Measurement Error in Estimates of Sprint Velocity from a Laser Displacement Measurement Device

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Key words
- athletics
- biomechanics
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Abstract

This study aimed to determine the measurement error associated with estimates of velocity from a laser-based device during different phases of a maximal athletic sprint. Laser-based displacement data were obtained from 10 sprinters completing a total of 89 sprints and were fitted with a fifth-order polynomial function which was differentiated to obtain instantaneous velocity data. These velocity estimates were compared against criterion high-speed video velocities at either 1, 5, 10, 30 or 50 m using a Bland-Altman analysis to assess bias and random error. Bias was highest at 1 m (+0.41 m/s) and tended to decrease as the measurement distance increased, with values less than +0.10 m/s at 30 and 50 m. Random error was more consistent between distances, and reached a minimum value (±0.11 m/s) at 10 m. Laser devices offer a potentially useful time-efficient tool for assessing between-subject or between-session performance from the mid-acceleration and maximum velocity phases (i.e., at 10 m and beyond), although only differences exceeding 0.22–0.30 m/s should be considered genuine. However, laser data should not be used during the first 5 m of a sprint, and are likely of limited use for assessing within-subject variation in performance during a single session.

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]. 1 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., **Fig. 1**), LDM device (and radar) data have previously been fitted with mathematical functions [2,8,21]. However, these velocity curves have only been assessed

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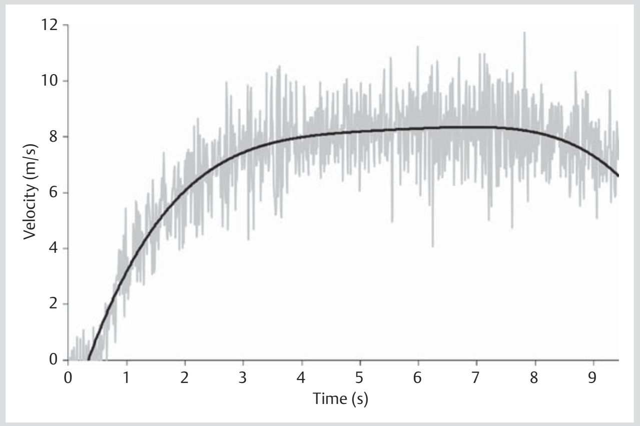

Fig. 1 An example of the fourth-order velocity profile from 1 trial (obtained following a fifth-order polynomial fit to the raw displacement data), plotted above the velocity data obtained from differentiating the raw LDM displacement data. This trial was selected for illustrative purposes because the athlete clearly decelerated prior to 60 m, which confirmed that the chosen polynomial order was also able to appropriately reflect any deceleration.

against split times over 3–10 m intervals from video or photocell data [2,8,21], and the measurement error in velocity estimates at discrete distances during different phases of a sprint remains unknown. The aim of this study was therefore to determine the measurement error in velocity data obtained with an LDM device during different phases of a maximal sprint, and consequently to evaluate the usability of LDM devices in order to analyse sprinters' velocity profiles.

Materials and Methods

7 male (mean ± SD: age = 23 ± 4 years, mass = 78 ± 5 kg, height = 1.78 ± 0.03 m, 100 m personal best (PB) = 10.76 ± 0.64 s) and 3 female (mean ± SD: age = 21 ± 1 years, mass = 64 ± 2 kg, height = 1.66 ± 0.02 m, 100 m PB = 12.48 ± 0.35 s) sprinters agreed to participate in this study and provided written informed consent following standard ethical procedures [14]. This cohort (incorporating both genders and a range of PBs) was selected so that the results would be applicable across all populations of sprinters. Whilst this would clearly affect the observed velocity magnitudes at different distances, the aim of this study was to assess the error associated with measurement equipment, and thus the nature of the cohort would not negatively influence the results [1,3,7].

