

**TITLE**

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Title: Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: which is the most appropriate measure?

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1 **Abstract**

2 Sprint start performance has previously been quantified using several different  
3 measures. This study aimed to identify whether different measures could influence  
4 the performance-based ranking within a group of 12 sprinters and if so, to identify the  
5 most appropriate measure. None of the ten performance measures ranked all  
6 sprinters in the same order; Spearman's rho correlations between different block  
7 phase measures ranged from 0.50 to 0.94, and between block phase measures and  
8 those obtained beyond block exit from 0.66 to 0.85. Based on consideration of what  
9 each measure quantifies, normalised average horizontal external power was  
10 identified as the most appropriate, incorporating both block velocity and the time  
11 spent producing this velocity. The accuracy with which these data could be obtained  
12 in an externally valid field setting was assessed against force platform criterion data.  
13 For an athlete producing  $678 \pm 40$  W of block power, a carefully set-up manual high-  
14 speed video analysis protocol produced systematic and random errors of +5 W  
15 and  $\pm 24$  W, respectively. Since the choice of performance measure could affect the  
16 conclusions drawn from a technique analysis, for example the success of an  
17 intervention, it is proposed that external power is used to quantify start performance.

18

19 198 words.

20 **Introduction**

21 Successful performance in any sprint event is evaluated based on an ability to cover  
22 a specific distance in the least possible time. However, when analysing a discrete  
23 part of a sprint such as the start the exact definition of success is less clear. For  
24 example, it is difficult to objectively determine whether reaching a specific distance  
25 (e.g. 5 m) earlier or reaching this distance slightly later but with a greater  
26 instantaneous velocity represents better performance. This may partly explain why  
27 several different performance measures have been used in previous sprint start  
28 research.

29

30 The most commonly used measure of sprint start performance is block velocity (e.g.  
31 Henry, 1952; Baumann, 1976; Vagenas and Hoshizaki, 1986; Mero, 1988; Mero and  
32 Komi, 1990; Guissard et al., 1992; Schot and Knutzen, 1992; Mendoza and  
33 Schöllhorn, 1993; Mero et al., 2006). This quantifies the horizontal velocity of a  
34 sprinter's centre of mass (CM) at the instant of block exit, and accurate values are  
35 typically calculated from horizontal force data via calculation of impulses. As shown  
36 in Table 1, previous studies using force transducers in or under the blocks have  
37 reported considerable variation in block velocities, even within sub-groups of  
38 relatively homogenous overall ability levels.

39

40 \*\*\*\*Table 1 near here\*\*\*\*

41

42 Other widely adopted measures (often used concurrently with block velocity) include  
43 the time taken to reach a specific distance (e.g. Henry, 1952; Mero et al., 1983;  
44 Vagenas and Hoshizaki, 1986; Schot and Knutzen, 1992; Mendoza and Schöllhorn,

45 1993; Mero et al., 2006), the instantaneous velocity at a specific distance (e.g. Schot  
46 and Knutzen, 1992; Salo and Bezodis, 2004), or the instantaneous velocity at a  
47 specific event such as first-step toe-off (e.g. Mero, 1988; Mero and Komi, 1990;  
48 Schot and Knutzen, 1992). Where velocity or time measures have been recorded at  
49 specific distances, the distances used have varied widely, from 2.29 m to 45.72 m  
50 (2.5 yards to 50 yards). A small number of studies have also reported other  
51 measures of performance such as peak block phase acceleration (Baumann, 1976),  
52 average block phase acceleration (Payne and Blader, 1971; Gagnon, 1978; van  
53 Coppenolle et al., 1989; Guissard et al., 1992) and average block phase power  
54 (Cavagna et al., 1965; Mero et al., 1983; Mendoza and Schöllhorn, 1993). Despite  
55 using sprinters of relatively similar ability levels, the block phase power values  
56 reported in these three studies did not clearly correspond to each other. This may  
57 have been due to the use of different methods for calculating power, as there are  
58 numerous 'types' of energy that can be incorporated when quantifying power  
59 (Winter, 1978; Willems et al., 1995). The aim of a sprint is to translate the body over  
60 a specific horizontal distance in the shortest time (i.e. each sprinter must perform a  
61 specific amount of horizontal external work in the least possible time). Therefore, an  
62 ability to produce horizontal external power (i.e. to translate the CM horizontally  
63 relative to the environment in a short period of time) appears to be a potentially  
64 useful measure of block phase performance despite having been largely overlooked  
65 in recent sprint start literature.

66

67 The use of different performance measures may be a reason why some  
68 experimental block phase studies have reported seemingly conflicting results. For  
69 example, Mendoza and Schöllhorn (1993) implemented an experimental intervention

70 to 'set' position kinematics and reported two main measures of performance (block  
71 velocity and time to 10 m). Only three of the sprinters increased their block velocity  
72 following the intervention, with three experiencing a decrease and one no change.  
73 Whilst the logical conclusion would therefore have been that their intervention was  
74 beneficial for less than half of the cohort, alternative performance data suggested  
75 otherwise since the interventions reduced the time it took for all but one of the  
76 sprinters to reach 10 m. The results of Mendoza and Schöllhorn (1993) therefore  
77 highlight an important issue – the choice of performance measure can potentially  
78 affect the conclusions reached in research focussing on sprint start technique and  
79 performance.

