



## Original research

# Validity of a low-cost laser with freely available software for improving measurement of walking and running speed<sup>☆</sup>



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## ABSTRACT

**Objectives:** Accurately measuring speed and acceleration during walking, running and sprinting has important implications for rehabilitation, planning training and talent identification in sporting and clinical populations. Light detection and ranging laser technology provides a continuous stream of distance data. It has the potential to allow rapid and precise measurement and may be advantageous compared with discrete methods of assessment, such as stopwatches and timing gates, which may be inaccurate over short distances. Therefore, the aim of this study was to assess the validity of a novel, low-cost and easy to implement laser-based system during walking and running trials.

**Design:** Cross-sectional study.

**Methods:** Thirty-two healthy adults performed walking and running trials from flying and static starts while monitored concurrently with reference standard three-dimensional motion analysis and laser systems. Velocity was calculated over short (0.5 m) and longer (3 m) intervals using both systems. Validity was assessed using absolute agreement intraclass correlation coefficients (ICC<sub>2,1</sub>), mean absolute errors, Pearson's correlations and regressions and Bland–Altman plots.

**Results:** All intraclass correlation coefficients and correlations were excellent (ICC > 0.88, R > 0.89). For the longer interval, all mean absolute errors were < 0.03 m/s (0.24–1.31%). Slightly higher mean absolute error values were reported for the shorter interval (3.16–5.10%), with the highest error of 0.184 m/s evident for the flying start running trial.

**Conclusions:** These results indicate that a low-cost and accessible laser system can be used to accurately assess walking and running speed. To aid implementation and further research, freely available hardware design descriptions and downloadable software can be accessed at [www.rehabtools.org/LIDAR](http://www.rehabtools.org/LIDAR).

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## 1. Introduction

The ability to accurately quantify walking and running speed and acceleration may be important in both sporting and clinical populations. For example, acceleration and maximal speed may be key indicators for talent identification in sports with a large running component including soccer,<sup>1</sup> and have also been associated with career success in Australian Football.<sup>2,3</sup> The assessment of gait speed is ubiquitous in clinical settings. It is cited as an important outcome measure following joint surgery,<sup>4,5</sup> cancer diagnosis<sup>6</sup> and

in people with neurological impairments.<sup>7</sup> It has well documented predictive value for long-term health outcomes, including mortality in older adults<sup>8</sup> and people living with cancer,<sup>6</sup> reduced physical activity levels in people living with stroke,<sup>9</sup> and the development of cognitive impairment in elderly populations.<sup>10</sup>

The simplest method for assessing gait speed is the use of a manual stopwatch or timer to calculate the time taken to cross a start and end distance threshold. While this method is commonly used, it is prone to significant user error when short distance trials are performed.<sup>11</sup> For this reason a number of other instrumented methods exist, ranging from photoelectric based timing gates, calibrated video, and global positioning systems<sup>11</sup> through to customised repurposing of video game controllers.<sup>12,13</sup> The two methods with the greatest potential for obtaining accurate information over small distances are high speed video and laser/radar

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guns, particularly if there are numerous phases of interest such as acceleration, attainment of maximal velocity and deceleration. The advantage of high speed video is its accessibility, as most smartphones and web cameras have the capacity to record high speed, high definition video. However, to obtain a velocity trace using a video system is difficult. Footage must be taken in the sagittal plane with a field of view that encompasses the entire testing range. This limits the applicability to situations where space is constrained, such as hospital corridors. Video also typically requires substantial calibration to reduce parallax error, in addition to post-processing if tracking markers are not used.

