

1 Title:

2 Relationships between lower limb kinematics and block phase performance in a cross-  
3 section of sprinters

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19 Abstract:

20 This study investigated lower limb kinematics to explain the techniques used to achieve high  
21 levels of sprint start performance. A cross-sectional design was used to examine  
22 relationships between specific technique variables and horizontal external power production  
23 during the block phase. Video data were collected (200 Hz) at the training sessions of 16  
24 sprinters who ranged in 100 m personal best times from 9.98 to 11.6 s. Each sprinter  
25 performed three 30 m sprints and reliable (all ICC(2,3)  $\geq$  0.89) lower limb kinematic data  
26 were obtained through manual digitising. The front leg joints extended in a proximal-to-distal  
27 pattern for 15 sprinters and a moderate positive relationship existed between peak front hip  
28 angular velocity and block power ( $r = 0.49$ , 90% confidence limits = 0.08 to 0.76). In the rear  
29 leg, there was a high positive relationship between relative push duration and block power  
30 ( $r = 0.53$ , 90% confidence limits = 0.13 to 0.78). The rear hip appeared to be important; rear  
31 hip angle at block exit was highly related to block power ( $r = 0.60$ , 90% confidence limits =  
32 0.23 to 0.82) and there were moderate positive relationships with block power for its range of  
33 motion and peak angular velocity (both  $r = 0.49$ , 90% confidence limits = 0.08 to 0.76). As  
34 increased block power production was not associated with any negative aspects of  
35 technique in the subsequent stance phase, sprinters should be encouraged to maximise  
36 extension at both hips during the block phase.

37

38 Keywords: acceleration, biomechanics, coaching, performance, training.

39

40 Introduction

41 In athletic sprinting, the block phase has been subject to numerous descriptive and  
42 experimental biomechanical studies. Much of this research has focussed on 'set' position  
43 technique and considerable inter-participant variation and weak relationships between self-  
44 selected 'set' position kinematics and sprint start performance have ultimately been reported  
45 (e.g. Atwater, 1982; Mero, 1988; Mero, Luhtanen, & Komi, 1983). Once a sprinter reacts to  
46 the starter's gun, they start to generate forces against the blocks and move out of the 'set'  
47 position. These external kinetics during the block phase have been well documented (e.g.  
48 Baumann, 1976; Lemaire & Robertson, 1990; Mero, 1988; Payne & Blader, 1971; van  
49 Coppennolle, Delecluse, Goris, Bohets, & Vanden Eynde, 1989) and the higher block exit  
50 velocities of better starters have been partly attributed to an increase in force generation with  
51 the rear leg (Lemaire & Robertson, 1990; Payne & Blader, 1971; van Coppennolle et al.,  
52 1989). However, despite the existence of a large body of information regarding 'set' position  
53 joint angles and the linear kinematics of the centre of mass (CM) during block exit, there has  
54 been limited quantitative assessment of the specific joint kinematics involved in the  
55 generation of these forces and thus CM motion (Slawinski et al., 2010b, 2013).

56

57 Slawinski et al. (2010b) described the average angular velocities and segmental kinetic  
58 energies of a group of eight sprinters, whilst Slawinski et al. (2013) determined the effects of  
59 experimental manipulations to 'set' position on the joint angular velocities exhibited during  
60 block exit. Although it was not the main aim of their study, closer inspection of the variation  
61 in the joint angular velocities presented by Slawinski et al. (2010b) indicated that there were  
62 considerable differences in the techniques used by the studied group of sprinters even when  
63 their overall level of block phase performance was reasonably homogenous (100 m personal  
64 best (PB) of 10.30,  $s = 0.14$  s). Investigating whether these variations in technique are  
65 related to performance levels across a group of sprinters would be useful to identify how  
66 higher levels of block phase performance are typically achieved. The aim of the current  
67 study was therefore to identify the key characteristics of the lower limb kinematic patterns

68 during the block phase in a cross-section of sprinters including world-class athletes and to  
69 determine the specific aspects of sprint start technique which are associated with higher  
70 levels of performance. Since it must be considered that the block phase is not a 'stand-  
71 alone' part of a sprint, and that striving to maximise block phase performance could  
72 potentially affect technique and performance during the subsequent phases, relationships  
73 between block phase performance and kinematics at the first touchdown on the track were  
74 also assessed.