80

81 Whilst it appears that the use of markedly different performance measures (e.g.  
82 block velocity and time taken to reach 10 m) could influence the perceived  
83 performance success, it is not clear whether such a conflict exists when using less  
84 diverse variables such as those determined solely from the block phase (e.g. block  
85 velocity, average block acceleration, average block power). Furthermore, if the  
86 choice of performance measure does influence the identification of trials or sprinters  
87 associated with higher levels of performance, it is important that a single optimal  
88 performance measure is determined so that an objective quantification of  
89 performance can be achieved. It is also important that this variable can be obtained  
90 to a sufficient level of accuracy in an externally valid applied setting where force data  
91 are unavailable so that high performance data can be confidently collected and  
92 analysed. The aim of this study was therefore to determine whether the choice of  
93 performance measure influences the performance-based ranking of a group of

94 sprinters, and if so, to determine the most appropriate and objective measure of  
95 performance, assessing the accuracy with which it can be quantified in the field.

96

## 97 **Methods**

### 98 *Participants and Procedures*

99 Following protocol approval from the Local Research Ethics Committee, 12  
100 university-level male sprinters (mean  $\pm$  s: height = 1.78  $\pm$  0.05 m, mass = 72.4  $\pm$   
101 8.5 kg, age = 21  $\pm$  4 years, 100 m personal best = 11.30  $\pm$  0.42 s) provided written  
102 informed consent for data to be collected at their normal indoor sprint start training  
103 sessions just prior to the competition phase of the indoor season. After coach-  
104 directed warm-ups, all 12 sprinters completed a series of three maximal effort sprints  
105 to 30 m commencing from starting blocks. Each sprinter adjusted the blocks  
106 according to their personal preference, and wore their own spiked shoes. Each sprint  
107 was initiated by the sprinters' coach, who provided standard '*on your marks*' and '*set*'  
108 commands. The coach then pressed a custom designed trigger button to provide the  
109 auditory start signal through a sounder device, and simultaneous signals were sent  
110 to initiate data collection with a high-speed camera and a Laser Distance  
111 Measurement (LDM) device. After each trial, sprinters were allowed their normal  
112 recovery (approximately 8-10 minutes).

113

### 114 *Data collection*

115 A high-speed digital video camera (Motion Pro<sup>®</sup>, HS-1, Redlake, USA) was mounted  
116 on a tripod, 8.00 m away from the centre of the running lane, with the lens centre  
117 1.00 m above the ground and directly in line with the start line. An area of 2.00 m  
118 horizontally by 1.60 m vertically was calibrated with its mid-point at the start line at

119 the centre of the lane inside a field of view 2.50 m wide. Images were collected at a  
120 resolution of 1280 × 1024 pixels using a shutter speed of 1/1000 s and a sampling  
121 frequency of 200 Hz. Due to the indoor conditions, an additional 4000 W of lighting  
122 was used to provide a sufficiently bright image. The LDM device (LDM-300C,  
123 Jenoptik, Germany) operating at 100 Hz was positioned approximately 20 m behind  
124 the start line in the centre of the lane to obtain data relating to the displacement of  
125 the lumbar region of the sprinter for the entire 30 m sprint. The exact distance  
126 between the LDM device and the start line was determined during a static trial prior  
127 to data collection so that all LDM device distances could subsequently be expressed  
128 relative to the start line (0.00 m).

129

### 130 *Data processing*

131 The raw video files were viewed to determine movement onset (the first frame in  
132 which movement was visible) and block exit (the first frame in which the front foot  
133 lost contact with the front block). The video files were then digitised (Peak Motus<sup>®</sup>, v.  
134 8.5, Vicon, USA) at full resolution with a zoom factor of 2, thus yielding a resolution  
135 of measurement of less than 1 mm. Eighteen specific anatomical points (vertex,  
136 seventh cervical vertebra, shoulder, elbow, wrist, third metacarpal, hip, knee, ankle  
137 and second metatarsophalangeal joint centres) were manually digitised from the  
138 frame prior to movement onset through to ten frames after first stance touchdown.  
139 The raw digitised co-ordinates were scaled (using projective scaling with the four  
140 corner points of the aforementioned rectangular calibration area). The resulting raw  
141 displacement time-histories were exported to Matlab<sup>™</sup> (v. 7.4.0, The MathWorks<sup>™</sup>,  
142 USA) for subsequent analysis. The raw displacement data were combined with  
143 segmental inertia data (de Leva, 1996) to create a 14-segment model. Inertia data



144 for the feet were taken from Winter (1990) to allow for a linked segment model to be  
145 created, and the measured mass of each individual sprinter's spiked shoe (group  
146 mean = 0.23 ± 0.05 kg) was added to both feet. The raw whole-body CM  
147 displacement time-history (required for the calculation of performance measures)  
148 was calculated from the segmental data using the summation of segmental moments  
149 approach (Winter, 1990).

