1   *Title:*

2   Measurement error in estimates of sprint velocity from a laser displacement measurement

3   device

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15

16 *Abstract*

17 This study aimed to determine the measurement error associated with estimates of velocity

18 from a laser-based device during different phases of a maximal athletic sprint. Laser-based

19 displacement data were obtained from 10 sprinters completing a total of 89 sprints and were

20 fitted with a fifth-order polynomial function which was differentiated to obtain instantaneous

21 velocity data. These velocity estimates were compared against criterion high-speed video

22 velocities at either 1, 5, 10, 30 or 50 m using a Bland-Altman analysis to assess bias and

23 random error. Bias was highest at 1 m (+0.41 m/s) and tended to decrease as the

24 measurement distance increased, with values less than +0.10 m/s at 30 and 50 m. Random

25 error was more consistent between distances, and reached a minimum value (±0.11 m/s) at

26 10 m. Laser devices offer a potentially useful time-efficient tool for assessing between-

27 subject or between-session performance from the mid-acceleration and maximum velocity

28 phases (i.e. at 10 m and beyond), although only differences exceeding 0.22 to 0.30 m/s

29 should be considered genuine. However, laser data should not be used during the first 5 m of

30 a sprint, and are likely of limited use for assessing within-subject variation in performance

31 during a single session.

32

33 *Key words:* athletics, biomechanics, methods, performance, running, sprinting.

34

Introduction

Biomechanical research in sprinting commonly restricts analysis to a single step within a specific phase of a sprint [5, 16, 17]. However, researchers are often also interested in performance during multiple steps or phases, and horizontal velocity-time profiles from larger sections of a sprint are therefore considered [4, 8, 21]. One time-efficient method of obtaining these velocity-time curves is through a laser distance measurement (LDM) device aimed at the back of the sprinter [4, 8]. These LDM devices have been found to produce valid and reliable static measures of distance at 10, 30, 50 and 70 m when several samples are averaged [13]. However, individual samples are less reliable [13] which could potentially be problematic for dynamic activities like sprinting. The reliability of LDM velocity data obtained during sprinting trials has previously been assessed [13], but was limited by comparison against linear hip velocities over a specific 3 m distance. This approach may have provided an artificially close match with the 'lower part of the runner's back' measured by the LDM device because the horizontal within-step mechanics of a single point on the lumbar region (similar to the hip) differ from those of the centre of mass (CM) during running [24]. This could be of particular importance if data from the acceleration phase of a sprint are required, as sprinters become more upright as they accelerate out of the starting blocks [19]. Furthermore, horizontal velocity fluctuates during every step of a sprint due to the antero-posterior forces [18], and thus instantaneous velocity data, or velocity data averaged over a predefined distance, may not be from the same phases within a step. For example, at the exact distance of interest, one sprinter could be at the end of the braking phase whereas another is at the end of the propulsive phase [23]. This is clearly an important issue for applied sprint performance measurement, as velocity data at specific distances are only truly comparable between sprinters or trials if they are independent of fluctuations due to the phase of the step cycle.

In an attempt to reduce the fluctuations in velocity-time profiles due to both the genuine within-step fluctuations and the inherent noise (e.g. Figure 1), LDM device (and radar) data

63 have previously been fitted with mathematical functions [2, 8, 21]. However, these velocity

64 curves have only been assessed against split times over 3 to 10 m intervals from video or

65 photocell data [2, 8, 21], and the measurement error in velocity estimates at discrete

66 distances during different phases of a sprint remains unknown. The aim of this study was

67 therefore to determine the measurement error in velocity data obtained with an LDM device

68 during different phases of a maximal sprint, and consequently to evaluate the usability of

69 LDM devices in order to analyse sprinters' velocity profiles.

70

71

72 *Materials & Methods*

73 Seven male (mean ± SD: age = 23 ± 4 years, mass = 78 ± 5 kg, height = 1.78 ± 0.03 m,

74 100 m personal best (PB) = 10.76 ± 0.64 s) and three female (mean ± SD: age = 21 ± 1

75 years, mass = 64 ± 2 kg, height = 1.66 ± 0.02 m, 100 m PB = 12.48 ± 0.35 s) sprinters

76 agreed to participate in this study and provided written informed consent following standard

77 ethical procedures [14]. This cohort (incorporating both genders and a range of PBs) was

78 selected so that the results would be applicable across all populations of sprinters. Whilst this

79 would clearly affect the observed velocity magnitudes at different distances, the aim of this

80 study was to assess the error associated with measurement equipment, and thus the nature

81 of the cohort would not negatively influence the results [1, 3, 7].