75

76 Methods

77 Participants

78 Following study approval from the Local Research Ethics Committee, 16 male sprinters with  
79 a mean age of 21,  $s = 5$  years, height of 1.78,  $s = 0.05$  m, and mass of 74.4,  $s = 8.3$  kg  
80 provided written informed consent to participate in this study. Their ability levels ranged from  
81 world-class (100 m PB of 9.98 s) to university-level (hand timed 100 m PB of 11.6 s); the  
82 group mean 100 m PB was 10.95,  $s = 0.51$  s.

83

84 Protocol

85 All data were collected at coach-prescribed training sessions. For 13 of the sprinters, data  
86 were collected indoors just prior to the competition phase of the indoor season. For the  
87 remaining three sprinters, data were collected outdoors during the early competition phase  
88 of the outdoor season. Each sprinter completed three maximal effort sprints to 30 m from  
89 starting blocks. Sprinters were allowed their usual recovery between sprints, which was  
90 typically 8-10 minutes. At all sessions, a single high-speed digital video camera (Motion  
91 Pro<sup>®</sup>, HS-1, Redlake, USA; 200 Hz, 1280 × 1024 pixel resolution) recorded movements  
92 within a calibrated field of view 2.5 m (indoors) or 4.0 m (outdoors) wide. Due to issues with  
93 the camera set-up at one session, rear foot data from one sprinter in the 'set' position were  
94 unavailable and this sprinter was removed from the analysis when variables reliant upon rear  
95 foot data from the early block phase were required.

96

97 Data processing

98 All video clips were imported into digitising software (Peak Motus<sup>®</sup>, v.8.5, Vicon<sup>®</sup>, UK) and  
99 eighteen points (vertex, seventh cervical vertebra, shoulder, elbow, wrist, third metacarpal,  
100 hip, knee, ankle and second metatarsal-phalangeal (MTP) joint centres) were manually  
101 digitised from one frame prior to the visually identified movement onset until 10 frames after  
102 first stance touchdown. The digitised points were projectively scaled to yield raw sagittal  
103 plane displacement data. All subsequent data analysis utilised custom routines developed in  
104 Matlab<sup>™</sup> (v. 7.4.0, The MathWorks<sup>™</sup>, USA). Following backward replication of the first  
105 frame 10 times to alleviate potential endpoint errors, the data were smoothed using a fourth-  
106 order Butterworth digital filter with cut-off frequencies determined individually for each  
107 displacement time-history (16 to 28 Hz) via residual analysis (Winter, 2005). Anatomical joint  
108 angles were calculated and joint angular velocities throughout the data set were derived  
109 using second central difference calculations (Miller & Nelson, 1973). Specific events ('set'  
110 position, movement onset, rear foot off blocks, block exit, first stance touchdown) were  
111 identified visually from the video clips. The push phase was defined as the time elapsing  
112 between movement onset and block exit, and the duration of the rear foot push was also  
113 determined. Joint angles at each event and the peak lower limb joint angular velocities  
114 during each leg's respective push phase were extracted for each trial.

115

116 Whole body CM location was determined (Winter, 2005) using segmental inertia data from  
117 de Leva (1996). Inertia data for the feet were taken from Winter (2005) and the measured  
118 mass of the spiked shoes was incorporated. Horizontal CM displacement was also  
119 calculated from the unfiltered displacement data for use in determining horizontal CM  
120 velocity at block exit using first flight phase data (Salo & Scarborough, 2006). The change in  
121 kinetic energy during the push phase was then calculated from these velocity data. Using the  
122 kinetic energy data and the push phase duration, average horizontal external block power  
123 (hereafter termed block power) was calculated as an objective measure of block phase

124 performance since it takes into account both the velocity at the end of the block phase and  
125 the time taken to achieve this velocity (Bezodis, Salo, & Trewartha 2010). Block power and  
126 all linear displacements were normalised to account for body size according to the  
127 convention of Hof (1996) with an adjusted power normalisation (Bezodis et al., 2010).

