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Abstract: Gait assessment is frequently used as an outcome measure to determine changes in an individual's mobility and disease processes. Inertial measurement units (IMUs) are quickly becoming commonplace in gait analysis. The purpose of this study was to determine and compare the validity of shank and lumbar IMU mounting locations in the estimation of temporal gait features. Thirty-seven adults performed 20 walking trials each over a gold standard force platform while wearing shank and lumbar-mounted IMUs. Data from the IMUs were used to estimate step times using previously published algorithms and were compared with those derived from the force platform. There was an excellent level of correlation between the force platform and shank ($r = 0.95$) and lumbar-mounted ($r = 0.99$) IMUs. Bland-Altman analysis demonstrated high levels of agreement between the IMU and the force platform step times. Confidence interval widths were 0.0782 s for the shank and 0.0367 s for the lumbar. Both IMU mounting locations provided accurate step time estimations, with the lumbar demonstrating a marginally superior level of agreement with the force platform. This validation indicates that the IMU system is capable of providing step time estimates within 2% of the gold standard force platform measurement.

Q1:
As per the journal style all references were renumbered by alphabetical order in text and reference list. Please check and confirm

Keywords: gait; IMU; lumbar; shank; step time.

Introduction

In recent times, there has been a shift away from traditional gait analysis tools towards unobtrusive ambulatory monitoring systems [7, 30]. Researchers have focused on the development of mobile health tools allowing clinicians to accurately monitor the type, quantity and quality of a patient's walking during daily activities [5]. Such systems incorporate inertial measurement units (IMUs) and gait event detection algorithms to provide spatiotemporal parameters [17, 19, 32]. These IMU systems have become the mainstay of ambulatory monitoring and are capable of capturing objective information surrounding the quality and quantity of an individual's mobility, which can be related to falls risk or disease progression [4, 31].

An important aspect to be considered in the use of IMUs is the development of algorithms capable of accurately identifying spatiotemporal variables during activities of daily living, and in different populations [6, 8, 34]. Such algorithms could be incorporated into remote monitoring systems in order to accurately detect gait periods and gait events while an individual goes about their daily life in the home and community. One such variable of interest is step time, defined as the amount of time from initial contact (IC) on one foot to IC on the contralateral foot [21]. With the development of these automated systems which may be utilised by clinicians, there comes a clear need to validate automatically calculated measurements against current gold standards. When validating a system, ecological validity needs to be considered. Riley et al. reported that treadmill and over-ground walking are quantitatively similar, although subtle differences in kinematic and kinetic variables exist between the two testing conditions [22]. Therefore, it is imperative to test feature detection algorithms under the conditions in which the algorithm is intended to be used.

When considering the use of IMUs in gait monitoring, the most suitable mounting location needs to be considered. Despite the increasing use of IMU technology, there is a lack of consensus surrounding which mounting location provides the most useful and valid gait metrics. Previous research has focused on utilising acceleration signals obtained from accelerometers mounted on the distal shank [11, 13, 14], while others have demonstrated the utility of angular velocity derived from shank-mounted gyroscopes [9, 28, 34]. Alternatively, lumbar-mounted accelerometers have been used to capture lower trunk acceleration to determine temporal gait characteristics [8, 27]. Recently, there has been a drive to determine which mounting location provides the most accurate estimation

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of temporal gait events. A recently published study by Mansour et al. demonstrated that in a healthy population, a shank gyroscope provided a more accurate temporal event estimation when compared with a lumbar-mounted accelerometer during treadmill walking [1]. Importantly, Jasiewicz et al. showed that in individuals with significant pathological gait, such as post spinal cord injury, the shank-mounted gyroscope may be less accurate due to shank oscillations during early and late stance phases [11]. As a result of the lack of consensus, a clear need exists to determine the optimal sensor mounting location for overground walking in order to provide the most relevant and reliable gait metrics.

The primary aim of this study was to investigate the validity of two IMU mounting locations, and directly compare the step time estimations derived from previously published processing methods. It is hypothesised that both lumbar and bilateral shank IMU mounting locations provide accurate step time estimations. Additionally, due to the more distal mounting location, the shank-mounted IMUs may provide a superior level of accuracy due to decreased levels of force attenuation during gait, when compared to the more proximally mounted lumbar IMU.