150

### 151 *Calculation of performance measures*

152 Block velocity was calculated using the raw CM displacement data from each frame  
153 of the first flight phase. The first derivative of a linear polynomial fitted through the  
154 raw horizontal CM coordinates from the first flight phase was used to calculate  
155 horizontal velocity at take-off (i.e. block velocity), as outlined by Salo and  
156 Scarborough (2006). Block velocity was also calculated with two other commonly  
157 used methods, but as the above polynomial method was found to provide the most  
158 accurate estimation (see Appendix for details) it was used throughout this study.  
159 Average horizontal block acceleration was calculated as block velocity divided by the  
160 duration of the push phase (i.e. from movement onset to block exit). Average  
161 horizontal external power during the push phase was calculated based on the rate of  
162 change of mechanical energy in a horizontal direction (i.e. change in kinetic energy  
163 divided by time):

$$164 \quad \bar{P} = \frac{m(v_f^2 - v_i^2)}{2 \cdot \Delta t}$$

165

166 in which  $v_i$  and  $v_f$  are the horizontal velocities at the start and end of the push phase,  
167 respectively (i.e.  $v_i = 0$  m/s),  $\Delta t$  is the duration of this phase, and  $m$  is the mass of the  
168 sprinter.

169

170 The LDM device was used to obtain displacement and velocity-based measures of  
171 performance from beyond the block phase for inclusion in the comparison of  
172 performance measures. It was important to obtain LDM device velocity time-histories  
173 that were relatively smooth functions, independent of any within-step fluctuations, as  
174 these could influence instantaneous velocity values taken from a specific point on  
175 the curve as shown by Salo and Bezodis (2004). To improve the ‘averaging method’  
176 used to calculate velocity by Salo and Bezodis (2004), a fifth-order polynomial  
177 function was fitted to the raw LDM displacement data to remove both the within-step  
178 velocity fluctuations and the random noise. This function was analytically  
179 differentiated with respect to time in order to yield a fourth-order representation of the  
180 velocity profile. From these functions, the time at which displacement equalled 10, 20  
181 and 30 m was identified, as were the corresponding velocity values at these  
182 distances.

183

184 From the high-speed camera and LDM device, nine measures of performance were  
185 thus obtained, all of which had been used in previous sprint start research. These  
186 were:

- 187 • Block velocity
- 188 • Average horizontal block acceleration
- 189 • Average horizontal external block power
- 190 • Time to 10 m
- 191 • Time to 20 m
- 192 • Time to 30 m
- 193 • Velocity at 10 m

194 • Velocity at 20 m

195 • Velocity at 30 m

196 Because smaller sprinters require less power to translate their CM to the same  
197 extent as a larger sprinter, a tenth performance measure (normalised average  
198 horizontal external block power) was calculated. This was based on a modification of  
199 the function presented by Hof (1996) in order to obtain a dimensionless normalised  
200 power ( $P_N$ ) value:

201 
$$P_N = \frac{\bar{P}}{m \cdot g^{3/2} \cdot l^{1/2}}$$

202 where  $m$  is the mass of the sprinter,  $g$  is the acceleration due to gravity, and  $l$  is the  
203 leg length of the sprinter. This was corrected from the function presented by Hof  
204 (1996) since that was found to produce normalised power with the units  $s^{-2}$  rather  
205 than as a dimensionless number as intended.

206

207 For all of the above variables used to quantify performance, the mean performances  
208 of each of the 12 sprinters were ranked from 1 (best) to 12 (worst). Spearman's rank  
209 order correlation co-efficients ( $\rho$ ) were then calculated from these ordinal data to  
210 determine whether different performance measures ranked the mean performances  
211 of the 12 sprinters in the same order, or whether the choice of performance measure  
212 affected the rank order of the sprinters.

213

#### 214 *Accuracy of high-speed video protocol*

215 The internal validity of the video set-up and data processing methods was evaluated  
216 against criterion kinetic data by replicating the previously described camera set-up in  
217 a laboratory setting. One trained male sprinter (age = 23 years, mass = 62.3 kg,

218 height = 1.71 m, 100 m personal best = 11.20 s) provided informed consent and  
219 completed a series of 20 sprint start trials. The starting blocks were firmly spiked into  
220 a 1 cm thick rubber mat which was strongly bonded to a sheet of thin steel, which in  
221 turn was securely bolted to a 0.900 x 0.600 m force platform (Kistler, 9287BA, Kistler  
222 Instruments Ltd., Switzerland) operating at 1000 Hz. The hands were placed on the  
223 front edge of the force platform, and the starting blocks were adjusted to the  
224 preference of the sprinter. The blocks were constrained to remaining on the force  
225 platform in order to ensure that all points of ground contact were on the platform. In  
226 each trial, the sprinter raised in to the 'set' position upon standard starting  
227 commands from the investigator. The investigator subsequently pressed a trigger  
228 button, sending a signal to the sounder device and high-speed video camera, and  
229 additionally to the computer collecting the force platform data. The trigger signal was  
230 also transmitted to a series of 20 light-emitting diodes (Wee Beastie Ltd, UK) placed  
231 in the camera view, one of which illuminated every 1 ms thus allowing  
232 synchronisation of the force and video data to the nearest millisecond.