82

83 Data were collected at outdoor track-based training sessions. The LDM device (LDM-300C,

84 Jenoptik, Germany; 100 Hz) was positioned on a tripod at a height of approximately 1 m,

85 20 m behind the start line. This exact distance was determined using a static object prior to

86 each session and was used to provide the reference distance of 0 m (start line). A high-

87 speed video camera (MotionPro HS-1, Redlake, USA; 200 Hz) was located perpendicular to

88 the running lane, 35 m from the lane centre. At each session, the camera was perpendicular

89 to a different distance from the start line so that video data were collected at 1, 5, 10, 30 and

90 50 m. The camera field of view was approximately 5.0 m wide, and an area of 4.50 × 1.60 m

4

91 (2.25 m either side of the distance of interest) was calibrated with four corner points in order

92 to obtain displacement data using projective scaling. A shutter speed of 1/1000 s was used

93 and images were captured at a resolution of 1280 × 1024 pixels. Each sprint commenced

94 from starting blocks following standard 'on your marks' and 'set' commands before a sounder

95 was activated to provide the starting signal. Video data collection was initiated manually just

96 prior to the sprinter entering the field of view. LDM device data collection was initiated

97 manually at the 'set' command, and the device was aimed at the lower part of the runner's

98 back (hereafter termed 'lumbar point'). All laser data processing took place in Matlab™

99 (v. 7.4.0, The MathWorks™, USA).

100

101 The raw displacement data obtained with the LDM device were fitted with a fifth-order

102 polynomial function. The polynomial order was selected to provide a close match to the

103 known underlying trends of the displacement and velocity profiles whilst eliminating any

104 within-step velocity fluctuations. The polynomial start point was identified from where the raw

105 displacement values increased and remained greater than 2 SD above the mean noisy pre-

106 start signal level, and the polynomial end point was 50 data points after displacement

107 exceeded 60 m. This displacement polynomial was analytically differentiated with respect to

108 time in order to yield a fourth-order representation of the velocity profile. Figure 1 shows an

109 example of the noisy velocity data obtained from numerically differentiating the raw LDM

110 device displacement data and the smooth fourth-order polynomial representation of the

111 velocity profile from one trial. For each trial, the time at which displacement equalled or first

112 exceeded the target distance was identified, and the corresponding velocity value was

113 recorded.

114

115 ****Figure 1 near here****

116

117 The raw video files were digitised in Peak Motus® (v. 8.5, Vicon, United Kingdom), exactly

118 replicating previously reported procedures [6], before all subsequent video data processing

119   took place in Matlab™ (v. 7.4.0, The MathWorks™, USA). Whole-body CM displacements

120   were calculated using segmental inertia data [10] and a summation of segmental moments

121   approach [25]. Inertia data for the feet were taken from Winter [25] as they allowed the

122   creation of a linked-segment model, and 0.2 kg was added to each foot to account for the

123   mass of each spiked shoe [5, 15]. Raw high-speed video CM velocities were calculated using

124   second central difference equations [20].

125

126   To determine the criterion high-speed video velocities at each of the target distances (i.e. 1,

127   5, 10, 30 or 50 m) without any influence of the phase of the step cycle, the following

128   procedure was undertaken. The first frame in which the raw CM displacement equalled or

129   exceeded the target distance was identified. The phase of the step cycle (i.e. stance or flight)

130   that the sprinter was in during this frame was identified, as was the closest adjacent

131   contrasting phase (i.e. flight or stance). The combined duration of these stance and flight

132   phases yielded the duration of the step cycle occurring at the target distance (at the 1 m

133   mark, the sprinters were typically in mid-stance, and as the two adjacent flight times were

134   often considerably different in length, the mean duration of the two flight phases was used in

135   obtaining total step duration). The determined step duration was then applied so that it was

136   evenly spaced either side of the frame in which the target distance was reached (e.g. if the

137   determined step duration was 41 frames and the target distance was reached in frame

138   number 67, the step cycle at the target distance was deemed to commence at frame 47 and

139   terminate at frame 87). This yielded a complete step cycle starting from an arbitrary point, but

140   in which the sprinter passed the specific target distance exactly halfway through the cycle.