Radar or laser tracking, typically performed from behind with the focal point being the lower back, may therefore be more optimal methods. These devices have the advantages of continuous motion tracking at relatively high speeds (often >200 Hz), no requirement to wear devices or markers, and can be used in settings such as narrow walkways. Recent advances in low-cost light detection and ranging (LIDAR) have made these systems more accessible. With simple programming and hardware design, a wireless LIDAR system can now be created for under \$USD250 that can provide real time gait speed information to the assessor via a computer, tablet or Smartphone. However, it is currently unknown whether these low-cost systems can provide accurate gait speed information. The primary aim of this study was therefore to assess the concurrent validity of a low-cost LIDAR system for assessing walking and running speed against a criterion reference marker-based three-dimensional motion analysis (3DMA) system.

## 2. Methods

A convenience sample of 32 healthy adults (age:  $31 \pm 10$  yrs, height:  $170.6 \pm 10.1$  cm, mass:  $70.5 \pm 13.3$  kg, female: 18) participated in this study. Institutional ethics approval was obtained before study commencement (University of the Sunshine Coast HREC no. A/17/965) and all participants provided written informed consent prior to data collection.

The participants performed a series of walking and running trials in a university gait laboratory. During these trials, both a LIDAR-based and marker-based 3DMA system were used to concurrently track displacement of the lower back. The LIDAR system consisted of a LIDAR (Garmin, USA) with an eight milliradian beam spread and a 40 m range sending position data via the serial port in millimetres at approximately 270 Hz to an Arduino Uno (Arduino, Italy) microprocessor, which relayed these data to a personal computer with custom software to record displacement and time information throughout the trial. These data were resampled to a constant interval 1000 Hz using spline interpolation, which is a common method utilised for unevenly sampled physiological data.<sup>14</sup>

A detailed description of the creation of this system, including circuit diagrams, 3D print models and freely available software, is available at [www.rehabtools.org/LIDAR](http://www.rehabtools.org/LIDAR). The 3DMA system consisted of a calibrated Qualisys 9-camera motion analysis system sampling at 200 Hz. These cameras were used to track the movement of a single reflective marker placed on the sacrum, with only data from the anterior–posterior plane used for analysis. No software-based signal filtering was performed for either device, as the interval approach used for data analysis itself is a form of averaging filter and our pilot work did not indicate that additional filtering provided significant advantages.

The trials consisted of a total of three trials per participant – one trial each of a static start walk, static start run and flying start run. The walking trials commenced with the feet together, shoulder width apart. The running trials commenced with the preferred, upright stance. For the walking trials, participants were instructed to walk at a comfortable pace to the end of the laboratory (approx-

imately 15 m). For the running trials, participants were asked to run at a fast but comfortable pace to 5 m before the end of the laboratory, which was opened onto a short track. The participants were not asked to perform a maximal sprint, as the confines of the laboratory environment requiring rapid deceleration would have increased the risk of injury. As the distance from the end of the capture volume to the end of the laboratory was 7.5 m, this was sufficient to remove any deceleration from being observed. One trial for each of the conditions was performed, as this is often how walking and running velocity may be measured in real-world public screening and athletic situations.

The capture volume used in this study corresponded to a distance from 4.0 m to 7.5 m from the LIDAR camera. This was set as it allowed the LIDAR to be placed on a tripod against a wall, focused along the anterior–posterior axis of the laboratory and adjusted to the height of the lower back. This target position was chosen as it would be least susceptible to changes in trunk posture. The 3.5 m distance limit was set as this was within the accurate field of view of the 3DMA system, with the starting position for the static start trials at the edge of the capture volume (i.e. 4 m from the LIDAR) and for the flying start trials 3 m back from the capture volume edge (i.e. 1 m from the LIDAR). Data from each system were analysed across two different distances for each trial. The first was a 3 m interval from 0.5 m to 3.5 m after the static starting line (i.e. 3.5 m–6.5 m after the flying start line), the second a 0.5 m interval from 0.5 m to 1 m after the static starting line (i.e. 3.5 m–4 m after the flying start line). This represented a relatively long and short timing split respectively, with the 0.5 m distance from the start position to the initial timing trigger chosen because it allowed us to quantify an acceleration period whilst ensuring that we did not record any false starts from normal postural sway.