128

## 129 Statistical analysis

130 For all variables of interest, mean values for each sprinter were calculated from their three  
131 trials. The reliability of these data was quantified using an intraclass correlation coefficient.  
132 Model 2,3 was used to include both systematic and random error, and to account for the  
133 mean of the three trials being used in the subsequent analysis (Vincent & Weir, 2012).  
134 Ensemble group mean and standard deviation data were determined from the individual  
135 mean data. For all variables of interest, the mean data from each of the sprinters (i.e. 16  
136 data points) were checked for normality using a Shapiro-Wilk test. The peak front ankle  
137 angular velocity was found to be non-normally distributed ( $P < 0.05$ ). Pearson's product  
138 moment correlation coefficients ( $r$ ) between specific technique variables and performance  
139 were quantified using the 16 mean values obtained from each individual's three trials.  
140 Relationships involving the peak front ankle angular velocity data were quantified using a  
141 Spearman's rank correlation coefficient ( $\rho$ ). Uncertainty in the observed relationships was  
142 quantified with 90% confidence limits determined using the Fisher z transformation (Fisher,  
143 1921). If these confidence limits overlapped both substantial positive and negative values  
144 (i.e.  $r = \pm 0.1$  based on the smallest clinically important correlation coefficient; Cohen, 1988;  
145 Hopkins, 2014), the magnitude was deemed unclear. Based on 16 participants, correlations  
146  $>0.35$  or  $<-0.35$  were considered clear and their strength was defined using the convention  
147 recommended by Cohen (1988) and Hopkins (2014): moderate (0.3 - 0.5), high (0.5 - 0.7),  
148 very high (0.7 - 0.9) or practically perfect (0.9 - 1.0).

149

## 150 Results

151 All intraclass correlation coefficients equalled or exceeded 0.89 (Tables 1 and 2). The mean  
152 push phase duration was 0.358,  $s = 0.022$  s (ICC (2,3) = 0.97), and the rear leg pushed  
153 against the rear block for 53,  $s = 5\%$  (ICC (2,3) = 0.97) of this total push duration. During the  
154 push phase, the sprinters generated a mean block power of 1171,  $s = 268$  W (ICC (2,3) =  
155 0.98; normalised mean = 0.53,  $s = 0.08$ , ICC (2,3) = 0.97). Across all 16 sprinters, a very  
156 high, negative relationship ( $r = -0.72$ , 90% confidence limits = -0.88 to -0.42) existed  
157 between 100 m PB time and normalised block power.

158

159 The relationships between lower limb joint and trunk angles in the 'set' position and  
160 normalised block power were all unclear (all  $-0.17 < r < 0.16$ ; Table 1). All 16 sprinters  
161 exhibited a rear leg sequencing in peak joint velocities of knee then hip, followed by ankle  
162 (Figure 1a-c). At the front leg, all sprinters with the exception of one exhibited a proximal-to-  
163 distal sequencing from hip to knee to ankle (Figure 1d-f). Relationships between peak joint  
164 extension angular velocities and normalised block power were unclear for both knees and  
165 ankles (Figures 1a, 1b, 1d, 1e). There were moderate relationships between normalised  
166 block power and peak angular velocity at both hips ( $r = 0.49$ ; 90% confidence limits = 0.08 to  
167 0.76; Figures 1c and 1f). Rear hip range of motion during rear block contact was moderately  
168 correlated with normalised block power ( $r = 0.49$ , 90% confidence limits = 0.08 to 0.76; Table  
169 1) and the rear hip angle at block exit was highly correlated with normalised block power  
170 ( $r = 0.60$ , 90% confidence limits = 0.23 to 0.82). A greater push duration with the rear leg (as  
171 a percentage of total block phase duration) was also highly correlated with greater levels of  
172 normalised block power ( $r = 0.53$ , 90% confidence limits = 0.13 to 0.78).

173

174 \*\*\*\*Table 1 near here\*\*\*\*

175 \*\*\*\*Figure 1 near here\*\*\*\*

176

177 Data from the first flight phase and first stance touchdown are presented in Table 2. There  
178 were unclear relationships between normalised block power and the subsequent flight

179 duration and each of the stance leg joint angles at touchdown. There was a moderate  
180 positive relationship between normalised block power production and normalised step length  
181 ( $r = 0.36$ , 90% confidence limits = -0.08 to 0.68), and a moderate negative relationship  
182 between normalised block power and normalised touchdown distance ( $r = -0.46$ , 90%  
183 confidence limits = -0.74 to -0.04).