233

234 Horizontal impulse data were obtained through integration (trapezium rule) of the raw  
235 horizontal force data, and the associated velocity data were subsequently  
236 determined. Criterion movement onset time was defined as the frame in which the  
237 horizontal force first increased, and then subsequently remained, two standard  
238 deviations above the mean horizontal force recorded during the first 50 ms following  
239 the starting signal (during which the athlete remained stationary in the set position  
240 before reacting to the signal). Criterion block exit time was determined as the frame  
241 in which horizontal force first dropped below a threshold of 10 N (this was different to  
242 the threshold used to identify movement onset due to the vibrations of the blocks on

243 the force platform rendering the previously used threshold inaccurate). The  
244 corresponding velocity at the instant of block exit was thus identified and recorded as  
245 the criterion measure of block velocity. Force platform power values were calculated  
246 from the product of the horizontal force and velocity time-histories, and were  
247 averaged across the push phase to yield a criterion measure of average horizontal  
248 external power.

249

250 The video data were reduced and processed exactly as outlined in the previous  
251 section in order to directly replicate the protocol used in the field. Difference scores  
252 were calculated between the high-speed video estimate of block velocity and the  
253 force platform criterion measure for all 20 trials (i.e. video minus criterion score).  
254 These difference scores were then plotted against the mean value of the video and  
255 criterion measures of block velocity from each corresponding trial (Altman and Bland,  
256 1983). To quantify the validity of the high-speed video data, 95% limits of agreement  
257 were calculated from the standard deviation of all the difference scores between the  
258 video and criterion values (Bland and Altman, 1986) using the appropriate critical  $t$ -  
259 value (2.093,  $p = 0.05$ ) for the number of trials analysed. Finally, using the block  
260 velocities and push phase durations estimated from the video data, average block  
261 acceleration and average horizontal external block power data were also calculated,  
262 and 95% limits of agreement were calculated for these variables against the  
263 associated criterion data.

264

## 265 **Results**

266 No two measures ranked the performances of all sprinters in the same order  
267 (Figure 1), and thus no two measures were perfectly correlated (in Figure 1 it would

268 be expected that there would be 12 horizontal lines if each measure ranked all  
269 subjects in the same order). Whilst the 'time to' and 'velocity at' measures were  
270 closely matched to each other (i.e. the right hand side of Figure 1, where the lines  
271 cross over each other considerably less;  $\rho = 0.91 - 0.99$ ,  $p < 0.01$ ), correlations  
272 between these and the block phase measures were weaker (i.e.  $\rho = 0.66 - 0.85$ ,  
273  $p < 0.05$ ). The high-speed video based measures of block phase performance for  
274 each subject are presented in Table 2, and correlations between these measures  
275 were typically moderate to strong. The correlation between block velocity and  
276 average horizontal block acceleration was  $\rho = 0.68$  ( $p < 0.05$ ), between block  
277 velocity and average horizontal external block power was  $\rho = 0.50$  ( $p = 0.10$ ), and  
278 between average horizontal block acceleration and average horizontal external block  
279 power was  $\rho = 0.80$  ( $p < 0.01$ ). Normalised average horizontal external block power  
280 values were correlated with the absolute values with a strength of  $\rho = 0.72$  ( $p <$   
281  $0.01$ ), and when these normalised power data were correlated with the block velocity  
282 and acceleration data, the coefficients were  $\rho = 0.88$  and  $\rho = 0.94$  (both  $p < 0.01$ ),  
283 respectively.

284

285 \*\*\*\*Figure 1 near here\*\*\*\*

286 \*\*\*\*Table 2 near here\*\*\*\*

287

288 The systematic bias associated with the high-speed video estimates of block velocity  
289 relative to the force platform criterion values was  $+0.005$  m/s, with 95% limits of  
290 agreement of  $\pm 0.048$  m/s (Figure 2). The duration of the push phase could be  
291 estimated from the high-speed video data to an accuracy of  $-0.001 \pm 0.007$  s. When  
292 these high-speed video estimates of block velocity and push phase duration were

293 used to calculate average horizontal block acceleration and average horizontal  
294 external block power, systematic and random errors of  $+0.025 \pm 0.173 \text{ m/s}^2$  and  
295  $+5 \pm 24 \text{ W}$ , respectively, were observed.

296

297 \*\*\*\*Figure 2 near here\*\*\*\*

298

## 299 **Discussion and implications**

300 This study determined that the choice of performance measure influenced the  
301 identification of successful performance during the block phase of an athletic sprint  
302 start. The controlled laboratory replication of the field-based methods confirmed that  
303 all of the high-speed video based measures of block phase performance (block  
304 velocity, average horizontal block acceleration and average horizontal external block  
305 power) could be accurately determined in an externally valid setting. The following  
306 section will briefly review the accuracy of the manual high-speed video protocol,  
307 before discussing the different performance measures and ultimately identifying  
308 which measure provides the most objective assessment of block phase  
309 performance.

