



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](https://doi.org/10.1080/14763141.2011.637118)

Publication date:

2012

Document Version

Peer reviewed version

[Link to publication](#)

This is an electronic version of an article published in Wilson, C. and Sides, D., 2012. Intra-limb coordinative adaptations in cycling. *Sports Biomechanics*, 11 (1), pp. 1-9. *Sports Biomechanics* is available online at <http://dx.doi.org/10.1080/14763141.2011.637118>

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Intra-limb Coordinative Adaptations in Cycling

Keywords: Cadence, Coordination, Cycling, Work Rate

Resubmission Date: 24 June 2011

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27 **Abstract**

28 This study aimed to establish the nature of lower extremity intra-limb coordination
29 variability in cycling and investigate the coordinative adaptations that occur in
30 response to changes in cadence and work rate. Six trained and six untrained males
31 performed nine pedalling bouts on a cycle ergometer at various cadences and work
32 rates (60,90,120 rpm at 120,210,300 W). Three dimensional kinematic data were
33 collected and flexion/extension angles of the ankle, knee and hip were subsequently
34 calculated. These data were used to determine two intra-limb joint couplings (hip
35 flexion/extension-knee flexion/extension [HK], knee flexion/extension–ankle plantar-
36 flexion/dorsi-flexion [KA]) which were analysed using continuous relative phase
37 analysis. Trained participants displayed significantly ($p < 0.05$) lower coordination
38 variability ($6.6 \pm 4.0^\circ$) than untrained participants ($9.2 \pm 4.7^\circ$). For the trained subjects,
39 the KA coupling displayed significantly more in phase motion in the 120 rpm
40 ($19.2 \pm 12.3^\circ$) than the 60 ($30 \pm 7.4^\circ$) or 90 rpm ($33.1 \pm 7.4^\circ$) trials and the HK coupling
41 displayed significantly more in phase motion in the 90 ($33.3 \pm 3.4^\circ$) and 120 rpm
42 ($27.9 \pm 13.6^\circ$) than in the 60 rpm trial ($36.4 \pm 3.5^\circ$). The results of this study suggest
43 that variability may be detrimental to performance and that a higher cadence is
44 beneficial. However, further study of on-road cycling is necessary before any
45 recommendations can be made.

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48

49 **Introduction**

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

63 A key component in the analysis of movement coordination is the role of variability
64 within the system under investigation (Wilson, Simpson, van Emmerik & Hamill,
65 2008). Possessing movement variability is important in skills where the adaptability
66 of complex motor patterns is necessary within dynamic performance environments
67 (Button, Davids & Schollhorn, 2006). This adaptability enables athletes to adjust to
68 both intrinsic and extrinsic factors (Bradshaw & Aisbett, 2006). However, in skills
69 where tight task constraints are imposed or in closed kinetic chain activities, such as
70 cycling, there is likely to be a reduced requirement for adaptability. This is despite the
71 fact that there are many factors (intrinsic and extrinsic) which may need
72 accommodating. Thus, any variability present in the system may be indicative of an
73 inconsistent performance. It is often assumed that individuals share a common

74 optimal pattern of movement in the belief that a single most efficient technique exists
75 in the majority of the population (Brisson & Alain, 1996). This notion is evident in the
76 cycling literature (Cannon, Kolkhorst & Cipriani, 2007; Ostler, Betts & Gore, 2008;
77 Ettema & Loras, 2009) and may offer an explanation into the lack of research on
78 movement variability in cycling.

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

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

97

98 **Methods**

99 *Participants*

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

109

110 *Experimental set-up*

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

115

116 *Protocol*

117 To control for potential effects of footwear all participants wore their own sports
118 trainers as opposed to cycling shoes with cleats. Participants set the seat to a
119 comfortable height and undertook a self-directed warm up for a period of two
120 minutes. Twenty-three active markers of 2-mm diameter were attached to the right
121 lower limb and the pelvis. The markers were located on the following anatomical
122 landmarks: 5th metatarsal head, 1st metatarsal head, lateral malleolus, medial
123 malleolus, heel, medial and lateral knee epicondyles, greater trochanters, anterior

124 superior iliac spines, iliac crests and posterior superior iliac spine. The remaining
125 markers were attached to polystyrene plates which were placed on the distal thigh
126 and shank. Each plate contained a cluster of 4 markers. An additional marker was
127 placed on the pedal axis in order to identify individual revolutions.
128 Participants undertook nine pedalling bouts at three cadences and three work rates
129 (60, 90, 120 rpm at 120, 210, 300 W) in a randomised order. Participants pedalled in
130 an upright position with their hands on the hoods and their elbows extended, and
131 maintained the same position across trials. In each condition participants were
132 instructed to reach the required cadence (visual feedback provided via a digital RPM-
133 meter) and maintain this for at least 10 s to establish a steady state. Data were
134 subsequently recorded for a minimum of 20 s (30 s for trials at cadences of 60 RPM)
135 to ensure that a minimum of 10 revolutions were recorded. Participants were
136 instructed to maintain the required cadence until told by the recorder that they could
137 stop. A minimum of a one-min recovery was given between trials.