141   The mean value of all raw CM velocities during this step cycle thus provided a value

142   representing the velocity of the sprinter at the target distance which was independent from

143   the phase of the step cycle the sprinter was in. Although the raw digitised video data

144   contained noise, this would likely have had minimal effect on these velocities over a

145   complete step cycle due to its presumed random nature. To confirm this, one trial (from

146   10 m) was redigitised on ten separate occasions to quantify any effects of noise in the video

6

147   data on the determined velocity value. Following a check for normality of these data, the

148   reliability of the high-speed video velocity data was determined by calculating a co-efficient of

149   variation (CV; standard deviation / mean [22]).

150

151   A Bland-Altman 95% limits of agreement approach [1, 7] was selected to assess the

152   measurement error (separated into bias and random error) of the LDM device estimates

153   relative to the criterion video data, as this approach would not be affected by the deliberately

154   broad cohort [1, 3, 7]. These limits were calculated as the standard deviation of the

155   difference scores between the video and LDM-based velocity data multiplied by the critical *t*-

156   value for the sample size at each distance. Normality of the difference scores was checked,

157   and a heteroscedasticity correlation coefficient was calculated between the difference scores

158   and the mean score from both devices to assess for any proportional bias [3, 7].

159

160   In order to allow the determined measurement error to be considered in a practical context,

161   the range in criterion velocity data was calculated at 1, 10 and 50 m (the distances when all

162   athletes completed more than two trials at a single distance). A single mean within-session

163   range was then calculated from all athletes at each of these three distances. This provided

164   an example of the typical levels of within-session performance variation that could be

165   expected and thus allowed an acceptable level of measurement error to be determined for

166   application in similar coach-led training settings [3, 7]. As the data from 1 m were collected at

167   four different sessions for one subject, these data were also used to provide an example of

168   the expected variation between sessions across six months of the season as training

169   progressed through different phases.

170

171   *Results*

172   A total of 89 trials were recorded and analysed, with at least ten trials obtained from each of

173   the individual distances. The amount of trials at each distance was not even due to the

174   number of athletes present and number of trials completed at each of the training sessions.

175   The bias and random errors associated with the calculation of instantaneous velocities at 1,

176   5, 10, 30 and 50 m from the LDM device are presented in Table 1 and Figure 2. Bias was

177   highest at 1 m (+0.41 m/s) and lowest at 30 m (+0.06 m/s) and the magnitude of random

178   error at the five distances ranged from ±0.11 m/s to ±0.21 m/s. All data were normally

179   distributed and free from heteroscedasticity (all r < 0.10; Figure 2). The ten redigitisations of

180   one trial revealed the criterion velocity data to be highly reliable (velocity = 7.66 ± 0.01 m/s;

181   CV = 0.15%). This confirmed that the noise due to operator error in the digitising process

182   was random, and that averaging the values from the duration of an entire step cycle provided

183   a highly repeatable measure of average step velocity at a specific distance. This therefore

184   also allowed the expected performance variation data (Table 2) to be considered with

185   confidence. The within-session individual variation in criterion data was low at 1 and 10 m

186   (average range in velocities = 0.09 and 0.14 m/s, respectively) but considerably higher

187   (0.75 m/s) at 50 m. The between-session variation in performance was higher (range =

188   0.47 m/s at 1 m) than the within-session variation.

189

190   ****Table 1 near here****

191   ****Table 2 near here****

192   ****Figures 2a-e near here****

193

194

195   *Discussion*

196   This study determined the measurement error associated with LDM estimates of velocity

197   during different phases of a maximal effort sprint to evaluate how useful LDM devices are for

198   analysing sprint velocity profiles. It was found that the measurement error varied between

199   different phases of a sprint, with a general trend for the magnitude of the bias to decrease as

200   the measurement distance increased (Table 1). The random error exhibited a slightly

201   unexpected trend, with the 95% limits of agreement being highest during the first 5 m before

202   decreasing considerably at 10 m and then gradually increasing thereafter (Table 1). Finally,

the lack of heteroscedastic data at any of the five distances (Figure 2) demonstrates that the magnitude of measurement error is not affected by any proportional bias across the range of velocities at any given distance. Therefore, although LDM measurement error appears to be influenced by how far away the sprinter is from the device (Table 1), it does not appear to be affected by the velocity of the sprinter at each given distance.

