning an individual experiments with different movement configurations and therefore performance may be subject to inconsistencies. This is in contrast to the more recent dynamical systems perspective which considers variability to be an essential element to normal healthy function (Hamill et al., 1999). The results of the current study do not therefore support this functional role of variability. However, it should be noted that this study is limited to the investigation of flexion-extension couplings and ignores movement in the other anatomical axes. Lower limb motion in cycling is constrained by the circular trajectory of the pedals, and is therefore subject to minimal influence from the environment. Consequently having the ability to adapt would appear to be unnecessary and may actually reflect an inconsistent performance. These results therefore suggest that variability within the perceptual-motor system is not functional for cycling performance. The potentially undesirable role of variability in cycling may also be a reflection of the functional purpose of *invariance* (i.e. consistency). Less variability has been previously identified as a reflection of a more stable system (van Emmerick & van Wegen, 1996) and this stability has been associated with the attentional and metabolic energy costs of inter-limb coordination (Sparrow, Lay & O'Dwyer, 2007). It is therefore proposed a similar relationship may exist in intra-limb coordination.

In terms of the coordination strategies adopted during human movement, out of phase motion has previously been considered to reflect a less stable coordinative state (Scholz, 1990). Therefore, the more out of phase motion of both the knee-ankle (KA) and hip-knee (HK) couplings during the recovery phase suggests less stable motion in this phase than in the propulsive phase. This may be indicative of the reduced effective force application during the recovery phase as highlighted by Sanderson and Black (2003).

When considering the effect of cadence on CRP, a more out of phase movement pattern was displayed during the 60 RPM trial for the HK coupling (recovery phase) and a more in phase motion was displayed during the 120 RPM trial for the KA coupling (propulsive phases). Both these findings suggest the higher the cadence the more stable the resulting movement pattern. A stable coordinative pattern is able to be maintained despite perturbations to the system (Robertson, 2001) and according to Zanone, Monno, Temprado and Laurent (2003), the more stable a movement pattern is, the lower the metabolic cost required to maintain the pattern at a given level of stability. This suggests that the coordination patterns exhibited at the higher cadences are more economical, however this would need to be confirmed with additional measures of cycling economy or metabolic cost. The support for the use of a higher cadence demonstrated in this study is in agreement with Lucia et al. (2004) who found that for a fixed work rate, economy improves at increasing pedalling cadences and this improvement was attributed to a lower motor unit recruitment. However, in contrast to this Marsh and Martin (1997) found that the most economical cadence was relatively low at around 60 rpm. In addition, they suggested that maximising economy is given a relatively low priority when selecting a cadence with the preferred cadence being greater than the most economical one.

The higher CRPv in the 60 RPM trial for the KA coupling during the recovery phase suggests a less consistent movement pattern and according to van Emmerick and van Wegen (2000) this is a sign of a less stable system. This is consistent with the CRP findings and also suggests that the variability present in the system is not beneficial to performance, something which has previously been suggested by Chapman et al. (2009). In addition, the higher CRPv displayed during the recovery phase in comparison with the propulsive phase suggests a less consistent and potentially less stable movement pattern in this phase. In comparison, Christiansen, Bradshaw and Wilson (2009) investigated the coordination variability at four points within the cycling revolution and found that the start of the propulsive and recovery phases displayed more variability when compared with the mid point of each phase.

The fact that no differences in coupling motion were identified between work rates may be surprising given the significant differences between cadences and the interdependent relationship of work rate and cadence. However, the work rates investigated in this study were limited and greater ranges may be required to identify any differences which exist.

The results of this study suggest that coordination variability is not beneficial to cycling performance, supporting the traditional motor learning theories which view variability as noise and indicative of an unskilled performance. However, these results should be considered with caution as the participants used a cycle ergometer which limits the ecological validity of the study. Using a cycle ergometer in a laboratory setting does not replicate the variable environmental conditions of road cycling which might affect the coordination strategies adopted and the need for variability within the system. The results of the study also suggest that changes in cadence influence changes in coordination and its associated variability and this may be indicative of a change in stability and potentially economy. Accepting the limitations of the study, the findings may have implications for training and competition. Specifically the results support the use of a higher cadence. Future research should consider the coordination strategies adopted during road cycling, although this may prove to be challenging, and also expand the study to include a measure of metabolic cost to confirm the inferences made regarding the influence of stability on cycling economy. In addition, this study has been limited to intra-limb coordination and future work investigating inter-limb coordination is advocated.