Statistical analysis consisted of the data from the two systems for each of the conditions being assessed for absolute reliability using the absolute agreement method of intraclass correlation coefficients (model 2,1). Mean absolute error (MAE) was determined by calculating the mean absolute difference between the two devices. Relative agreement was assessed using Pearson's (relative score) correlations. Visualisation of agreement was performed using Bland–Altman plots and a linear regression with 95% confidence interval between the two systems. All analyses and statistical figures were generated using the online statistical calculator available at [www.rehabtools.org/stats.html](http://www.rehabtools.org/stats.html), which incorporates analysis methods using the Matlab Statistical Toolbox (Mathworks, USA). Estimates of correlation and ICC values were interpreted as excellent (0.75–1), modest (0.4–0.74), or poor (0–0.39).<sup>15</sup> For the Bland–Altman plots and regression lines the raw score were used, for the other statistical analysis and reporting data were converted to velocity (m/s) to aid interpretation.

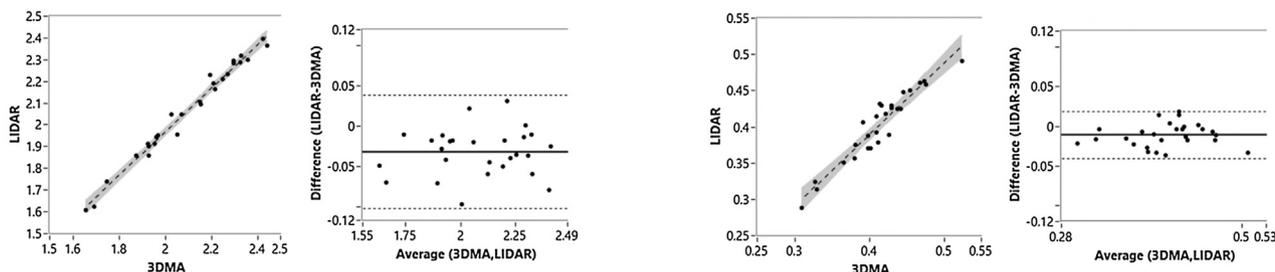
## 3. Results

The results for the two intervals (0.5 and 3 m) for each of the three conditions are provided in Table 1. Linear regression and Bland–Altman plots are provided in Fig. 1. An example of the data collected during a running trial with the LIDAR and 3DMA data overlaid is provided in Fig. 2. All correlation and ICC analyses exceeded the threshold for excellent agreement. Results for the longer 3 m interval were superior to the shorter 0.5 m interval. For the longer interval, all ICC and correlation values were >0.96 and the MAE was <0.027 m/s ( $\leq 1.31\%$ ). The ICC and correlation values for the shorter 0.5 m interval ranged from 0.88 to 0.96. The flying running trial had a slightly larger MAE of 0.184 m/s (5.10%), in contrast with the static walking and running trial MAE of 0.039 m/s (3.16%) and 0.082 m/s (3.84%) respectively. Assessment

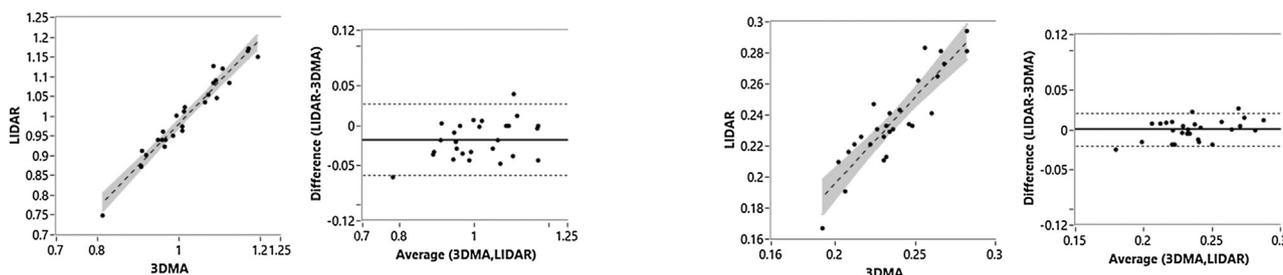
**Table 1**  
A comparison of timing results from the LIDAR system and the criterion reference marker-based motion capture system (3DMA). Trials consisted of recording either a 3 m or 0.5 m interval of walking and running from a static start and running from a flying start, with the timing result converted to velocity (m/s). Data reported includes median and interquartile range, intraclass correlation coefficient (ICC model 2,1), mean absolute error (MAE), %MAE, and Pearson's correlation coefficient. 3DMA and LIDAR data are reported as median (interquartile range), ICC as value (95% confidence interval).