Materials and methods

Subjects

Thirty-seven (37) subjects, 14 female and 23 male (26 years ± 8 years, height 175 cm ± 9 cm, weight 72 kg ± 13 kg, BMI 23 ± 3) were recruited from the University campus and the wider community by means of posters and advertisements. Subjects were eligible to participate in this study if they were over 18 years of age and were capable of providing informed consent. Exclusion criteria included (1) unexplained falls within the last year, (2) active medical treatment, (3) fractures, surgery or hospitalisation within the last 3 months and (4) serious neurological pathology. Ethical approval was sought and obtained from the University Human Research Ethics Committee. All subjects provided written informed consent prior to being included.

Protocol

The testing protocol consisted of a controlled gait trial conducted at the University biomechanics laboratory. The controlled gait trial was designed to allow a direct comparison of step time measures derived from the gold standard force platform with those derived from two algorithms which estimated gait events from raw inertial sensor data [8, 34]. Prior to the commencement of the walking protocol, each subject's height and weight were obtained. A number of practice trials were then carried out in order to familiarise the subjects with the walking trials and allow the tester to determine the correct starting position, ensuring accurate force platform contact. The subjects were instructed to walk along a 10-m walkway at a self-selected "normal" walking speed. They were asked to focus on a preselected point at the end of the walkway and were not aware of the force platform location to ensure a normal gait pattern. The tester deemed the trial successful if two consecutive force platform foot contacts were present. The starting leg and the force platform step numbers were recorded for each walking trial. The procedure was repeated until 20 successful (10 right foot and 10 left foot force platform steps) trials were completed. In order to ensure accurate off-line synchronisation of the force platform and IMU data, the start and stop times of each walking trial, the number of steps and the force platform steps were recorded by the assessor.

Sensor setup

Three IMUs were used in total: one placed on each subject's distal shanks and one on the lumbar spine (Figure 1). The shank sensors were placed 10 cm superior to the bisection of the lateral malleolus, bilaterally. This location ensured minimal soft tissue attachment in order to limit the amount of skin and muscle movement. Sagittal plane gyroscope data were the signal ultimately used from the shank sensor (see "IMU processing"); thus, the sensor could be placed anywhere along the same plane of movement, providing an identical signal [6, 26]. The lumbar sensor was placed at the level of the 3rd lumbar vertebra in order to closely match the lower trunk acceleration during gait [12, 18]. Each sensor was fixed in place with an elastic strap and secured using double-sided tape, thus reducing any additional sensor movement during gait. Additionally, the IMU mounting location and orientation was monitored at regular intervals by a chartered physiotherapist (member of the Irish Society of Chartered Physiotherapists) to minimise the introduction of any error, thus reducing

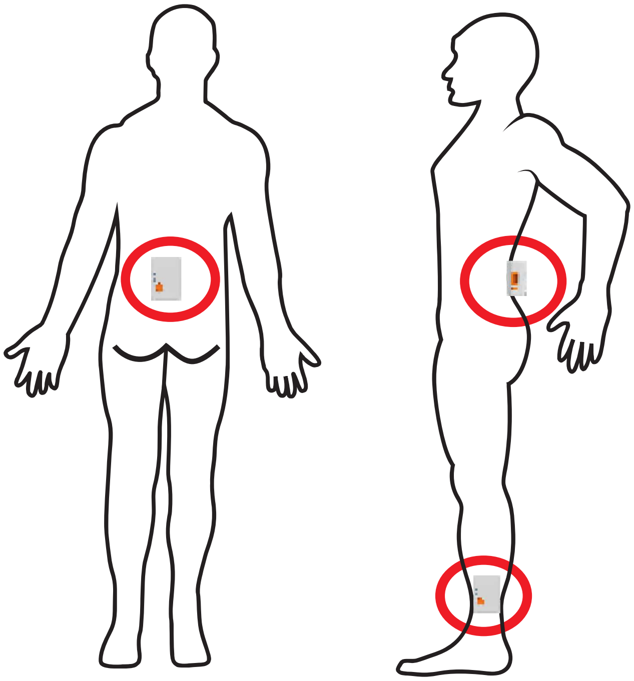

Figure 1: The shank and lumbar IMU mounting locations.

the need for orientation correction. The three inertial sensors were time-synchronised with each other and the inertial and timestamp data were stored in the on-board memory. The step number in which the first force platform IC occurred was noted by the study investigator. This ensured that the correct corresponding IC was obtained from the IMU data.