184

185 \*\*\*\*Table 2 near here\*\*\*\*

186

187 Discussion

188 We investigated the angular kinematic patterns of the lower limbs during the block phase  
189 and aimed to understand specific aspects of technique that were associated with higher  
190 levels of block phase performance. The main findings were that improved block phase  
191 performance was associated with increased contributions from the rear leg, particularly the  
192 hip, and also the angular velocity of the front hip. Furthermore, higher levels of block phase  
193 performance did not negatively affect first stance touchdown kinematics. The high intraclass  
194 correlation coefficients provide confidence in the reliability of the presented data with respect  
195 to the within-sprinter variability relative to the total between-sprinter variability (Vincent &  
196 Weir, 2012).

197

198 The very high negative relationship ( $r = -0.72$ ) between 100 m PB time and normalised block  
199 power reiterates previous findings that sprinters with faster PB times are also typically better  
200 starters (Baumann, 1976; Mero, 1988; Mero et al., 1983). However, the imperfect correlation  
201 reinforces that block phase technique should be compared against current performance from  
202 just the phase of interest, not previous performance measures, particularly those which  
203 include subsequent phases of a sprint (Bezodis et al., 2010). The unclear correlations  
204 between 'set' position joint angles and normalised block power (Table 1) suggest that block  
205 positioning is not likely to be an important differentiating factor between sprinters of different  
206 performance levels, and thus a single optimal 'set' position cannot be recommended. This



207 supports previous research where relatively large standard deviations have commonly been  
208 observed in 'set' position kinematics, even within relatively homogeneous groups of sprinters  
209 (Atwater, 1982; Mero, 1988; Mero et al., 1983).

210

211 The proximal-to-distal pattern of peak front leg joint angular velocities (Figure 1) is consistent  
212 with the data presented by Slawinski et al. (2010b) and suggests these sprinters used a  
213 strategy commonly adopted in power demanding tasks, which is to transfer power distally  
214 using the biarticular muscles. With such a strategy, as each joint approaches full extension,  
215 its deceleration is largely achieved using the biarticular flexor muscles to absorb rotational  
216 energy and transfer it distally to assist extension at the next distal joint rather than using the  
217 mono-articular flexor muscles which would dissipate the energy (Bobbert & van Ingen  
218 Schenau, 1988; Gregoire, Veeger, Huijing, & van Ingen Schenau, 1984). A proximal-to-distal  
219 strategy was not used when extending the rear leg where the knee joint angular velocity  
220 peaked first (Figure 1), again consistent with Slawinski et al. (2010b). This may be due to the  
221 rear knee joint starting from a more extended angle in the 'set' position, limiting its range and  
222 duration of extension (Table 1). This could affect the overall force producing capability of the  
223 rear leg due to changes in the gastrocnemius muscle-tendon unit length (Mero, Kuitunen,  
224 Harland, Kyröläinen, & Komi, 2006) and the consequent effects of the force-length  
225 relationship (Guissard, Duchateau, & Hainaut, 1992; Mero et al., 2006). Ultimately, these  
226 group-wide findings highlight the asymmetrical nature of the sprint start and its demands. As  
227 it has previously been shown that the choice of rear block leg can affect both reaction time  
228 and push phase duration due to hemispheric specialisation (Eikenberry et al., 2008),  
229 consideration should be given to this in training programmes focussing on both block phase  
230 technique (e.g. Vagenas & Hoshizaki, 1986) and physical development.

231

232 Whilst there were consistent group-wide trends in the joint angular velocity sequencing  
233 during the block phase, the lack of high correlations between discrete angular kinematic  
234 variables and normalised block power across the group of sprinters highlighted that there

235 was generally no single aspect of technique that was critical for success. However, the  
236 moderate correlations between normalised block power and peak angular velocity of both  
237 hip joints (both  $r = 0.49$ ) suggest that rapid hip extension should be one of the first things to  
238 consider when addressing a sprinter's technique during the start. This increased rate of hip  
239 extension could explain the greater rate of external force development previously observed  
240 by Slawinski et al. (2010a) in higher level sprinters during the early part of the block phase  
241 compared to their less able counterparts. A relatively early extension of the hips may be  
242 important for rapidly increasing force generation from movement onset, generating power  
243 which is transferred distally down the front leg in particular. Furthermore, the relationship  
244 between normalised block power and change in rear hip angle during rear block contact ( $r =$   
245  $0.49$ ), but also with the rear hip angle at block exit ( $r = 0.60$ ), suggest that greater rear hip  
246 extension, in particular through the higher end of its range of motion, may be important for  
247 generating greater block power. The high positive relationship between push duration with  
248 the rear leg (as a percentage of total block phase duration) and normalised block power ( $r =$   
249  $0.53$ ) reinforces previous suggestions regarding the importance of rear leg force generation  
250 (Lemaire & Robertson, 1990; Payne & Blader, 1971; van Coppenolle et al., 1989), and the  
251 above relationships between rear hip extension and normalised block power suggest that hip  
252 extension may be an important feature in achieving this. Findings from a recent experimental  
253 study by Slawinski et al. (2013) suggest that front and rear hip angular velocity can be  
254 altered by manipulating block spacing. Whilst our data suggest that there appears to be no  
255 optimal 'set' position that is applicable for all sprinters, and strength limitations must also be  
256 considered, it is possible that alterations to block spacing could be used as an acute means  
257 through which to improve performance if a sprinter is identified as exhibiting relatively slow  
258 hip extension.