	3DMA (m/s)	LIDAR (m/s)	ICC (2,1)	MAE (m/s)	%MAE	Pearson's
<b>3 m interval</b>						
Static walk	2.061 (1.927–2.254)	2.050 (1.890–2.230)	0.98 (0.81–0.99)	0.027 (0.017–0.048)	1.31	0.99
Static run	2.956 (3.115–2.751)	2.956 (2.765–3.193)	0.96 (0.82–0.98)	0.020 (0.005–0.037)	0.68	0.98
Flying run	3.788 (3.476–4.172)	3.856 (3.499–4.264)	0.97 (0.94–0.99)	0.009 (0.005–0.019)	0.24	0.98
<b>0.5 m interval</b>						
Static walk	1.217 (1.142–1.319)	1.252 (1.163–1.364)	0.93 (0.73–0.98)	0.039 (0.015–0.066)	3.16	0.96
Static run	2.127 (1.969–2.227)	2.141 (1.960–2.250)	0.88 (0.76–0.95)	0.082 (0.035–0.146)	3.84	0.89
Flying run	3.676 (3.334–3.937)	3.546 (3.165–4.135)	0.91 (0.82–0.96)	0.184 (0.114–0.311)	5.10	0.93

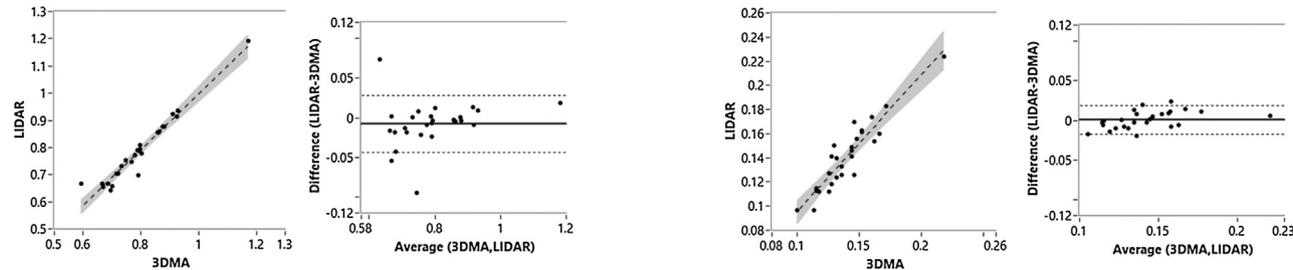
### Static Start Walking



### Static Start Running



### Flying Start Running



### 3m interval

### 0.5m interval

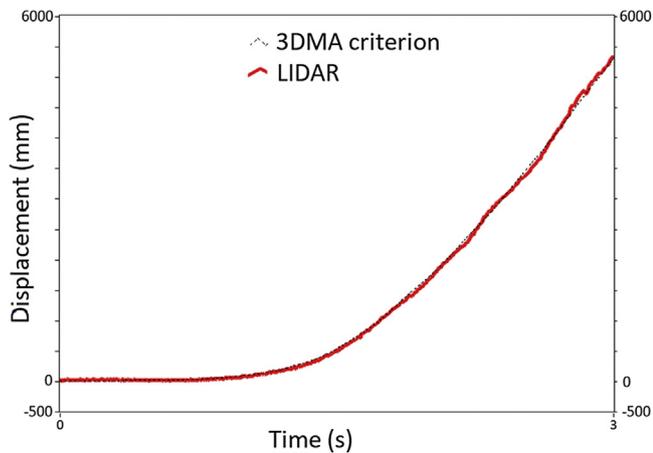
**Fig. 1.** Linear regression with 95% confidence intervals and Bland–Altman plots comparing the LIDAR system with the criterion reference marker-based motion capture system (3DMA). Analysis consisted of extracting a 3 m (left) and 0.5 m (right) interval of displacement/time data from (1) static start walking and running trials, and (2) running from a flying start. All data are reported in seconds.

of the Bland–Altman plots showed no obvious fixed or proportional biases.

#### 4. Discussion

The results of this study show that low cost LIDAR technology can be used to accurately measure walking and running speed

at interval distances as short as 0.5m, with excellent agreement observed for both intervals measured for all conditions. For intervals of 3m, which are difficult to obtain accurately using traditional methods of timing such as single beam optoelectronic systems, stopwatches or radar guns,<sup>11</sup> the LIDAR was particularly accurate with very low error rates. We observed reduced measurement error and greater agreement for the 3 m interval compared to the 0.5 m



**Fig. 2.** An example of overlaid traces from the LIDAR and 3DMA system during a running trial.

interval, which is logical given the increased distance would attenuate some of the sources of hardware error such as timing jitter and distance measurement inaccuracy. For example, a 1 ms jitter could result in the start and end interval time being recorded 0.1 ms late and early respectively, which over a 0.1 or 1 s trial could create a timing error of 2% and 0.2% respectively.