Force platform

As a validation tool, two embedded force platforms (AMTI, Watertown, MA, USA) were used to obtain a gold standard measurement of IC. CODA Analysis software v6.79.3-CX1 (Leicester, UK) was used to record and store data from the force platforms. The force platforms were located in the centre of the walkway. Force platform kinematic data acquisition was made at 1000 Hz and was passed through a fourth-order zero-phase Butterworth low-pass digital filter with a 6-Hz cut-off frequency [33]. In compliance with the recommendations outlined by Tirosh and Sparrow, a vertical force threshold of 10 N was selected to identify IC [25].

IMU processing

Q2:
In the sentence beginning with “The tri-axial accelerometer….”, please check if ±4G should be $\pm 4 \times g$

Shimmer3 IMUs (Shimmer, Dublin, Ireland) were used to measure acceleration and angular rate with a sampling rate of 256 Hz. The tri-axial accelerometer and gyroscope signals were set to ranges of ±4G and ±1000 deg/s, respectively.

The algorithm to estimate gait events from the lumbar-mounted IMU found IC by identifying a peak on the anterior-posterior acceleration signal prior to a sharp decrease, associated with the foot making full contact with the ground in front of the body [36]. As the subject’s heel makes contact with the ground (IC), a maximal vertical acceleration occurs [36]. This algorithm was selected as it demonstrated high levels of gait event detection validity [36].

The algorithm to estimate IC from the shank sensors was based on the use of the sagittal plane gyroscope signal [9]. There is a large increase in this signal associated with the swing phase of walking, and IC is found at the minimum values before this large increase. This algorithm was chosen based on previous work which indicated it was the most accurate algorithm compared to other commonly used shank-based algorithms [20].

Statistics

Statistical analysis was performed in order to determine the validity of the algorithms’ estimation of step time. From each laboratory walking trial, three step time values were obtained: one from the gold standard force plates, one from the shank IMUs and one from the lumbar IMU. Each step time was averaged over all 20 trials for each subject. These average values were used for the final comparison. Pearson’s correlation coefficient [15] was calculated for both mounting locations to determine the level of correlation between the force platform and the IMU measures. High levels of correlation between measurement systems do not mean that the two methods agree well [16]; thus, a Bland-Altman style analysis was conducted to determine the levels of agreement between the gold standard gait parameters, as determined by the force platform, and those derived from the gait detection algorithms [16]. Mean differences between the IMU and force platform step time estimation were calculated. The 95% confidence interval (CI) was calculated to demonstrate the precision of the estimated limits of agreement, using the formula

$$\mathrm{CI} = X \pm t_{(1-\alpha/2)}(\sqrt{2s_D^2})$$

where X is the mean of the mean difference between the IMU and force platform step time measurements, $\sqrt{2s_D^2}$ is the corrected standard deviation (SD) and $t_{1-\alpha/2}$ is dependent on the probability level chosen and degrees of freedom [24]. Some of the effects of repeated measurement error have been removed because repeated measures on each subject were averaged and the mean values were compared. For this reason, the SD of the means was corrected, according to methods proposed by Bland and Altman [3]. The CI width was determined in order to estimate the range within which 95% of the results should be expected to fall. This range demonstrates the accuracy of the IMU’s estimations, outlining the error of the IMU’s estimations relative to the gold standard force platform. Percentage error of the IMU measurement was calculated by finding the mean difference between the IMU and force platform measurement as a percentage of the group mean of the force platform. A paired sample t-test was utilised in order to demonstrate whether the difference between the two IMU mounting location estimations of step time were statistically significant ($p < 0.05$).