Data were collected at outdoor track-based training sessions. The LDM device (LDM-300C, Jenoptik, Germany; 100 Hz) was positioned on a tripod at a height of approximately 1 m, 20 m behind the start line. This exact distance was determined using a static object prior to each session and was used to provide the reference distance of 0 m (start line). A high-speed video camera (MotionPro HS-1, Redlake, USA; 200 Hz) was located perpendicular to the running lane, 35 m from the lane centre. At each session, the camera was perpendicular to a different distance from the start line so that video data were collected at 1, 5, 10, 30 and 50 m. The camera field of view was approximately 5.0 m wide, and an area of 4.50 × 1.60 m (2.25 m either side of the distance of interest) was calibrated with 4 corner points in order to obtain displacement data using projective scaling. A shutter speed of 1/1 000 s was used and images were captured at a resolution of 1280 × 1024 pixels. Each sprint commenced from starting blocks following standard 'on your marks' and 'set' commands before a sounder was activated to provide the starting signal. Video data collection was initiated manually just prior to the sprinter entering the field of view. LDM device data collection was initiated manually at the 'set' command, and the device was aimed at the lower part of the runner's back (hereafter termed 'lumbar point'). All laser data processing took place in Matlab™ (v. 7.4.0, The MathWorks™, USA).

The raw displacement data obtained with the LDM device were fitted with a fifth-order polynomial function. The polynomial order was selected to provide a close match to the known underlying trends of the displacement and velocity profiles whilst eliminating any within-step velocity fluctuations. The polynomial start point was identified from where the raw displacement values increased and remained greater than 2 SD above the mean noisy pre-start signal level, and the polynomial end point was 50 data points after displacement exceeded 60 m. This displacement polynomial was analytically differentiated with respect to time in order to yield a fourth-order representation of the velocity profile. ▶ **Fig. 1** shows an example of the noisy velocity data obtained from numerically differentiating the raw LDM device displacement data and the smooth fourth-order polynomial representation of the velocity profile from 1 trial. For each trial, the time at which displacement equalled or first exceeded the target distance was identified, and the corresponding velocity value was recorded.

The raw video files were digitised in Peak Motus® (v. 8.5, Vicon, United Kingdom), exactly replicating previously reported procedures [6], before all subsequent video data processing took place in Matlab™ (v. 7.4.0, The MathWorks™, USA). Whole-body CM displacements were calculated using segmental inertia data [10] and a summation of segmental moments approach [25]. Inertia data for the feet were taken from Winter [25] as they allowed the creation of a linked-segment model, and 0.2 kg was added to each foot to account for the mass of each spiked shoe [5,15]. Raw high-speed video CM velocities were calculated using second central difference equations [20].

To determine the criterion high-speed video velocities at each of the target distances (i.e., 1, 5, 10, 30 or 50 m) without any influence of the phase of the step cycle, the following procedure was undertaken. The first frame in which the raw CM displacement equalled or exceeded the target distance was identified. The phase of the step cycle (i.e., stance or flight) that the sprinter was in during this frame was identified, as was the closest adjacent contrasting phase (i.e., flight or stance). The combined duration of these stance and flight phases yielded the duration of the step cycle occurring at the target distance (at the 1 m mark, the sprinters were typically in mid-stance, and as the 2 adjacent flight times were often considerably different in length, the mean duration of the 2 flight phases was used in obtaining total step duration). The determined step duration was then applied so that it was evenly spaced either side of the frame in which the target distance was reached (e.g., if the determined step duration was 41 frames and the target distance was reached in frame number 67, the step cycle at the target distance was deemed to commence at frame 47 and terminate at frame 87). This yielded a complete step cycle starting from an arbitrary point, but in which the sprinter passed the specific target distance exactly halfway through the cycle. The mean value of all raw CM velocities during this step cycle thus provided a value representing the velocity of the sprinter at the target distance which was inde-

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

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

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

pendent from the phase of the step cycle the sprinter was in. Although the raw digitised video data contained noise, this would likely have had minimal effect on these velocities over a complete step cycle due to its presumed random nature. To confirm this, one trial (from 10 m) was redigitised on 10 separate occasions to quantify any effects of noise in the video data on the determined velocity value. Following a check for normality of these data, the reliability of the high-speed video velocity data was determined by calculating a co-efficient of variation (CV; standard deviation/mean [22]).