Our finding for typically excellent agreement over short distances is different to that reported by Bezodis et al.,<sup>16</sup> who reported that a laser should not be used over the first 5 m of a sprint because of high inaccuracy. While we did use a different laser to that study, we believe that the method of data analysis was the key difference. In the present study we simply measured the time it took to travel a set distance, which is akin to a timing gate approach. In that study a fifth order polynomial was used to filter the data, which was then differentiated to calculate instantaneous velocity. We chose our method as calculating instantaneous velocity amplifies any data collection timing jitter and distance measurement error. This can result in very noisy data, as can be seen in Fig. 1 of the Bezodis et al.<sup>16</sup> study, and requires stringent filtering schemes. The authors of that study achieved this by using a fifth order polynomial, however given the relatively low order and visual inspection of the data reported in Fig. 1 of their study, this may have overly smoothed the initial acceleration stage of the trial hence contributing to measurement inaccuracy.

A low-cost LIDAR such as the one in this study has numerous advantages over other gait timing systems such as optoelectronic single or dual beam devices. The primary advantage is that it provides a continuous measure of distance from the LIDAR, and this does not require calibration other than aligning the focal point with the lower back. This overcomes a major issue with standard measurement devices in that they must be placed at known distances from each other to form timing gates, which requires either a permanent testing position with affixed markers or measuring a known distance.<sup>17</sup> The ability to obtain a continuous position stream is advantageous in that it allows for intervals of varying distances and number to be obtained without requiring additional equipment. Radar guns also provide these advantages and are the most similar to LIDAR devices in terms of operation. However, based on a systematic review<sup>18</sup> the most commonly used radar gun in prior studies, the Stalker ATS, has a stated error in the user manual of approximately 0.44 m/s. This makes it unusable for assessment of walking speed over short distances, but feasible for use during running trials over longer distances where some of the measurement error may be filtered out. The LIDAR used in this study provides distance measurements with accuracy within centimetres and can be sampled at 200+ times per second. Combin-

ing the high distance accuracy with the relatively high acquisition frequency allows velocity over short distances to be accurately measured.