Results

Seven hundred and forty complete walking trials, each consisting of a single step, were obtained from 37 participants during the data collection phase of this study. Twelve individual steps, dispersed throughout the subjects, had to be excluded from the analysis, due to data corruption at the data collection phase, resulting in a total of $n = 728$ steps for analysis. Table 1 lists the mean, SD and minimum and maximum of the subjects’ mean step times, as derived from the shank IMU, lumbar IMU and force platform.

Table 2 presents a direct comparison between the estimated step times from each of the IMU locations and the gold standard force platform. The Pearson correlation

Table 1: Mean and SD over 20 trials, overall step time mean and SD for all trials and the minimum and maximum step time values obtained from the force platform and the two IMU mounting locations.

	Force platform	Shank IMU	Lumbar IMU
Mean of 20 trials (s)	0.5317	0.5392	0.5387
SD of 20 trials (s)	0.0399	0.0445	0.0404
Overall mean (s)	0.5315	0.5390	0.5385
Overall SD (s)	0.0415	0.0824	0.0454
Maximum (s)	0.5926	0.6242	0.5948
Minimum (s)	0.4508	0.4619	0.4492

Table 2: A comparison between each of the IMU mounting locations and the gold standard force platform, showing the correlation coefficient, upper and lower CIs, CI width, mean differences, corrected SD of the difference and the percentage error of the IMUs.

	Shank IMU vs. force platform	Lumbar IMU vs. force platform
Pearson correlation coefficient	0.9487	0.9864
Upper 95% CI (s)	0.0466	0.0254
Lower 95% CI (s)	−0.0316	−0.0113
CI width (s)	0.0782	0.0367
Mean difference (s)	0.0075	0.0070
Corrected SD of the difference (s)	0.0199	0.0094
Percentage error (%)	1.41%	1.32%

coefficients show the level of correlation between the force plates and IMU step time measures. The mean of the differences between the step times measured from each of the IMU locations and those measured by the force platform are also shown, with the step time derived from the lumbar IMU showing a smaller absolute difference when compared to the shank IMU. A paired sample t-test demonstrated that there was no statistically significant difference between the two IMU estimations of step time (p = 0.84). Additionally, the percentage error of the IMU measurements, when compared to the force platform, indicates that the lumbar IMU demonstrates a marginally lower error in estimation (1.32%) when compared to the shank IMU (1.41%). The comparison between the step times estimated from each of the IMU locations and from the force platform has been visualised using Bland-Altman style plots (Figures 2 and 3). Upper and lower CIs were found to be relatively small for both IMU locations, resulting in small CI widths (Table 2). Figure 4 shows a scatter plot illustrating the agreement between the IMU and force platform.

Q3: Please check if “mean” should be “means” in “The mean of the differences between the step times...”

Discussion

The key findings of this study are that both shank and lumbar IMU mounting locations yield step times that are highly correlated with those obtained from the gold standard force platform. When directly comparing the two IMU locations with the gold standard force platform, both IMUs demonstrated similar levels of accuracy, with the lumbar IMU demonstrating a marginally higher level of accuracy than the shank IMU.

Pearson correlation coefficients were calculated to determine the strength of the relationship between the step times derived from each of the IMU mounting