A Bland-Altman 95 % limits of agreement approach [1, 7] was selected to assess the measurement error (separated into bias and random error) of the LDM device estimates relative to the criterion video data, as this approach would not be affected by the deliberately broad cohort [1, 3, 7]. These limits were calculated as the standard deviation of the difference scores between the video and LDM-based velocity data multiplied by the critical *t*-value for the sample size at each distance. Normality of the difference scores was checked, and a heteroscedasticity correlation coefficient was calculated between the difference scores and the mean score from both devices to assess for any proportional bias [3, 7].

In order to allow the determined measurement error to be considered in a practical context, the range in criterion velocity data was calculated at 1, 10 and 50 m (the distances when all athletes completed more than 2 trials at a single distance). A single mean within-session range was then calculated from all athletes at each of these 3 distances. This provided an example of the typical levels of within-session performance variation that could be expected and thus allowed an acceptable level of measurement error to be determined for application in similar coach-led training settings [3, 7]. As the data from 1 m were collected at 4 different sessions for 1 subject, these data were also used to provide an example of the expected variation between sessions across 6 months of the season as training progressed through different phases.

Results

A total of 89 trials were recorded and analysed, with at least 10 trials obtained from each of the individual distances. The amount of trials at each distance was not even due to the number of athletes present and number of trials completed at each of the training sessions. The bias and random errors associated with the calculation of instantaneous velocities at 1, 5, 10, 30 and 50 m from the LDM device are presented in ▸ **Table 1** and ▸ **Fig. 2**. Bias was highest at 1 m (+ 0.41 m/s) and lowest at 30 m (+ 0.06 m/s) and the magnitude of random error at the 5 distances ranged from ± 0.11 m/s to ± 0.21 m/s. All data were normally distributed and free from heteroscedasticity (all r < 0.10; ▸ **Fig. 2**). The 10 redigitisations of 1 trial revealed the criterion velocity data to be highly reliable (velocity = 7.66 ± 0.01 m/s; CV = 0.15 %). This confirmed that the noise due to operator error in the digitising process was random, and that averaging the values from the duration of an entire step cycle provided a highly repeatable measure of average step velocity at a specific distance. This therefore also allowed the expected performance variation data (▸ **Table 2**) to be considered with confidence. The within-session individual variation in criterion data was low at 1 and 10 m (average range in velocities = 0.09 and 0.14 m/s, respectively) but considerably higher (0.75 m/s) at 50 m. The between-session variation in performance was higher (range = 0.47 m/s at 1 m) than the within-session variation.

Discussion

This study determined the measurement error associated with LDM estimates of velocity during different phases of a maximal effort sprint to evaluate how useful LDM devices are for analysing sprint velocity profiles. It was found that the measurement error varied between different phases of a sprint, with a general trend for the magnitude of the bias to decrease as the measurement distance increased (▸ **Table 1**). The random error exhibited a slightly unexpected trend, with the 95 % limits of agreement being highest during the first 5 m before decreasing considerably at 10 m and then gradually increasing thereafter (▸ **Table 1**). Finally, the lack of heteroscedastic data at any of the 5 distances (▸ **Fig. 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 4 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 (▸ **Fig. 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. 1s 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 4 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.