310

311 Relative to the criterion force platform data, the systematic bias associated with the  
312 high speed video block velocities ( $+0.005 \text{ m/s}$ ) represented less than 0.2% of the  
313 mean criterion block velocity measured from the 20 laboratory trials ( $2.89 \text{ m/s}$ ). The  
314 random error (quantified by the 95% limits of agreement) associated with block  
315 velocity measurement was also small ( $\pm 0.048 \text{ m/s}$ , less than 1.7% of the mean  
316 criterion value). If using block velocity as a measure of performance, the current  
317 high-speed video protocol could therefore be used to distinguish between trials or

318 sprinters separated by just under 0.1 m/s. Compared to the block velocity data  
319 presented in Table 1 from sprinters of a similar ability range to those in the current  
320 study, this appears to be a sufficient level of accuracy with which to distinguish levels  
321 of performance both within and between individual sprinters. The systematic biases  
322 associated with average horizontal acceleration and average horizontal external  
323 power were also small ( $+0.025 \text{ m/s}^2$  and  $+5 \text{ W}$ , respectively) due to the duration of  
324 the push phase being accurately determined from the video clips. This systematic  
325 error in the measurement of acceleration represented less than 0.4% of the mean  
326 value ( $7.45 \text{ m/s}^2$ ), whilst the random error ( $\pm 0.173 \text{ m/s}^2$ ) associated with the  
327 estimation of acceleration represented a 2.3% error. For the power data, the  
328 systematic error ( $5 \text{ W}$ ) represented 0.7% of the mean value ( $678 \text{ W}$ ), and the 95%  
329 limits of agreement ( $\pm 24 \text{ W}$ ) associated with the high-speed video measurement of  
330 power were 3.5% of this mean value. Given the lower ability level of the sprinter  
331 used for the laboratory analysis, and the fact that a slightly 'bunched' start was used  
332 (due to the constraint that all points of contact were required to be on the force  
333 platform), these velocity, acceleration and power values were lower than those  
334 typically observed in the literature (e.g. Table 1; van Coppenolle et al., 1989;  
335 Mendoza and Schöllhorn, 1993). The percentage errors presented above would  
336 therefore be expected to be lower in externally valid field settings using more well-  
337 trained sprinters (with higher velocity, acceleration and power) adopting their normal  
338 'set' positioning since the errors relate to the data collection and processing protocol  
339 rather than the ability level of the sprinters. The results of this validity analysis  
340 therefore revealed that manual high-speed video estimates of block velocity, average  
341 horizontal block acceleration and average horizontal external block power all  
342 contained appropriately low levels of systematic and random error.



343

344 None of the ten measures ranked all of the sprinters in the same order, as indicated  
345 by the Spearman's rank order correlations which revealed that no two measures of  
346 performance were perfectly correlated (Figure 1). Despite some strong and  
347 significant correlations in this study, any rank order correlation coefficient less than  
348 1.00 indicated inconsistency in the performance-based ranking of these 12 sprinters.  
349 The correlation coefficients between the measures obtained at block exit and those  
350 obtained further down the track ( $\rho = 0.66 - 0.85$ ) confirmed the ideas developed  
351 from the results of Mendoza and Schöllhorn (1993) that although measures obtained  
352 from beyond block exit have been widely used when investigating the block phase,  
353 their direct relevance to technique and performance during just the block phase must  
354 be considered with caution. Whilst they clearly provide meaningful sprint  
355 performance data, the time taken to reach set distances or the velocity at these  
356 distances is a function of the techniques used in every step prior to that distance,  
357 and not just technique during the block phase. Whilst it is acknowledged that as the  
358 distance at which performance is measured moves further from the start line, the  
359 value obtained will get continually closer to the key performance indicator in sprinting  
360 (i.e. the time taken to reach the finishing distance), performance should ideally be  
361 quantified during just the phase over which technique is analysed, allowing the  
362 observed performance levels to be directly attributed to the observed techniques.

363

364 Whilst all of the performance data calculated solely from the block phase (i.e. block  
365 velocity, average horizontal block acceleration, average horizontal external block  
366 power and normalised average horizontal external block power) could be accurately  
367 calculated from high-speed video data, the correlation coefficients between each of

368 these measures highlighted that even the use of different block phase measures  
369 could affect the outcome of a study. The correlation ( $\rho = 0.72$ ) between the average  
370 and normalised block power data confirmed that different subject morphologies  
371 influence the absolute magnitudes of power generated, and thus power data should  
372 be normalised to account for this when used as a measure of performance between  
373 subjects. Even when body size was accounted for in these normalised power data,  
374 the sprinters were still ranked in a conflicting order to both the block velocity and  
375 acceleration data ( $\rho = 0.88$  and  $\rho = 0.94$ , respectively). The potential influence of the  
376 choice of performance measure on the perceived ability of one single sprinter within  
377 the cohort is well illustrated by sprinter I – ranked the third best sprinter based on  
378 block velocity, the eleventh best based on average horizontal block acceleration, the  
379 worst based on average horizontal external block power, and the eighth best based  
380 on normalised average horizontal external block power. It is therefore clearly  
381 important to consider what each measure actually quantifies, and to determine the  
382 most objective and appropriate measure of sprint start performance.