259

260 Beyond block exit, large inter-participant variation in stance leg joint angles existed at first  
261 touchdown (Table 2). These stance leg configurations at touchdown affected touchdown  
262 distance which can have a considerable effect on a sprinter's ability to generate propulsive

263 force during stance. A smaller negative touchdown distance means that the CM must be  
264 rotated further in front of the stance foot prior to leg extension for this extension to propel the  
265 sprinter in a more favourable horizontal direction (Bezodis, Salo, & Trewartha, 2008; Jacobs  
266 & van Ingen Schenau, 1992). Whilst the relationship between normalised block power and  
267 the subsequent flight duration was unclear, there existed moderate correlations with  
268 normalised touchdown distance ( $r = -0.46$ ) and normalised step length ( $r = 0.36$ ). Both of  
269 these relationships are potentially favourable for performance; striving to produce greater  
270 power during the block phase therefore does not appear to inhibit subsequent technique in a  
271 sprint and may actually be associated with landing in a better position at touchdown.

272

273 Data were collected non-invasively at athletes' planned training sessions. The collection of  
274 data during competition would clearly be of interest but the possibility of this is limited due to  
275 access constraints (particularly when studying world-class sprinters) as well as the number  
276 of athletes (outside lane(s) only) and repetitions (often only one sprint) that could be studied.  
277 In the current study, data were collected as close to the competition phase of the season as  
278 possible and no changes were made to the sprinters' training programme. Where access  
279 permits, future research could also study the physical attributes across a cross-section of  
280 sprinters to investigate their influence on some of the technical aspects highlighted in this  
281 study.

282

283 The 'set' position of a sprinter in the blocks does not appear to be an important differentiating  
284 factor between sprinters of different performance levels. The joints of the front leg typically  
285 extended over a considerable range of motion in a proximal-to-distal extension pattern, and  
286 correlations suggested that greater peak hip joint velocity was associated with increased  
287 external power production. The rear leg joints extended over a smaller range, but a longer  
288 rear leg push as a percentage of total push phase duration was associated with higher levels  
289 of external power production during the block phase. Greater rear hip extension and rate of  
290 extension during the block phase was also associated with higher levels of external power

291 production. As higher levels of power production during the block phase were not  
292 subsequently associated with any potentially disadvantageous aspects of technique at the  
293 onset of the first stance phase, sprinters should be encouraged to maximise the rate of  
294 extension at both hips during the block phase in an attempt to achieve maximal power  
295 production.

296

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301 References

302 Atwater, A. E. (1982). Kinematic analyses of sprinting. *Track and Field Quarterly Review*,  
303 82(2), 12-16.

304

305 Baumann, W. (1976). Kinematic and dynamic characteristics of the sprint start. In P. V. Komi  
306 (Ed.), *Biomechanics V-B* (pp. 194-199). Baltimore, MD: University Park Press.

307

308 Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2008). Understanding elite sprint start  
309 performance through an analysis of joint kinematics. In Y.-H. Kwon, J. Shim, J. K.  
310 Shim & I.-S. Shin (Eds.), *Proceedings of XXVI International Symposium on*  
311 *Biomechanics in Sports* (pp. 498-501). Seoul, Republic of Korea: Seoul National  
312 University Press.

313

314 Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2010). Choice of sprint start performance  
315 measure affects the performance-based ranking within a group of sprinters: which is  
316 the most appropriate measure? *Sports Biomechanics*, 9(4), 258-269.

317

318 Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal*  
319 *of Biomechanics*, 21(3), 249-262.

320

321 Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2<sup>nd</sup> edn.). Hillsdale,  
322 NJ: Lawrence Erlbaum.