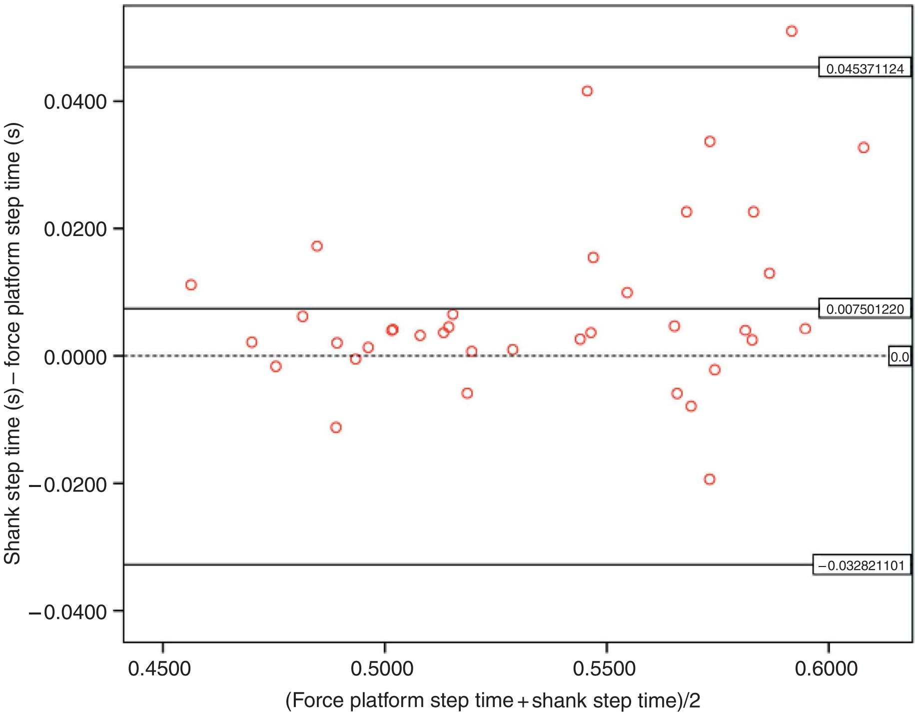

Figure 2: Bland-Altman plot comparing the step time estimations derived from the gold standard force plate and the shank-mounted IMU. Each circle represents the average step time for each subject.

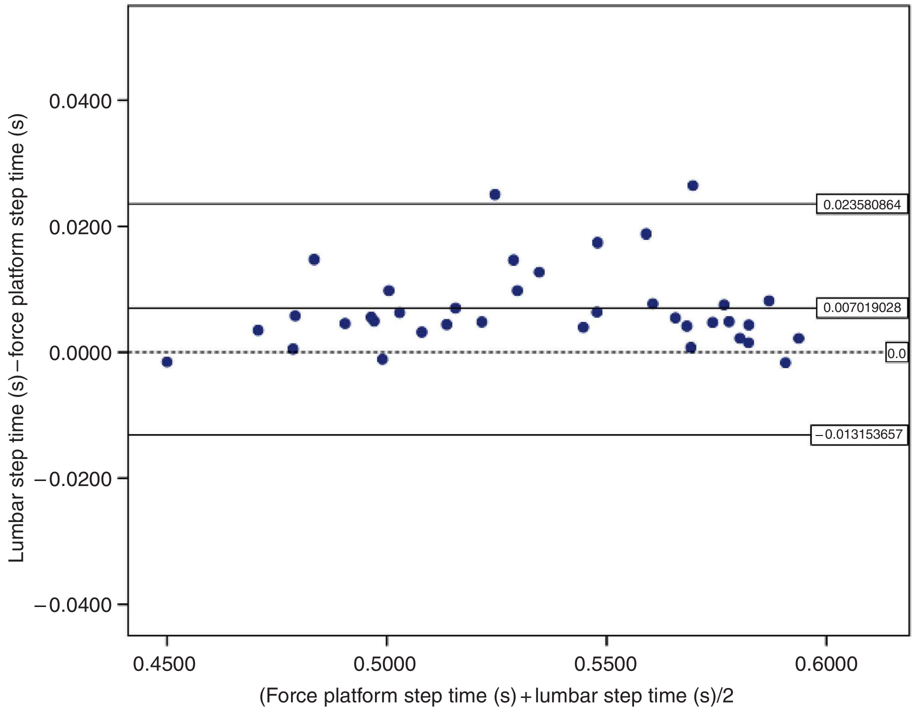

Figure 3: Bland-Altman plot comparing the step time estimations derived from the gold standard force plate and the lumbar-mounted IMU. Each circle represents the average step time for each subject.