138

139 *Data processing*

140 Three-dimensional (3-D) kinematic data were recorded for each trial. Raw coordinate
141 data were smoothed using a fourth order Butterworth digital filter with a cut-off
142 frequency of 8 Hz, selected using Winter's (1990) residual analysis technique. Visual
143 3D motion analysis software (C-motion, Inc., Rockville MD, USA) was used to
144 calculate 3-D joint angles of the hip, knee and ankle according to the method outlined
145 by Grood and Suntay (1983). Only the flexion/extension component of the 3-D angle
146 was used for subsequent analysis. For each participant 10 consecutive revolutions
147 within ± 2 rpm of the required cadence were selected for further analysis. One
148 revolution was identified as the time between the pedal reaching 12 o'clock on two

149 consecutive occasions, defined when the pedal marker reached its maximal value in
150 the z-axis. Monaghan, Delahunt and Caulfield (2006) concluded 10 trials were
151 sufficient to maximise intra-rater reliability of kinematic data when using a CODA 3-D
152 motion analysis system. The time series of each joint angular position and velocity
153 was assessed on a revolution-by-revolution basis and interpolated to 100 data points
154 using a cubic spline technique.

155

156 *Data analysis*

157 Many techniques exist to quantify joint coordination, each with advantages and
158 limitations. Continuous relative phase (CRP) was used in the current study due to the
159 cyclical nature of the movement and the inclusion of temporal data, which has been
160 deemed to be more sensitive to changes in coordination (Davids, Bennett & Newell,
161 2006). Phase plots of the hip, knee and ankle were employed to compare lower limb
162 motion. These joints were selected based on their significance in cycling (Ericson et
163 al., 1988). Each phase plot was determined in raw units with angular displacement
164 on the abscissa with its first derivative, angular velocity, on the ordinate (Scholz,
165 1990). The joint angle and angular velocity data were normalised to the maximum
166 and minimum of each athlete-specific data set according to the procedure presented
167 by Hamill, van Emmerik, Heiderscheit and Li (1999). This resulted in the angle data
168 being normalised to between -1.0 to 1.0 and the angular velocity data being
169 normalised to its greatest absolute value to maintain zero velocity at the origin.
170 Phase angles were subsequently calculated from the normalised phase plot using
171 the arctangent function of the normalised position and velocity time series (Kurz &
172 Stergiou, 2002). CRP was assessed over two intra-limb couplings of interest; (i) knee
173 flexion/extension - ankle plantar-flexion/dorsi-flexion (KA) and (ii) hip

174 flexion/extension-knee flexion/extension (HK). CRP was defined as the difference
175 between the normalised phase angles of the coupling throughout the revolution,
176 measured in degrees ($^{\circ}$). For each coupling the distal angle was subtracted from the
177 proximal. A CRP of 0° corresponds to in phase coupling, meaning the phase angles
178 for the two motions are identical, and a potentially stable coupling pattern exists as
179 they are behaving similarly (Dierks, Davis, Scholz & Hamill, 2006). As the CRP
180 moves away from 0° the two motions become more out of phase and are behaving in
181 a less similar fashion until a CRP of 180° indicates an anti-phase coupling.

182

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

188

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

192

193 *Statistical analysis*

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

198

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

212

213 **Results**

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

218 ** Insert Table 1 here **

219

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

224 vs $32.5^{\circ} \pm 6.8$, $p < 0.001$). Significant differences in CRPv were also found between
225 the recovery and propulsive phases for the KA coupling with a higher CRPv
226 displayed during the recovery phase (propulsive vs recovery; $8.6^{\circ} \pm 2.9$ vs $12.4^{\circ} \pm$
227 6.9 , $p < 0.001$), however no significant differences were found for the HK coupling.