383

384 The use of block velocity as the sole measure of performance is potentially  
385 misleading. Velocity is directly determined by horizontal impulse production, and  
386 because impulse is equal to the product of force and time, an increased block  
387 velocity could therefore be due to either an increase in the net propulsive force  
388 generated, or to an increased push duration. Spending a longer time in the blocks  
389 conflicts with the 'least possible time' nature of a sprint, and therefore if an increased  
390 block velocity were associated solely with an increase in push duration, it would not  
391 be beneficial for overall sprint performance. Although measures of both velocity and  
392 time could be obtained, the relative weighting of each of these variables would be

393 difficult to objectively determine, and so a single measure of performance is a more  
394 appropriate and unbiased approach. Average horizontal block acceleration is  
395 potentially a more useful measure of performance than block velocity due to the  
396 additional incorporation of time, and it has previously been shown that whilst one  
397 athlete may exhibit a higher block velocity, another could have a higher acceleration  
398 due to a shorter push phase duration (van Coppenolle et al., 1989). Power also  
399 incorporates the effects of both time and velocity; however, acceleration and  
400 normalised power-based rank orders were not perfectly correlated ( $\rho = 0.94$ ). Being  
401 a kinetic variable, power production ultimately determines acceleration (a kinematic  
402 variable), and since the overall aim in sprinting is to reach the finish in the least  
403 possible time (each sprinter must perform a specific amount of work to translate their  
404 CM horizontally over 100 m, and the time it takes to do this depends on horizontal  
405 external power production), power production is of critical importance. Average  
406 horizontal external power is not the same as total power, since it ignores the  
407 necessary vertical motions and the internal power associated with the relative motion  
408 of body segments (Winter, 1978). However, reducing metabolic cost is not the main  
409 goal in sprinting (Caldwell and Forrester, 1992) and thus neither the total power nor  
410 the efficiency of movement are of major importance when using power as a measure  
411 of sprint performance. Theoretical studies have suggested that the most preferable  
412 strategy in sprint events is one in which maximal horizontal external power is  
413 produced from the very beginning. Although more energy is theoretically lost to air  
414 resistance and thus velocity is reduced towards the end of the race, this is  
415 outweighed by less time being spent running at submaximal velocities at the start  
416 (van Ingen Schenau et al., 1991, 1994; de Koning et al., 1992). Maximal external  
417 power production during the block phase therefore appears paramount for

418 performance. Furthermore, based on these theoretical data, maximal external power  
419 production also appears important during every part of a sprint, and thus normalised  
420 average horizontal external power potentially offers an appropriate measure of  
421 performance for any stage of a sprint which is being analysed (be it trying to  
422 maximise power generation during the early stages of a sprint, or to minimise power  
423 loss during the latter stages of a sprint).

424

425 Although it was not the main aim of this study, the performance data in Table 2 also  
426 provide further information about the block phase to the literature. Sprinters A and B,  
427 who had the two best personal bests, also achieved the highest power values, both  
428 in absolute and normalised terms. The absolute power values for these two subjects  
429 were comparable to values presented by Mendoza and Schöllhorn (1993),  
430 suggesting that sprinters able to run close to 10.5 s possess the ability to generate  
431 such power in the blocks. Interestingly the sprinter with the third fastest personal  
432 best (sprinter C) exhibited the lowest level of block phase performance (normalised  
433 block power). This suggests that his start is relatively weak and improvements could  
434 potentially be achieved in this area. Similarly, sprinters E and F seem to have better  
435 normalised block power values than other sprinters of similar calibre. This might  
436 suggest that sprinters E and F could focus more on their actual running than on the  
437 block phase to improve their performance. Overall, this type of comparison could  
438 give coaches a clear indication of an athlete's relative strengths and weaknesses,  
439 and thus help to guide their training.

440

441 **Conclusion**

442 The results of this study revealed that each of ten previously used measures of block  
443 phase performance ranked the performances of a cohort of 12 sprinters in different  
444 orders. Therefore, if a coach or researcher intended to associate aspects of block  
445 phase technique with changes or improvements in performance, the choice of  
446 performance measure could clearly influence the conclusions reached. Normalised  
447 average horizontal external power was identified as the most appropriate measure of  
448 performance because it objectively reflects, in a single measure, how much a  
449 sprinter is able to increase their velocity and the associated length of time taken to  
450 achieve this, whilst accounting for variations in morphologies between sprinters.  
451 Furthermore, external power is clearly directly relevant to overall sprint performance  
452 and can be used to analyse performance from any phase of a sprint. The accuracy  
453 with which these power data could be determined from a carefully set-up manual  
454 high-speed video analysis protocol was also assessed, and it was shown that  
455 accurate high-performance data could be obtained using this non-invasive approach  
456 in field settings.