The large bias during the early part of a sprint (particularly at 1 m) was not measurement artefact. This bias was systematic and highlights the limitations of using an LDM device to estimate velocity during early acceleration as it records the displacement of the lumbar point instead of the CM. A retrospective analysis of synchronised video and LDM data from four trials of a single sprinter revealed that the horizontal motion of the lumbar point differed from that of the CM during the first second of a sprint (Figure 3). In the 'set' position the lumbar point was on average 0.40 m behind the CM, but as the sprinter began to accelerate his posture became more upright. One second after movement onset (at which point the sprinter had typically covered just over 2 m), the lumbar point was only on average 0.15 m behind the CM. The lumbar point was therefore covering a greater horizontal distance in the same amount of time, thus explaining why the velocities from the LDM device were higher than the criterion CM velocities (Table 1). There were also clear differences in the distance between the CM and the lumbar point between these four trials during this first second of a sprint, and as these were from a single sprinter and inter-athlete variation will likely exceed this (e.g. Table 2), applying a fixed offset to account for any bias is not a feasible solution.

****Figure 3 near here****

The horizontal distance between the CM and the lumbar point will never be likely to reach zero because the CM should remain in front of the lumbar point throughout the duration of a sprint. However, this distance will likely plateau as sprinters adopt a relatively consistent, and more upright, posture as the sprint progresses. This was confirmed in the current study by

231 the considerably lower biases observed at distances beyond 1 m, particularly at 30 and 50 m

232 (Table 1). This also concurred with previous video-based data [24], whereby it was found that

233 although there is a temporal shift in the individual within-step fluctuations in horizontal

234 velocity between the CM and the lumbar point during constant velocity running, overall

235 changes in displacement and velocity across one step were similar. Therefore, by smoothing

236 out the within-step fluctuations in the raw LDM device data, a non-biased representation of

237 the motion of a sprinter can be obtained once they have adopted a more upright stance

238 beyond the early parts of a sprint.

239

240 The higher random error at 1 and 5 m (±0.18 and ±0.21 m/s, respectively) may be related to

241 the aforementioned inconsistency in tracking the lumbar point as the sprinter rises out of the

242 blocks. When these random errors are combined with the high bias during the early part of a

243 sprint, LDM device estimates of velocity prior to 10 m (i.e. the initial acceleration phase [11])

244 appear to contain unacceptably high levels of error relative to the expected levels of variation

245 in performance (Table 2). By the 10 m mark, random error had decreased (±0.11 m/s),

246 before increasing slightly at the 30 and 50 m marks (±0.13 and ±0.15 m/s, respectively). This

247 gradual increase in random error from 10 to 50 m is likely due to the divergence of the laser

248 beam as the sprinter moved further from the start line because a greater area of the sprinter

249 was measured by the wider laser beam at these distances (beam diameter = 0.06 m at the

250 start line, 0.21 m at the 50 m mark). Movement of any segments near to the lumbar point,

251 any clothing movement, or even a large leg retraction and thus high foot displacement

252 behind the sprinter could therefore all have affected these velocity estimates. Also, any

253 movements of the LDM device itself by the operator have a larger pointing effect (deviation)

254 the further from the device the athlete travels.

255

256 The measurement error associated with the LDM device generally compares well against

257 other time-efficient devices used to obtain velocity estimates during sprinting. Based on

258 published differences in velocity estimates between tested devices and a criterion,

259 measurement errors comparable to those presented in the current study (i.e. 95% limits of

260 agreement using the standard deviation of the differences and the appropriate critical *t*-value)

261 can be calculated. Commonly used photocell systems have been found to possess random

262 errors of ±0.14 m/s over a range of speeds from 5 to 9 m/s, with photocells positioned on

263 average 4.0 m apart [26]. However, it must be considered that photocell systems are limited

264 to providing average velocities over a set distance and the measurement error increases as

265 the distance between a pair of photocells decreases (e.g. to ±0.36 m/s at an average of

266 2.0 m apart [26]). Photocells are thus limited in their use for obtaining a velocity profile,

267 particularly during acceleration. A radar system, based on the Doppler effect but used

268 similarly to the LDM device to obtain a continuous velocity-time profile, has been found to be

269 associated with random errors of ±0.70 m/s at a range of distances from 10 to 45 m [12]

270 (criterion velocities from 7.23 to 10.09 m/s). More recently, a large-scale light-sensor network

271 system being developed for use in a sprint coaching context [9] was shown to currently

272 possess random measurement errors in velocity of ±0.56 m/s.