228

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

231

232 Significant differences in CRP were found between the cadences for the HK coupling
233 during the recovery phase with the 60 RPM trial displaying more out of phase motion
234 than either the 90 RPM or 120 RPM trials (main effect of cadence, $p < 0.05$; post-hoc
235 test results, $36.4^{\circ} \pm 3.5$ for 60 RPM vs $33.3^{\circ} \pm 3.4$ for 90 RPM, $p = 0.030$ and $27.9^{\circ} \pm$
236 13.6 for 120 RPM, $p = 0.026$; Figure 1). Differences in CRP for the KA coupling were
237 found during the propulsive phase only with the 120 RPM trials displaying
238 significantly more in phase motion than either the 60 RPM or the 90 RPM trials (main
239 effect of cadence, $p < 0.05$; post-hoc test results, $19.2^{\circ} \pm 12.3$ for 120 RPM vs $30.0^{\circ} \pm$
240 7.1 for 60 RPM, $p = 0.011$ and $33.1^{\circ} \pm 7.4$ for 90 RPM, $p = 0.024$; Figure 1).

241

** Insert Figure 1 here **

242

243 There were no differences in CRPv across the cadence conditions for the HK
244 coupling however in the KA coupling a significantly higher CRPv was displayed
245 during the recovery phase in the 60 RPM trials compared to either the 90 RPM or
246 120 RPM trials (main effect of cadence, $p < 0.05$; post-hoc test results, $16.6^{\circ} \pm 7.6$ for
247 60 RPM vs $11.6^{\circ} \pm 6.5$ for 90 RPM, $p = 0.005$ and $8.9^{\circ} \pm 4.1$ for 120 RPM, $p = 0.003$;
248 Figure 2).

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** 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

274 function (Hamill et al., 1999). The results of the current study do not therefore support
275 this functional role of variability. However, it should be noted that this study is limited
276 to the investigation of flexion-extension couplings and ignores movement in the other
277 anatomical axes. Lower limb motion in cycling is constrained by the circular trajectory
278 of the pedals, and is therefore subject to minimal influence from the environment.
279 Consequently having the ability to adapt would appear to be unnecessary and may
280 actually reflect an inconsistent performance. These results therefore suggest that
281 variability within the perceptual-motor system is not functional for cycling
282 performance. The potentially undesirable role of variability in cycling may also be a
283 reflection of the functional purpose of *invariance* (i.e. consistency). Less variability
284 has been previously identified as a reflection of a more stable system (van Emmerick
285 & van Wegen, 1996) and this stability has been associated with the attentional and
286 metabolic energy costs of inter-limb coordination (Sparrow, Lay & O'Dwyer, 2007). It
287 is therefore proposed a similar relationship may exist in intra-limb coordination.

288
289 In terms of the coordination strategies adopted during human movement, out of
290 phase motion has previously been considered to reflect a less stable coordinative
291 state (Scholz, 1990). Therefore, the more out of phase motion of both the knee-ankle
292 (KA) and hip-knee (HK) couplings during the recovery phase suggests less stable
293 motion in this phase than in the propulsive phase. This may be indicative of the
294 reduced effective force application during the recovery phase as highlighted by
295 Sanderson and Black (2003).

296
297 When considering the effect of cadence on CRP, a more out of phase movement
298 pattern was displayed during the 60 RPM trial for the HK coupling (recovery phase)
299 and a more in phase motion was displayed during the 120 RPM trial for the KA

300 coupling (propulsive phases). Both these findings suggest the higher the cadence
301 the more stable the resulting movement pattern. A stable coordinative pattern is able
302 to be maintained despite perturbations to the system (Robertson, 2001) and
303 according to Zanone, Monno, Temprado and Laurent (2003), the more stable a
304 movement pattern is, the lower the metabolic cost required to maintain the pattern at
305 a given level of stability. This suggests that the coordination patterns exhibited at the
306 higher cadences are more economical, however this would need to be confirmed with
307 additional measures of cycling economy or metabolic cost. The support for the use of
308 a higher cadence demonstrated in this study is in agreement with Lucia et al. (2004)
309 who found that for a fixed work rate, economy improves at increasing pedalling
310 cadences and this improvement was attributed to a lower motor unit recruitment.
311 However, in contrast to this Marsh and Martin (1997) found that the most economical
312 cadence was relatively low at around 60 rpm. In addition, they suggested that
313 maximising economy is given a relatively low priority when selecting a cadence with
314 the preferred cadence being greater than the most economical one.