457

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552

## 553 **Appendix**

### 554 *The accuracy of different methods for calculating block velocity*

555 In addition to the method used to calculate block velocity from high-speed video data  
556 in this article (i.e. the first derivative of a linear polynomial fitted through raw CM data  
557 from the subsequent flight phase), the accuracy of two other available methods for

558 calculating block velocity was assessed to ensure that the most accurate method  
559 was used. Firstly, the commonly adopted process of digitally filtering the CM data  
560 from the block phase and first flight, and extracting the instantaneous block exit  
561 velocity was undertaken. Secondly, the gradient of a straight line fitted between the  
562 raw CM displacement data from first and last frames of flight only was calculated (Yu  
563 and Hay, 1996). The block velocity values obtained from these two methods were  
564 compared to the criterion force platform data using a 95% limits of agreement  
565 approach (Bland and Altman, 1986). Relative to the criterion data, the digital filtering  
566 method yielded systematic and random errors of  $+0.084 \pm 0.190$  m/s, respectively,  
567 whilst the method of Yu and Hay (1996) yielded systematic and random errors of  
568  $+0.018 \pm 0.056$  m/s, respectively. Despite using the same raw displacement data,  
569 these methods were less accurate than the polynomial method ultimately used in the  
570 current article (systematic and random errors of  $+0.005 \pm 0.048$  m/s).

Table 1. Force transducer-based estimates of block velocity for male sprinters of a similar ability range to those in the current study (mean  $\pm$  s).

Study	n	PB* (s) (range if reported)	Block velocity (m/s)
Baumann (1976)	12	10.35 $\pm$ 0.12 (10.20 – 10.60)	3.60 $\pm$ 0.20
Baumann (1976)	8	11.11 $\pm$ 0.16 (10.90 – 11.40)	3.10 $\pm$ 0.15
Baumann (1976)	10	11.85 $\pm$ 0.24 (11.60 – 12.40)	2.90 $\pm$ 0.20
Mero (1988)	8	10.79 $\pm$ 0.21 (10.45 – 11.07)	3.46 $\pm$ 0.32
Mero and Komi (1990)	4	10.76 $\pm$ 0.19	3.42 $\pm$ 0.38
Mero and Komi (1990)	4	10.82 $\pm$ 0.23	3.50 $\pm$ 0.22

\* PB = 100 m personal best time.

Table 2. High-speed video recorded measures of block phase performance for each of the 12 sprinters (mean  $\pm$  s).

Sprinter	100 m PB (s)	Block velocity (m/s)	Horizontal block acceleration (m/s <sup>2</sup> )	Average horizontal external block power (W)	Normalised average horizontal external block power
A	10.53	3.52 $\pm$ 0.06	10.52 $\pm$ 0.58	1449 $\pm$ 95	0.63 $\pm$ 0.04
B	10.70	3.83 $\pm$ 0.09	10.55 $\pm$ 0.13	1703 $\pm$ 57	0.66 $\pm$ 0.02
C	10.90	3.00 $\pm$ 0.01	7.94 $\pm$ 0.14	912 $\pm$ 14	0.40 $\pm$ 0.01
D	11.10	3.28 $\pm$ 0.12	9.43 $\pm$ 0.44	1113 $\pm$ 93	0.52 $\pm$ 0.04
E	11.19	3.31 $\pm$ 0.04	10.56 $\pm$ 0.08	1298 $\pm$ 24	0.58 $\pm$ 0.01
F	11.2*	3.39 $\pm$ 0.11	9.69 $\pm$ 0.31	1013 $\pm$ 63	0.56 $\pm$ 0.03
G	11.2*	3.13 $\pm$ 0.03	8.75 $\pm$ 0.27	953 $\pm$ 33	0.47 $\pm$ 0.02
H	11.3*	3.24 $\pm$ 0.09	8.95 $\pm$ 0.18	874 $\pm$ 35	0.48 $\pm$ 0.02
I	11.3*	3.41 $\pm$ 0.06	8.06 $\pm$ 0.21	803 $\pm$ 32	0.46 $\pm$ 0.02
J	11.55	3.11 $\pm$ 0.07	8.49 $\pm$ 0.15	966 $\pm$ 37	0.44 $\pm$ 0.02
K	11.6*	2.97 $\pm$ 0.07	8.14 $\pm$ 0.21	951 $\pm$ 42	0.41 $\pm$ 0.02
L	11.6*	3.12 $\pm$ 0.08	8.58 $\pm$ 0.51	1097 $\pm$ 93	0.44 $\pm$ 0.04
Mean $\pm$ s	11.30 $\pm$ 0.42	3.28 $\pm$ 0.24	9.14 $\pm$ 0.99	1094 $\pm$ 264	0.51 $\pm$ 0.09

\* 100 m personal best (PB) times reported to the nearest 0.1 s are hand timed. The presented mean value includes a standard 0.24 s adjustment to the hand timed values.