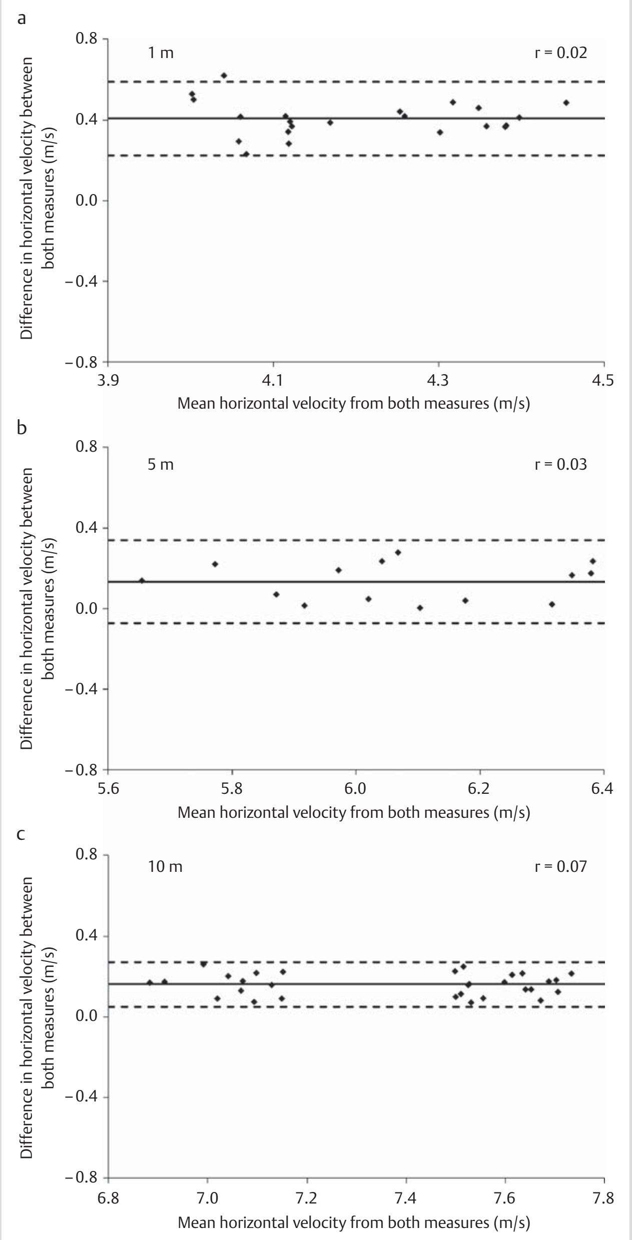

Fig. 2 a–c Bland-Altman plots to illustrate the bias and random error at each of the 5 distances.

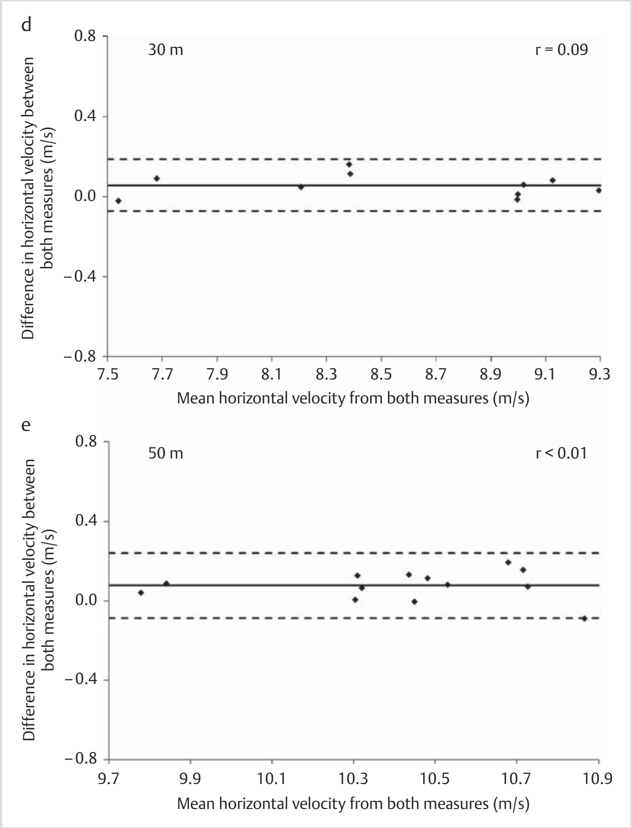

Fig. 2 d, e Bland-Altman plots to illustrate the bias and random error at each of the 5 distances.

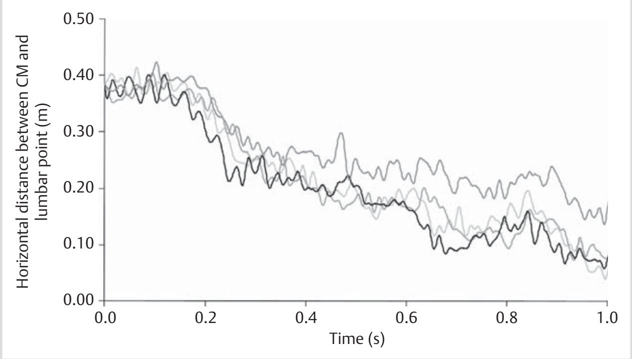

Fig. 3 The horizontal distance between the lumbar point (at which the LDM was aimed) and the centre of mass during the first second of 4 trials from 1 sprinter.