A second advantage, particularly important for clinical assessment, is that the use of LIDAR does not require any attention by the assessor during the trial or markings to be placed on the floor. The continuous data stream allows for a timing interval to be assigned for assessment, which can be automatically identified and the gait speed generated without user input. Consequently, a clinician can ignore the device and focus solely on their patient during trials. This contrasts with the standard stopwatch based measurements performed in hospital settings, which requires the assessor to visually track the patient's feet as they cross assigned positions on the floor whilst at the same time manipulate a stopwatch or timer. Being able to focus attention on patient observation becomes particularly important in high falls risk patients. Additionally, the application of floor markers may be not feasible in some clinical or home-based settings due to factors such as infection control or aesthetics.

The novelty of this specific system is that the LIDAR is low cost and mass produced. It can be easily built into a fully functioning system using a low-cost microcontroller such as the Arduino and beginner level circuitry. As the example on the webpage demonstrates, a simple system can be powered from a USB cable and built in under 1 h, with a 3D printed shell created to enclose the circuitry. It can also easily be constructed wireless, battery powered, connected to a visible laser for alignment or wall mounted to allow the flexibility to be used quickly and easily in field or clinical settings. A LIDAR may also be used to assess spatiotemporal aspects of gait, which have been reported in previous research,<sup>19</sup> however the magnitude of error relative to the true signal may deem this infeasible and would require further research.

This study had several limitations. Assessment was restricted to a maximum of a 3 m increment due to the limited capture volume of the 3DMA system, however our visual observation of the LIDAR data indicates that it was capable of detecting at least 10 m of running with minimal or no missing data points. Additionally, the specifications indicate that its maximum range is 40 m and beam diameter is only 20 cm at a distance of 20 m, and therefore it should be able to measure sprinting speed until at least this distance. However, this is still an issue if longer distance sprint (e.g. 100 m) timing is necessary and may also be problematic at shorter distances given the potential for the texture of the clothing worn to impact results (described in detail in the devices user manual) which we did not control for. It is recommended that future research examines the accuracy of LIDAR technology over longer distances, and the optimal choice of clothing to provide the most accurate results. Limitations in measurement over longer distance may also be overcome by including multiple LIDAR systems, which would effectively create a start and end timing gate. Conversely, combining the LIDAR with methods such as a stopwatch or secondary timing gate to obtain precise acceleration and gait initiation velocity with a subsequent total sprint time over a longer distance could be performed.

Participants in this study were not athletes, and the running was performed in an enclosed laboratory environment, and as such the speeds obtained do not reflect what a high-level athlete would achieve when sprinting in a field setting. This should be evaluated in future research. We also did not include assessment of peak instantaneous velocity or acceleration as has been reported previously, as this technique is heavily reliant on the application of the correct filtering technique. This makes incorporating this method onto a small microprocessor difficult due to their typically low memory capacity. In essence, the computationally simple interval method implemented in this study equates to a mean filter and could be easily converted into a sliding window method to obtain instantaneous values without the need for finite impulse response filters such as the Butterworth. Finally, the LIDAR and 3DMA systems did

not directly compare the exact same segment of the body, and this may have resulted in error. The LIDAR system tracks a circular position on the lower back that increases in size the further from the device, whereas the 3DMA system tracked a marker placed on the sacrum.

## 5. Conclusion

The results of this study have demonstrated that a low cost, easy to build and implement LIDAR system can be used to accurately measure aspects of gait speed over short and longer intervals up to 3 m. This has numerous potential benefits, including feasible yet far more precise assessment of distinct regions of gait in the clinical and sporting setting. Future research should examine whether the additional data derived from LIDAR based systems in comparison with stopwatch or timing gate methods is useful as part of large scale testing in clinical and sporting settings.

## Practical implications

- Walking and running speed can be measured with high precision using a low-cost light detection and ranging technology (LIDAR) system.
- The LIDAR system may be a feasible option for accurately measuring speed in sports and clinical settings.
- Freely available software and hardware guides are provided online.

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