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Table 1. Comparison of CRPv (º) for the Knee-Ankle (KA) and Hip-Knee (HK) couplings for the trained and untrained participants

Coupling	Trained	Untrained
KA	9.7 ± 1.2*	12.4 ± 1.2
HK	3.8 ± 0.4*	6.0 ± 1.0

.*Significantly different to the untrained group ($p < 0.05$)

List of Figures

Figure 1. Comparison of CRP during the propulsive and recovery phases for the three selected cadences for the knee-ankle (KA) and hip-knee (HK) couplings. Data represent the main effect from ANOVA and therefore include all three work rates. *Significantly different from 60 RPM ($p < 0.05$); ** significantly different from 120 RPM ($p < 0.05$).

Figure 2. Comparison of CRPv during the propulsive and recovery phases for the three selected cadences for the knee-ankle (KA) and hip-knee (HK) couplings. Data represent the main effect from ANOVA and therefore include all three work rates. *Significantly different from 60 RPM ($p < 0.05$) in the KA coupling.

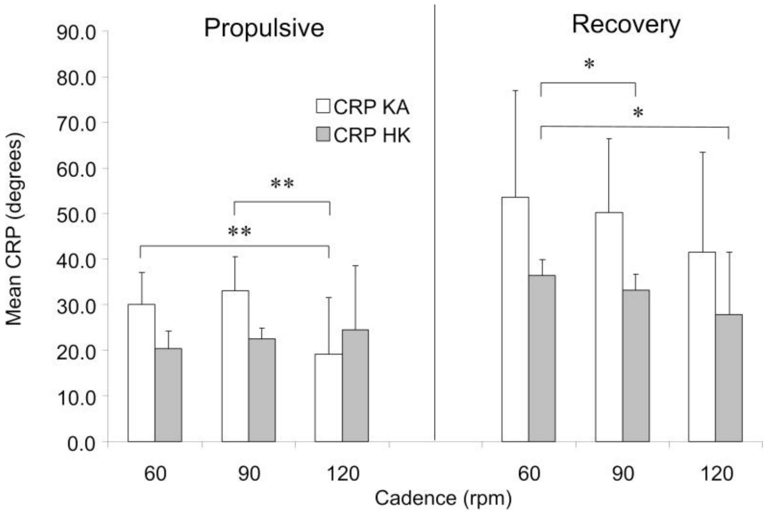
Propulsive
Recovery
CRP KA
CRP HK
**
**
*
*
Mean CRP (degrees)
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
60
90
120
60
90
120
Cadence (rpm)

Figure 1

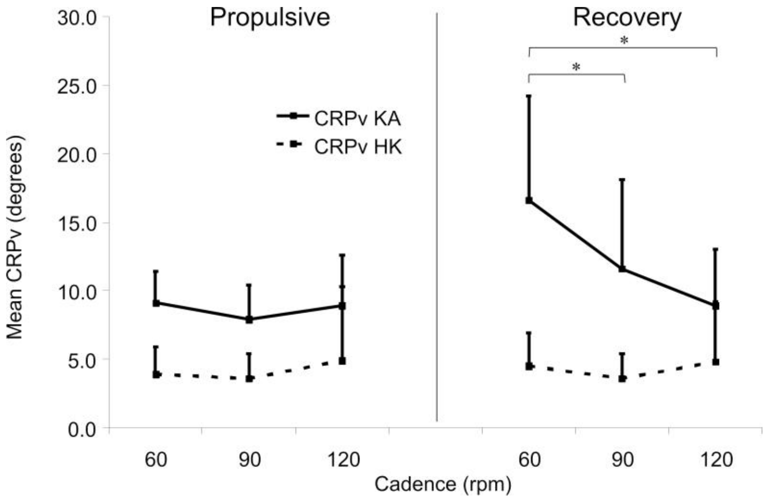
Propulsive
Recovery
CRPv KA
CRPv HK
Mean CRPv (degrees)
Cadence (rpm)
*
*
30.0
25.0
20.0
15.0
10.0
5.0
0.0
60
90
120
60
90
120

Figure 2