315

316 The higher CRPv in the 60 RPM trial for the KA coupling during the recovery phase
317 suggests a less consistent movement pattern and according to van Emmerick and
318 van Wegen (2000) this is a sign of a less stable system. This is consistent with the
319 CRP findings and also suggests that the variability present in the system is not
320 beneficial to performance, something which has previously been suggested by
321 Chapman et al. (2009). In addition, the higher CRPv displayed during the recovery
322 phase in comparison with the propulsive phase suggests a less consistent and
323 potentially less stable movement pattern in this phase. In comparison, Christiansen,
324 Bradshaw and Wilson (2009) investigated the coordination variability at four points

325 within the cycling revolution and found that the start of the propulsive and recovery
326 phases displayed more variability when compared with the mid point of each phase.

327

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

333

334 The results of this study suggest that coordination variability is not beneficial to
335 cycling performance, supporting the traditional motor learning theories which view
336 variability as noise and indicative of an unskilled performance. However, these
337 results should be considered with caution as the participants used a cycle ergometer
338 which limits the ecological validity of the study. Using a cycle ergometer in a
339 laboratory setting does not replicate the variable environmental conditions of road
340 cycling which might affect the coordination strategies adopted and the need for
341 variability within the system. The results of the study also suggest that changes in
342 cadence influence changes in coordination and its associated variability and this may
343 be indicative of a change in stability and potentially economy. Accepting the
344 limitations of the study, the findings may have implications for training and
345 competition. Specifically the results support the use of a higher cadence. Future
346 research should consider the coordination strategies adopted during road cycling,
347 although this may prove to be challenging, and also expand the study to include a
348 measure of metabolic cost to confirm the inferences made regarding the influence of

349 stability on cycling economy. In addition, this study has been limited to intra-limb
350 coordination and future work investigating inter-limb coordination is advocated.

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470 Table 1. Comparison of CRPv (°) for the Knee-Ankle (KA) and Hip-Knee (HK)
471 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

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

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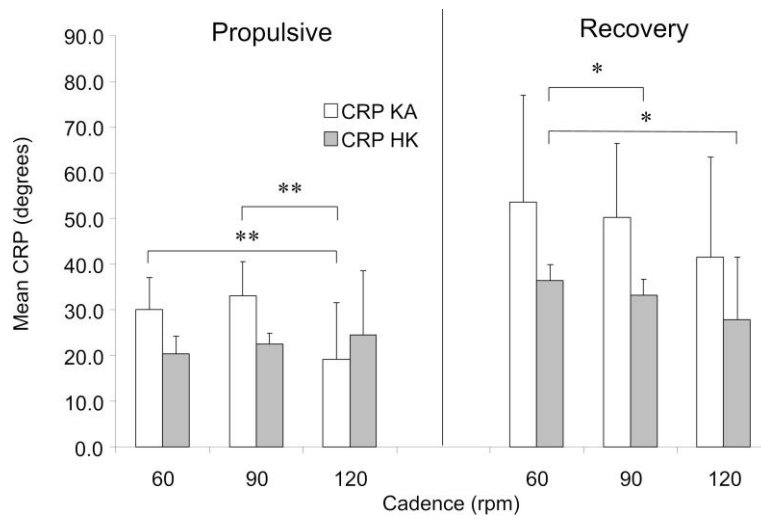
474 **List of Figures**

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

480

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

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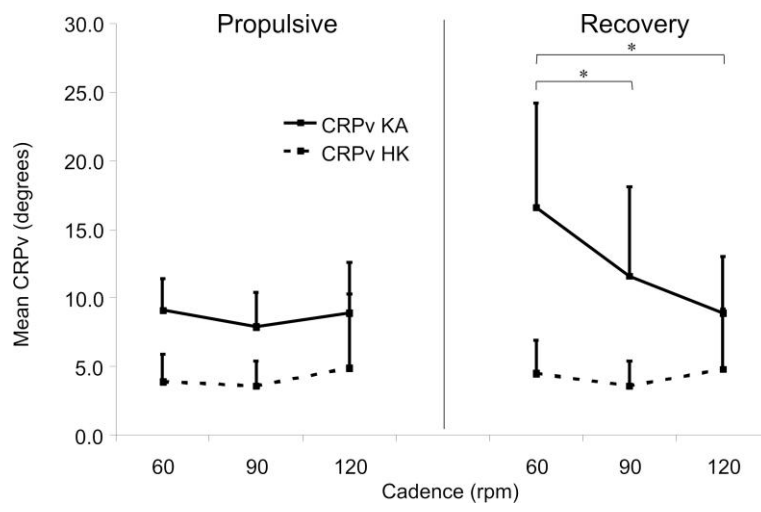
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503 Figure 1

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516 Figure 2

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