273

274 Although the LDM device clearly compares well with other non-video-based measures, when

275 put in the context of typical within-subject performance variation (Table 2), LDM device

276 measurement error in estimates of velocity is relatively high. Velocity data obtained using an

277 LDM device during the first 5 m of a sprint possess an unacceptable level of error due to both

278 the over-estimation of velocity and considerable random error as sprinters become

279 increasingly upright during this early acceleration phase. However, the levels of

280 measurement error during the mid-acceleration and maximum velocity phases of a sprint (i.e.

281 10, 30 and 50 m) suggest that the LDM device can be used to obtain estimates of velocity

282 from these phases, provided only differences in excess of 0.22 to 0.30 m/s (i.e. twice the

283 random errors presented in Table 1) are regarded as genuine. Combining this with the typical

284 performance variation data presented in Table 2, the LDM may therefore be useful for

285 comparing between sprinters or across sessions as training progresses during a season,

286 particularly at further distances in a sprint. However, it appears to be of limited use for

11

287   determining within-sprinter variation in maximal effort sprint performance during a single

288   session.

289

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374

375   Table 1. Bias and random error (quantified by 95% limits of agreement) in velocity values

376   between the criterion video data and the LDM device data at each of the distances.

Distance (m)	Number of trials (and athletes)	Average velocity* (m/s)	Bias** (m/s)	Random error (m/s)
1	22 (3)	4.00 ± 0.15	+ 0.41	± 0.18
5	14 (7)	6.01 ± 0.23	+ 0.13	± 0.21
10	30 (7)	7.30 ± 0.29	+ 0.16	± 0.11
30	10 (5)	8.52 ± 0.62	+ 0.06	± 0.13
50	13 (3)	10.38 ± 0.31	+ 0.08	± 0.15

377   *Velocities presented are the criterion values (mean ± standard deviation) from the high-

378   speed video data.

379   **Positive bias indicates that the LDM device data gave a higher estimate of velocity than the

380   high speed video data.

381

382 Table 2. Ranges in criterion velocity data to illustrate the expected within-session and

383 between-session genuine performance variation.

| Distance (m)	Athlete	Number of trials	Mean velocity (range) (m/s)	Average within-session range (m/s)	Maximum between-session range (m/s)
1	A1	4	4.16 (4.07 – 4.20)	0.09	0.47
	A2	4	3.94 (3.90 – 3.98)		
	A3	3	3.94 (3.91 – 3.95)		
	A4	4	3.77 (3.73 – 3.85)		
	B	4	4.16 (4.12 – 4.21)		n/a
	C	3	4.02 (3.95 – 4.05)		
10	D	4	7.47 (7.44 – 7.51)	0.14	n/a
	E	5	6.90 (6.80 – 7.06)		
	F	4	7.91 (6.97 – 7.05)		
	G	5	7.45 (7.38 – 7.52)		
	H	3	7.03 (6.99 – 7.10)		
	I	5	7.58 (7.45 – 7.63)		
	J	4	7.58 (7.51 – 7.64)		
50	A	3	10.49 (10.24 – 10.61)	0.75	n/a
	B	5	10.40 (9.76 – 10.91)		
	C	5	10.29 (9.80 – 10.49)		