323

324 de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters.  
325 *Journal of Biomechanics*, 29(9), 1223-1230.

326

327 Eikenberry, A., McAuliffe, J., Welsh, T. N., Zerpa, C., McPherson, M., & Newhouse, I.  
328 (2008). Starting with the "right" foot minimizes sprint start time. *Acta Psychologica*,  
329 127(2), 495-500.

330

331 Fisher, R. A. (1921). On the probable error of a coefficient of correlation deduced from a  
332 small sample. *Metron*, 1, 3-32.

333

334 Grégoire, L., Veeger, H. E., Huijing, P. A., & Ingen Schenau, G. J. V. (1984). Role of mono-  
335 and biarticular muscles in explosive movements. *International Journal of Sports*  
336 *Medicine*, 5(6), 301-305.

337

338 Guissard, N., Duchateau, J., & Hainaut, K. (1992). EMG and mechanical changes during  
339 sprint starts at different front block obliquities. *Medicine & Science in Sports &*  
340 *Exercise*, 24(11), 1257-1263.

341

342 Hof, A. L. (1996). Scaling gait data to body size. *Gait & Posture*, 4(3), 222-223.

343

344 Hopkins, W. G. (2014). A scale of magnitudes for effect statistics. Retrieved from  
345 <http://www.sportsci.org/resource/stats/>.

346

347 Jacobs, R., & van Ingen Schenau, G. J. (1992). Intermuscular coordination in a sprint push-  
348 off. *Journal of Biomechanics*, 25(9), 953-965.

349

350 Lemaire, E. D., & Robertson, D. G. E. (1990). Force-time data acquisition-system for sprint  
351 starting. *Canadian Journal of Sport Sciences*, 15(2), 149-152.

352

353 Mero, A. (1988). Force-time characteristics and running velocity of male sprinters during the  
354 acceleration phase of sprinting. *Research Quarterly for Exercise and Sport*, 59(2),  
355 94-98.

356

357 Mero, A., Kuitunen, S., Harland, M., Kyröläinen, H., & Komi, P. V. (2006). Effects of muscle-  
358 tendon length on joint moment and power during sprint starts. *Journal of Sports*  
359 *Sciences*, 24(2), 165-173.

360

361 Mero, A., Luhtanen, P., & Komi, P. V. (1983). A biomechanical study of the sprint start.  
362 *Scandinavian Journal of Sports Science*, 5(1), 20-28.

363

364 Miller, D., & Nelson, R. (1973). *Biomechanics of sport: A research approach*. Philadelphia,  
365 PA; Lea and Febiger.

366

367 Payne, A. H., & Blader, F. B. (1971). The mechanics of the sprint start. In J. Vredenburg &  
368 J. Wartenweiler (Eds.), *Biomechanics II* (pp. 225-231). Baltimore, MD: University  
369 Park Press.

370

371 Salo, A. I. T., & Scarborough, S. (2006). Changes in technique within a sprint hurdle run.  
372 *Sports Biomechanics*, 5(2), 155-166.

373

374 Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R., & Chèze, L.  
375 (2010a). Kinematic and kinetic comparisons of elite and well-trained sprinters during  
376 sprint start. *Journal of Strength and Conditioning Research*, 24(4), 896-905.

377

378 Slawinski, J., Bonnefoy, A., Ontanon, G., Leveque, J. M., Miller, C., Riquet, A., Chèze, L., &  
379 Dumas, R. (2010b). Segment-interaction in sprint start: analysis of 3D angular

380 velocity and kinetic energy in elite sprinters. *Journal of Biomechanics*, 43(8), 1494-  
381 1502.

382

383 Slawinski, J., Dumas, R., Chèze, L., Ontanon, G., Miller, C., & Mazure-Bonnefoy, A. (2013).  
384 Effect of postural changes on 3D joint angular velocity during starting block phase.  
385 *Journal of Sports Sciences*, 31(3), 256-263.

386

387 Vagenas, G., & Hoshizaki, T. B. (1986). Optimization of an asymmetrical motor skill: sprint  
388 start. *International Journal of Sport Biomechanics*, 2, 29-40.

389

390 van Coppenolle, H., Delecluse, C., Goris, M., Bohets, W., & Vanden Eynde, E. (1989).  
391 Technology and development of speed: evaluation of the start, sprint and body  
392 composition of Pavoni, Cooman and Desruelles. *Athletics Coach*, 23(1), 82-90.