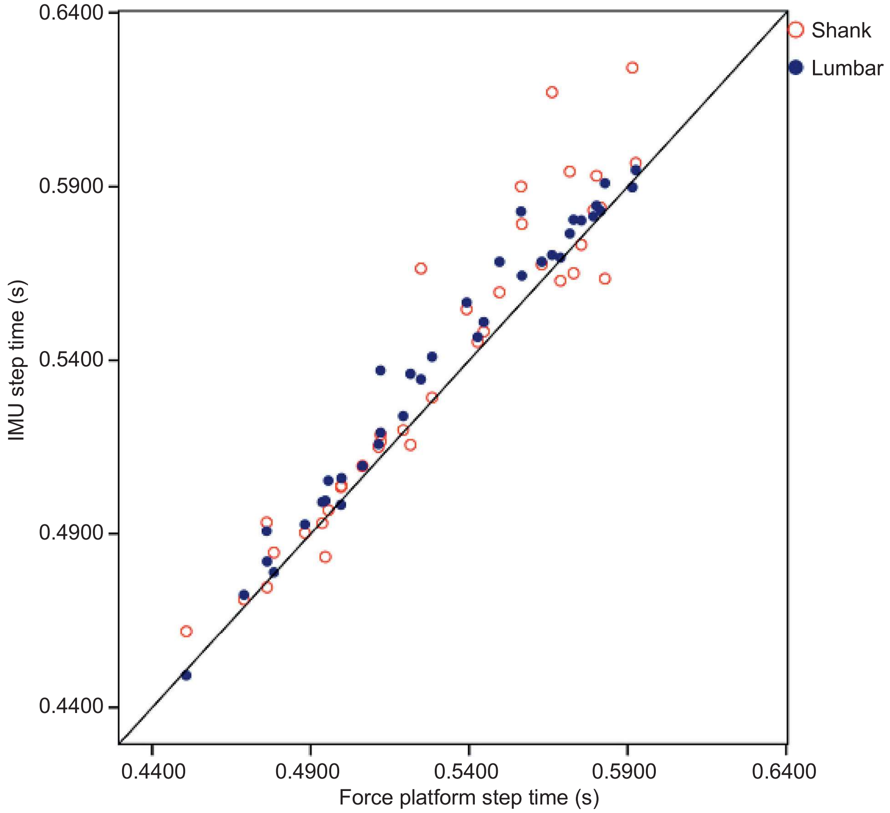

Figure 4: The degrees of agreement between the IMU and the force platform measurements.
The line of equality represents where all the points would lie if the IMU and force platform measurements were exactly the same. Each circle represents the average step time for each subject.

locations and the force platform. The Pearson correlation coefficients demonstrated excellent levels of positive correlation for both the lumbar and shank IMU mounting locations [10]. When directly comparing the two mounting locations, the lumbar sensor showed a slightly higher level of correlation with the gold standard measurement.

A Bland-Altman analysis was conducted to determine the levels of agreement between the IMU and force platform measures (Figures 2 and 3). The CI widths for both IMU locations were relatively small, with a low average discrepancy between the measures (Table 2). The lumbar IMU achieved a greater degree of accuracy than the shank IMU. When this is viewed in conjunction with the sampling frequency of 256 Hz, a step time difference of anything up to 0.004 s cannot be treated as significant, as this is the sample time of the IMUs. The paired samples t-test analysis demonstrated that the difference between the mean step time estimations was not statistically significant, suggesting that the two mounting locations are capable of providing estimations of similar accuracy. The smaller CI width, demonstrated by the lumbar IMU (Figure 3), results in the mean differences falling closer to the mean line when compared with that of the shank IMU (Figure 2). Neither IMU location demonstrated a tendency for the step time estimation to overestimate or underestimate as the gold standard step time measure increased or decreased. This suggests that both IMU mounting locations are suitable for estimating step time across the "normal" range presented in this study, without having to account for over or underestimation.