384

385
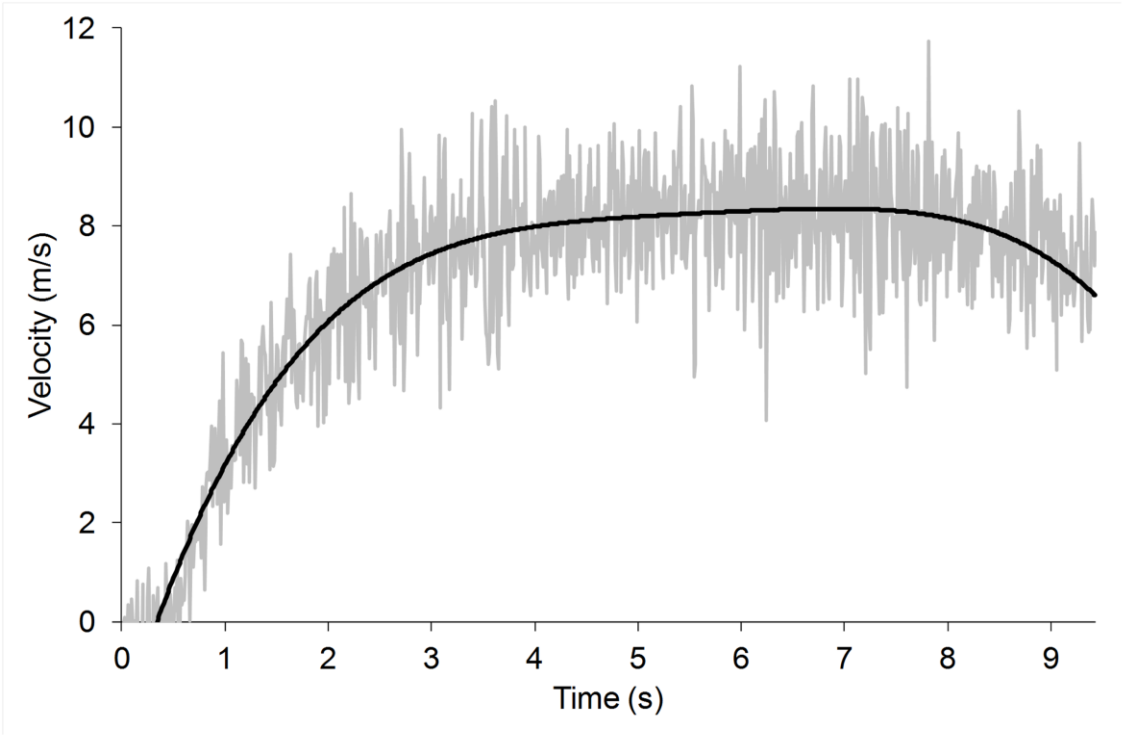
Figure 1. An example of the fourth-order velocity profile from one trial (obtained following a fifth-order polynomial fit to the raw displacement data), plotted above the velocity data obtained from differentiating the raw LDM displacement data. This trial was selected for illustrative purposes because the athlete clearly decelerated prior to 60 m, which confirmed that the chosen polynomial order was also able to appropriately reflect any deceleration.