393

394 Vincent, W. J., & Weir, J. P. (2012). *Statistics in kinesiology* (4th ed.). Champaign, IL:  
395 Human Kinetics.

396

397 Winter, D. A. (2005). *Biomechanics and motor control of human movement* (3rd ed.).  
398 Hoboken, NJ: Wiley.



399 Tables

400

401 Table 1. Group mean and standard deviation values for trunk and lower limb joint angles in the 'set' position and their ranges of motion during  
402 the respective block contact, reliability of these values, and their relationships (including 90% confidence limits) with normalised average  
403 horizontal external block power.

Joint or segment	Set position angle (°)				Range of motion during block exit (°)			
	Mean ± s	ICC	Relationship with block power		Mean ± s	ICC	Relationship with block power	
			<i>r</i>	90% confidence limits			<i>r</i>	90% confidence limits
Trunk	-17 ± 4	0.89	0.16	-0.29 to 0.55	46 ± 8	0.94	0.09	-0.35 to 0.50
Rear hip	77 ± 9	0.97	0.05	-0.39 to 0.47	31 ± 13	0.97	0.49	0.08 to 0.76
Rear knee	109 ± 9	0.93	0.07	-0.37 to 0.48	18 ± 6	0.90	-0.18	-0.56 to 0.27
Rear ankle	111 ± 12	0.93	-0.17	-0.57 to 0.29	19 ± 9	0.95	0.04	-0.41 to 0.47
Front hip	47 ± 6	0.95	0.08	-0.36 to 0.49	113 ± 9	0.92	0.27	-0.18 to 0.62
Front knee	86 ± 5	0.89	0.11	-0.33 to 0.51	73 ± 7	0.90	-0.04	-0.46 to 0.39
Front ankle	107 ± 12	0.96	-0.07	-0.48 to 0.37	36 ± 10	0.95	0.004	-0.42 to 0.43

404 The intraclass correlation coefficients (ICC) were calculated using model 2,3 to quantify the reliability of these data with respect to the within-  
405 sprinter variability relative to the total between-sprinter variability.<sup>16</sup> Pearson's correlation coefficients (*r*) were calculated between each of these

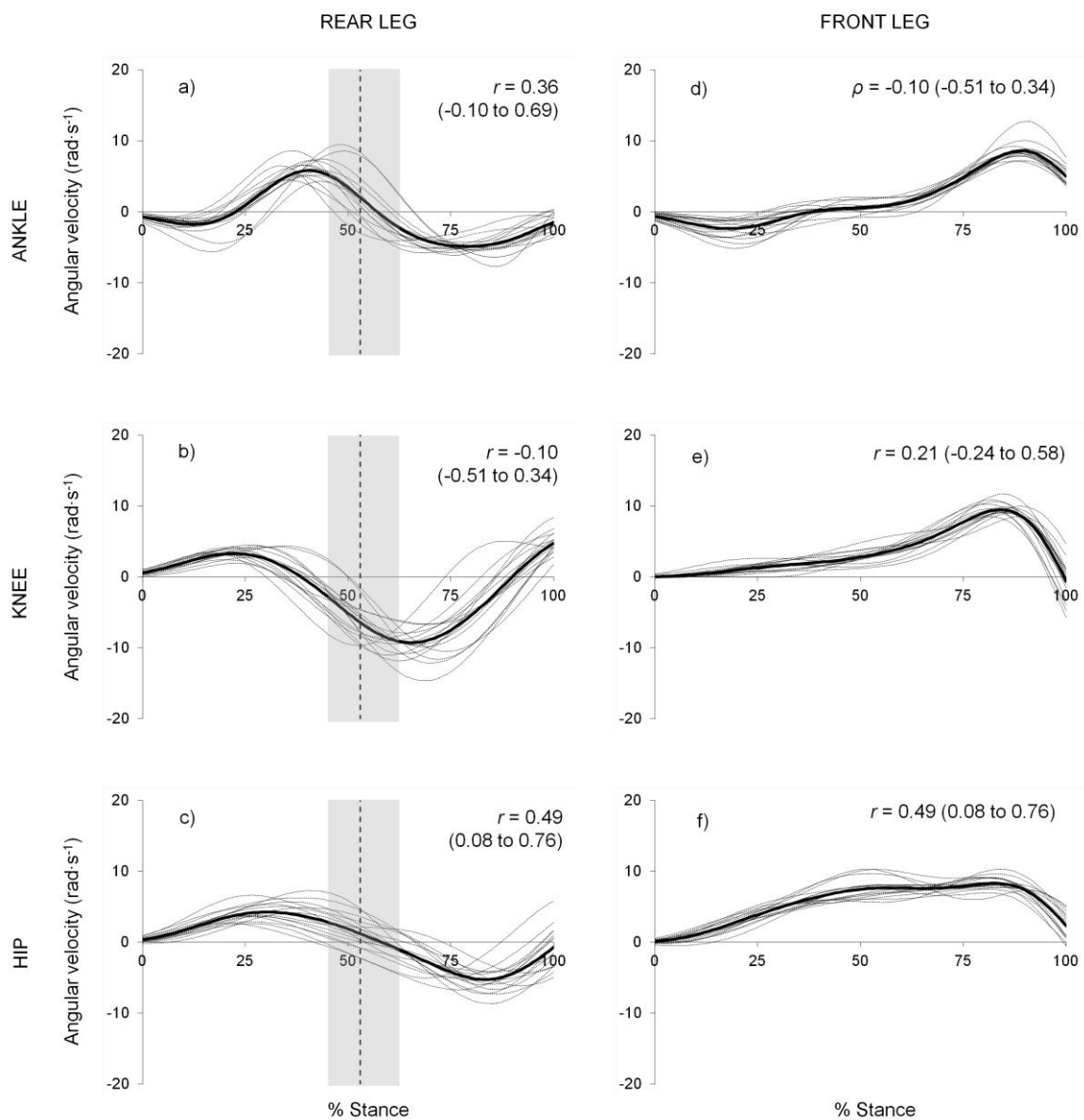
406 discrete variables and normalised average horizontal external block power ('block power'). The 90% confidence limits were determined using  
407 the Fisher z transformation.<sup>17</sup> Trunk angle is presented relative to the horizontal with a negative value representing the shoulders below the  
408 hips. Ranges of motion during block exit for the rear leg joints are during rear block contact only.