Figure 4 represents the levels of agreement between the IMU and force platform measurements. Both IMU locations fall close to the line of equality, which represents where all points would lie if the measurements were exactly the same [16]. The step times from both IMU locations show good agreement with the gold standard force platform measurement; however, they demonstrate a slight degree of step time overestimation when compared to the force platform, which is more pronounced in the shank IMU. This slight overestimation is seen through the mean differences (Table 2), and is consistent with the findings of Mansour et al., who demonstrated a tendency for lumbar and shank-based IMUs to overestimate step times across a range of five gait speeds [1]. When comparing the step time estimations derived from the IMUs and the gold standard force platform, the shank IMU showed a marginally greater percentage error (1.41%) than the lumbar IMU (1.32%) (Table 2).

The accuracy findings presented in this paper are consistent with those presented by Godfrey et al. [7] and Greene et al. [9] for the lumbar and shank IMU mounting locations, respectively. Godfrey et al. [7] reported a step time mean difference of 0.0020 s compared to the force platform with a CI of 0.005 s. In contrast, our results demonstrated a marginally larger mean difference of 0.0070 s and a CI width of 0.005 s. Additionally, Greene et al. [9] reported a mean difference between the IMU and force plates estimation of 0.0066 s, similar to the mean difference of 0.0075 s demonstrated in this study.

The comparative mounting location findings presented in this study contrast with the results of Mansour et al., who found that a shank-mounted gyroscope provides superior levels of step time estimation accuracy, when compared to a lumbar-mounted accelerometer, during treadmill walking [1]. The conflicting results may be the result of three main methodological differences. Firstly, our study followed the 10-N threshold guidelines for the detection of IC [25]. Due to the increase in noise present in the force platform signal induced by movement of the treadmill belt and motor, Mansour et al. implemented a threshold of 20 N [1]. This is a potential source of error as a higher threshold may delay the identification of the IC gait event [35]. Secondly, in our study, a force platform sampling frequency of 1000 Hz was used, as recommended by Winter [33]. A significantly lower sampling frequency of 200 Hz was implemented by Mansour et al., potentially decreasing the force platform's gait event detection accuracy, due to decreased time resolution [1]. While the time resolution observed in this study was relatively high, with a force platform accuracy of 5 ms compared to the error of 23–40 ms observed by Mansour et al. [1], this relatively small error may combine with the increased IC detection threshold and the noise produced by the treadmill to effect the level of force platform accuracy. Finally, these contrasting findings may be the result of the differences imposed by treadmill walking, compared with over-ground walking. During treadmill walking, the foot is placed on a constantly moving surface, whereas during over-ground walking, the foot is placed on a stationary surface and lower body joint moments are required to propel the person forward [35]. As a result, inertial sensor data may demonstrate higher levels of linear translation during over-ground walking when compared to treadmill walking, resulting in gait event detection algorithms behaving differently for different walking conditions. It has been shown that inertial sensor outputs are different in over-ground compared to treadmill locomotion [2]. It is important to consider that treadmill validation explains how well certain algorithms and mounting locations work during treadmill walking only; the findings from such validation studies cannot be directly assumed to be true for over-ground walking.

While the results presented in this study demonstrate the accuracy in a healthy population, it is important to consider the accuracy in different populations. Previous research has demonstrated the validity of these IMU mounting locations and temporal event detection algorithms in healthy and pathological populations [20, 29]. Trojaniello et al. [29] demonstrated that a lumbar-mounted IMU, utilising the IC event detection algorithm developed by Zijlstra and Hof [36], provides accurate, but marginally greater step time error, in pathological populations than the results presented in our study. It was reported that the percentage error in healthy elderly and Parkinson's disease patients was 4%. Similarly, Patterson and Caulfield [20] concluded that a shank-mounted IMU utilising the algorithm developed by Greene et al. [9] can provide accurate estimations of temporal gait metrics in individuals with constrained gait conditions simulating pathological gait. These results may be expected due to the different gait characteristics observed in different populations [20, 23, 29]. These differences in the estimation accuracy across different populations stress the importance of contextualising the information which is collected. Providing a level of accuracy in one population does not mean that this level of accuracy can be generalised across all populations. However, it provides a marker as to what level of accuracy can be expected in individuals with similar levels of mobility. This stresses the importance of future research investigating the accuracy of the different sensor mounting locations in different populations.