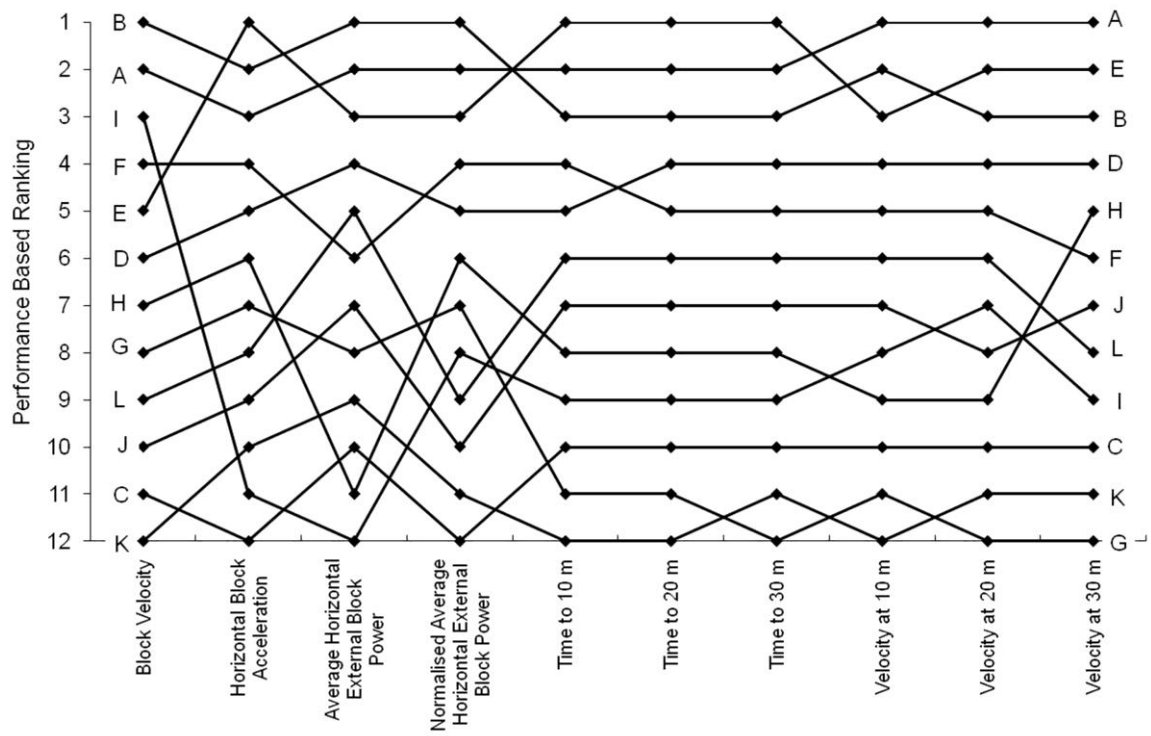


Figure 1. Rank order of all of the 12 sprinters using each of the different performance measures.

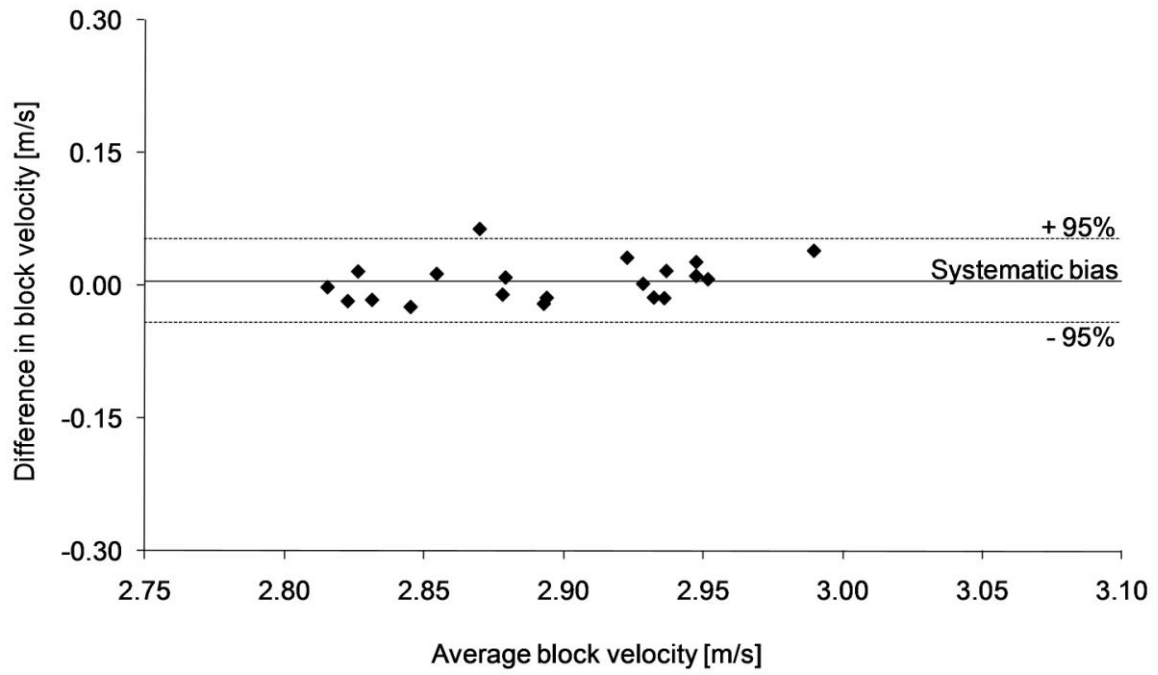


Figure 2. Illustration of the systematic bias and 95% limits of agreement for the high-speed video block velocity data.