409 Table 2. Group mean and standard deviation values for selected kinematic variables from the first flight and first stance phases, reliability of  
 410 these values, and their relationships (including 90% confidence limits) with normalised average horizontal external block power.

	Mean $\pm$ s	ICC	<i>r</i>	90% confidence limits
Flight duration (s)	0.073 $\pm$ 0.022	0.99	0.20	-0.25 to 0.58
Normalised step length	1.10 $\pm$ 0.07	0.92	0.36	-0.08 to 0.68
Normalised touchdown distance	-0.20 $\pm$ 0.07	0.94	-0.46	-0.74 to -0.04
Hip angle at touchdown (°)	95 $\pm$ 9	0.90	0.11	-0.33 to 0.51
Knee angle at touchdown (°)	101 $\pm$ 7	0.89	-0.10	-0.51 to 0.34
Ankle angle at touchdown (°)	96 $\pm$ 7	0.95	0.31	-0.13 to 0.65

411 The intraclass correlation coefficients (ICC) were calculated using model 2,3 to quantify the reliability of these data with respect to the within-  
 412 sprinter variability relative to the total between-sprinter variability.<sup>16</sup> Pearson's correlation coefficients (*r*) were calculated between each of these  
 413 discrete variables and normalised average horizontal external block power. The 90% confidence limits were determined using the Fisher z  
 414 transformation.<sup>17</sup> The normalised values were divided by leg length.<sup>15</sup> Touchdown distance represents the horizontal distance between the CM  
 415 and the stance leg metatarsal-phalangeal joint at touchdown with a negative value representative of the metatarsal-phalangeal joint behind the  
 416 CM.

417 Figure 1. Joint angular velocities throughout the push phase for a) rear ankle, b) rear knee,  
 418 c) rear hip, d) front ankle, e) front knee and f) front hip. Positive values represent joint  
 419 extension. The bold line represents the mean of all sprinters and the dotted lines represent  
 420 each individual sprinter's mean data. The dotted vertical line in figures a-c represents the  
 421 mean time of rear block exit and the shaded area represents the range in this variable  
 422 across all sprinters. The values in the top right hand corner of each figure are the strength  
 423 and 90% confidence limits of the relationships between the peak angular velocity at each  
 424 joint and normalised average horizontal external block power across all of the sprinters.  
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