In addition to the different accuracies demonstrated in different populations, it is important to consider the effect gait speed has on the accuracy of the gait event estimations. In their comparison of sensor mounting locations, Mansour et al. demonstrated the effect gait speed has on the event detection algorithm accuracy. It was found that as the gait speed decreased, so too did the accuracy of the event detection algorithm. Despite this, Greene et al. [9] demonstrated that the shank event detection algorithm utilised in our study demonstrated consistent levels of step time error at normal (5.59% error) and slow (5.21% error) walking speeds. Additionally, Zijlstra and Hof [36] investigated the accuracy of their algorithm's ability to detect ground reaction force at different gait speeds, finding that the mean difference between the lumbar sensor and the gold standard measures at five different gait speeds was relatively constant. These comparisons demonstrate that the algorithms utilised in this study are relatively robust to changes in gait speeds and suggest that the accuracy results presented in our study at a "normal" gait speed are relatively translatable to different gait speeds. Despite this, future comparisons should consider the effect gait speed has on the accuracy of gait event detection.

An important aspect to consider when implementing ambulatory monitoring is an individual's comfort and preference. Some individuals may prefer to wear a belt-like lumbar IMU for prolonged periods of time, while others may find it less invasive to wear a shank-mounted IMU. Clothing preferences may also be a factor in driving which IMU location a person would prefer. The high level of accuracy obtained from both IMU locations demonstrates that it may be possible to take into account the individual's preference without adversely affecting accuracy. This is an important consideration, as the wearer's comfort and preference may lead to higher levels of compliance.

There were a number of limitations to this study. Firstly, the participant's gait speed was not controlled and, therefore, it was not possible to assess the validity of the event detection system across a range of different controlled walking speeds. However, the use of the participant's chosen walking speed ensured that individuals were allowed to walk in a natural manner. Secondly, due to the layout of the in-floor force platform system, it was not possible to obtain a gold standard measurement of metrics that require a full stride, as the platform was too short to capture two successive ICs from one leg. This meant that it was not possible to validate the system's capability to accurately estimate stride time. However, as our study only investigated the accuracy of temporal metrics derived from IC during a single step (step time), it may be inferred that other IC-derived temporal gait metrics such as stride time may demonstrate similar accuracy levels. While other temporal metrics such as stance time, swing time and double support incorporate IC in their calculation and, thus, may demonstrate similar levels of accuracy, it is important to note that due to the other gait events such as toe-off required to calculate these metrics, conclusive inferences cannot be drawn on the accuracy of these metrics from the results presented in this study. Thirdly, this study only investigated the validity of temporal gait event estimation in a healthy population; further research is required to determine the validity in a pathological population.

In conclusion, both the shank and lumbar IMU mounting locations provided a valid estimate of step time, when compared to the gold standard force platform system. The accuracy, relatively small deviation from the gold standard measures and the ease of set-up indicate that the IMU system is a reliable and easily accessible tool, capable of providing accurate and valid temporal gait measures. Additionally, when directly comparing the accuracy of both mounting locations and force platform-based gait

Q4:
Please check if "measurements" would be more appropriate than "measures" in phrases such as "temporal gait measures" and "step time measures." Please check the word throughout the article

event detection algorithms, it can be concluded that the lumbar IMU provides a marginally more accurate estimation of step time. This study has implications for both research and clinical practice by increasing the accessibility of such systems by reducing the cost needed to obtain accurate and valid measurements (2× force plates cost ~€20,000 and 2× IMU cost ~€500). Further research is required to determine the differences between treadmill and over-ground walking using IMU systems, the utility of such systems in various clinical populations, the accuracy and robustness of these event detection algorithms when monitoring individuals over a prolonged period of time without supervision and the validity and accuracy of these IMU mounting locations in the calculation of other spatiotemporal variables of gait.

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Conflicts of interest statement: The authors declare that Dr. Matthew Patterson and Dr. Niamh O'Mahony were employees of Shimmer, Dublin, Ireland, at the time that this study was carried out.

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Q5: Please supply missing details in refs. [10, 21, 24]

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