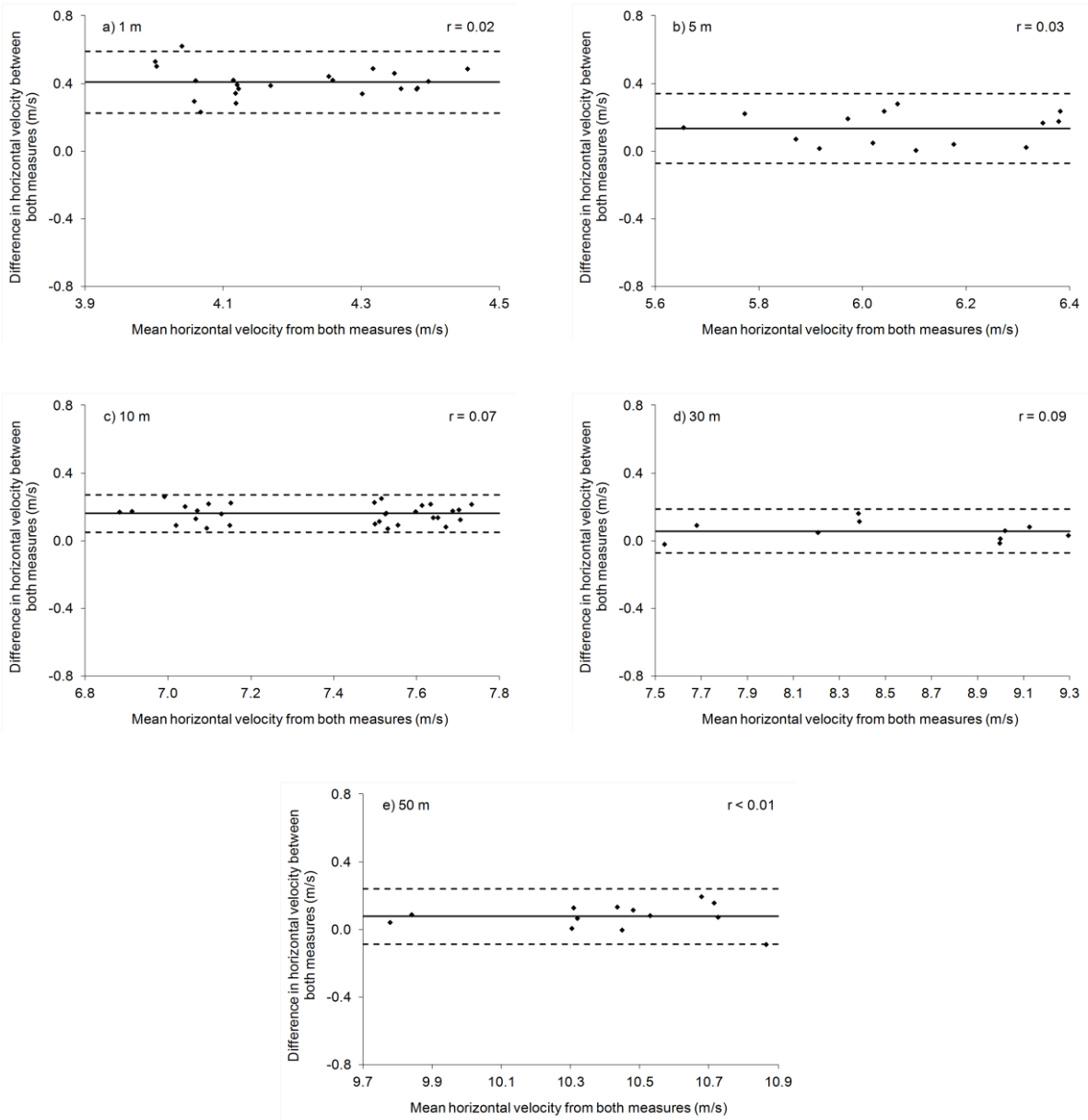
Figure 2 a-e. Bland-Altman plots to illustrate the bias and random error at each of the five distances.
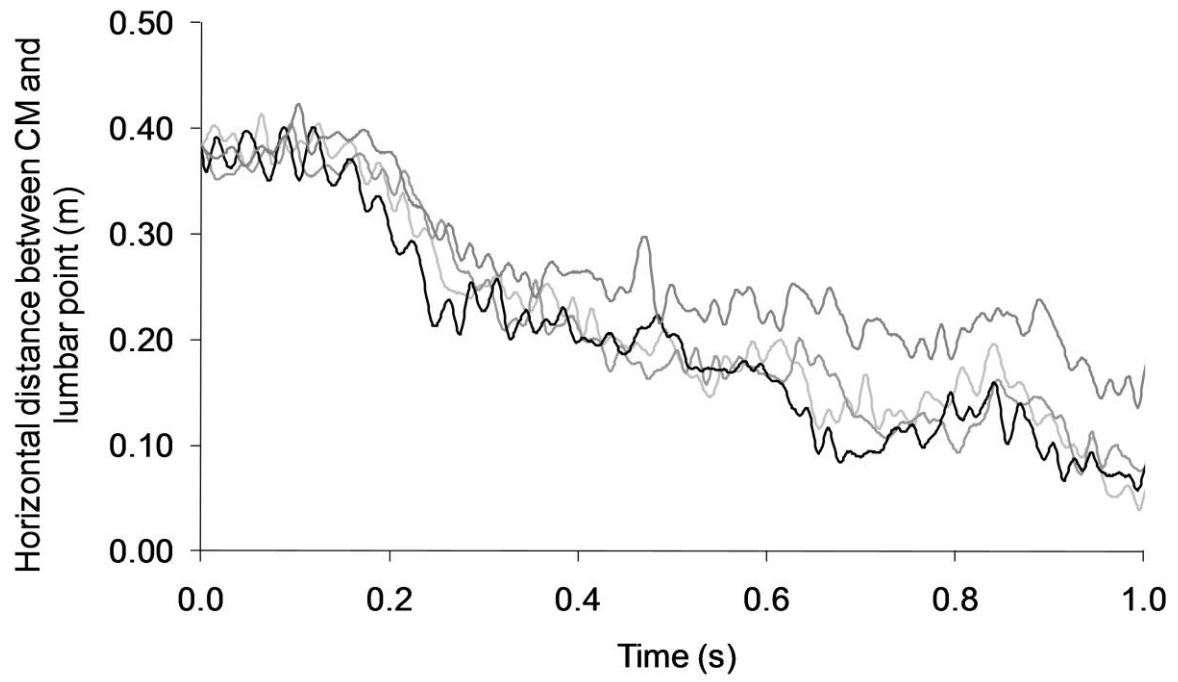
Figure 3. The horizontal distance between the lumbar point (at which the LDM was aimed) and the centre of mass during the first second of four trials from one sprinter.

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