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 the considerably lower biases observed at distances beyond 1 m, particularly at 30 and 50 m (◉ **Table 1**). This also concurred with previous video-based data [24], whereby it was found that although there is a temporal shift in the individual within-step fluctuations in horizontal velocity between the CM and the lumbar point during constant velocity running, overall changes in displacement and velocity across 1 step were similar. Therefore, by smoothing out the within-step fluctuations in the raw LDM device data, a non-biased representation of the motion of a sprinter can be obtained once they have adopted a more upright stance beyond the early parts of a sprint.

The higher random error at 1 and 5 m (±0.18 and ±0.21 m/s, respectively) may be related to the aforementioned inconsistency in tracking the lumbar point as the sprinter rises out of the blocks. When these random errors are combined with the high bias during the early part of a sprint, LDM device estimates of velocity prior to 10 m (i.e., the initial acceleration phase [11]) appear to contain unacceptably high levels of error relative to the expected levels of variation in performance (◉ **Table 2**). By the 10 m mark, random error had decreased (±0.11 m/s), before increasing slightly at the 30 and 50 m marks (±0.13 and ±0.15 m/s, respec-

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)		

Table 2 Ranges in criterion velocity data to illustrate the expected within-session and between-session genuine performance variation.

tively). This gradual increase in random error from 10 to 50 m is likely due to the divergence of the laser beam as the sprinter moved further from the start line because a greater area of the sprinter was measured by the wider laser beam at these distances (beam diameter = 0.06 m at the start line, 0.21 m at the 50 m mark). Movement of any segments near to the lumbar point, any clothing movement, or even a large leg retraction and thus high foot displacement behind the sprinter could therefore all have affected these velocity estimates. Also, any movements of the LDM device itself by the operator have a larger pointing effect (deviation) the further from the device the athlete travels.

The measurement error associated with the LDM device generally compares well against other time-efficient devices used to obtain velocity estimates during sprinting. Based on published differences in velocity estimates between tested devices and a criterion, measurement errors comparable to those presented in the current study (i. e., 95 % limits of agreement using the standard deviation of the differences and the appropriate critical *t*-value) can be calculated. Commonly used photocell systems have been found to possess random errors of ±0.14 m/s over a range of speeds from 5 to 9 m/s, with photocells positioned on average 4.0 m apart [26]. However, it must be considered that photocell systems are limited to providing average velocities over a set distance and the measurement error increases as the distance between a pair of photocells decreases (e. g., to ±0.36 m/s at an average of 2.0 m apart [26]). Photocells are thus limited in their use for obtaining a velocity profile, particularly during acceleration. A radar system, based on the Doppler effect but used similarly to the LDM device to obtain a continuous velocity-time profile, has been found to be associated with random errors of ±0.70 m/s at a range of distances from 10 to 45 m [12] (criterion velocities from 7.23 to 10.09 m/s). More recently, a large-scale light-sensor network system being developed for use in a sprint coaching context [9] was shown to currently possess random measurement errors in velocity of ±0.56 m/s.

Although the LDM device clearly compares well with other non-video-based measures, when put in the context of typical within-subject performance variation (▶ **Table 2**), LDM device measurement error in estimates of velocity is relatively high. Velocity data obtained using an LDM device during the first 5 m of a sprint possess an unacceptable level of error due to both the over-estimation of velocity and considerable random error as sprinters become increasingly upright during this early acceleration phase. However, the levels of measurement error during the mid-acceleration and maximum velocity phases of a sprint (i. e., 10, 30 and 50 m) suggest that the LDM device can be used to obtain estimates of velocity from these phases, provided only differences in excess of 0.22–0.30 m/s (i. e., twice the random errors presented in ▶ **Table 1**) are regarded as genuine. Combining this with the typical performance variation data presented in ▶ **Table 2**, the LDM may therefore be useful for comparing between sprinters or across sessions as training progresses during a season, particularly at further distances in a sprint. However, it appears to be of limited use for determining within-sprinter variation in maximal effort sprint performance during a single session.

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