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Comparison of kinematic and pressure measurement reference methods used in gait event detection

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Purpose: A variety of methods have been proposed for detection of initial contact (IC) and foot off (FO) and some comparative analysis is reported in the literature. Pressure measurement insoles and kinematic systems are often part of footwear analysis. Although gait event detection algorithms using these systems have been proposed and evaluated against kinetic data (KN) from force platforms (typically used as a 'gold standard'), they have not been compared directly. The objective of this work was to undertake this comparison using the same volunteer dataset and test conditions.
Methods: Data from 10 healthy adults walking at self-selected normal speed were collected. Two kinematic algorithms (one using a fixed threshold, KM, and the other using high pass-filtering, HPA) and one algorithm using pressure measurement data from an insole (Contact Area Detection, AD) were tested and compared with the detection provided by KN. All data were synchronised and sampled at 200 Hz. Six basic spatio-temporal parameters were also calculated.
Results: The absolute mean difference (AMD) in event detection between the three methods and KN was below 25 ms. However, the methods presented tendencies to detect events earlier or later than KN and this influenced the AMD between the methods, which increased to 47 ms for IC detection between HPA and AD. The spatio-temporal parameters showed no statistically significant differences between AD and KM, but differences reached statistical significance between AD and HPA.
Conclusion: It is possible to compare gait events and basic spatio-temporal parameters detected using data from pressure measurement insoles and kinematic algorithms; however the kinematic algorithm used will influence the results. Hence the comparison of findings from alternative detection methods is an important issue for which information about the behaviour of the method used is required.

Keywords: gait event detection; pressure detection; kinetic; kinematic; initial contact; foot off

1. Introduction

Conventionally, the gait cycle is divided into stance and swing phases. Initial contact (IC) and end of contact or foot off (FO) can be used to determine the start and end of these phases. Their detection is used for the analysis of spatio-temporal gait parameters, which in turn are used for a variety of applications including the characterisation of gait (Lythgo *et al*. 2009, Moreno-Hernández *et al*. 2010) or running styles (Hardin *et al*. 2004, Lohman *et al*. 2011) under shod and barefoot conditions and to evaluate the effect of specific footwear on human biomechanics (Shroyer and Weimar 2010, Zhang *et al*. 2012, Horsak and Baca 2013, TenBroek *et al*. 2013).

Force platforms are considered the gold standard for determining gait events (Morris Bamberg *et al*. 2008, Hanlon and Anderson 2009, González *et al*. 2010). Despite their recognised accuracy, the number of force platforms available often limits the number of steps per trial that can be recorded. Also, it is not uncommon for subjects to step on two platforms at the same time or contact one platform with both feet, which at best increases data collection time. These limitations have led to the development of new approaches.

Several alternative systems have been used for the detection of gait events, including kinematic methods using optical systems (Pappas *et al*. 2001, Smith *et al*. 2002, Lauer *et al*. 2005), foot switches (Aminian *et al*. 2002, Sabatini *et al*. 2005), pressure matrices (Beauchet *et al*. 2008, Sant'Anna and Wickström 2010, Lopez-Meyer *et al*. 2011), pressure insoles (Han *et al*. 2009, Catalfamo *et al*. 2010), and sensors such as tilt sensors (Dai *et al*. 1996), accelerometers (Williamson and Andrews 2000, Selles *et al*. 2005, Hanlon and Anderson 2009) and gyroscopes (Miyazaki 1997, Aminian *et al*. 2002, Ghoussayni 2004, Catalfamo *et al*. 2010). The variety of detection methods utilised is even greater when taking into account the different algorithms used for event detection using the same technology. Kinematic methods,

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for example, make use of different marker positions, variables (such as position, velocity and acceleration of single or combined markers) and a range of data processing techniques to calculate IC and FO (for example, threshold-based algorithms (Mickelborough *et al*. 2000, Pappas *et al*. 2001, Ghoussayni *et al*. 2004, Zeni Jr *et al*. 2008) and algorithms that do not use fixed thresholds (O'Connor *et al*. 2006, Desailly *et al*. 2009)). A set of selected kinematic algorithms proposed and evaluated in the literature is presented in Pantall *et al*. (2012).

The accuracy of the methods proposed for the detection of gait events is normally evaluated by comparing the algorithm against the gold standard (force platform or kinetic method). For example, kinematic methods using optical motion analysis systems have been evaluated on overground (Ghoussayni *et al*. 2004, O'Connor *et al*. 2006, Desailly *et al*. 2009) and treadmill walking (Zeni Jr *et al*. 2008, De Witt 2010, Kiss 2010) against force platforms.

More recently, however, and given the number of alternative methods proposed, researchers have focused on the comparison between non-gold-standard detection algorithms. The comparison is important for the selection of the most appropriate method for a given application while providing information regarding the agreement between methods. This information is useful when contrasting the results of investigations, which were obtained using different detection algorithms.

Methods using similar technology have been recently compared. For example kinematic algorithms have been compared for detection during walking (O'Connor *et al.* 2006, Desailly *et al*. 2009, De Witt 2010, Pantall *et al.* 2012) or running (Maiwald *et al*. 2009, De Witt 2010, Sinclair *et al*. 2011) and foot switches have been evaluated against pressure matrices (Beauchet *et al*. 2008). However, in a number of applications such as when the effects of different footwear are under investigation, it is common to use kinematic (Shroyer and Weimar 2010, Hardin *et al*. 2004, Zhang *et al*. 2012, Horsak and Baca 2013, TenBroek *et al*. 2013) or pressure insoles (Lythgo *et al*. 2009, Moreno-Hernández *et al*. 2010, Price *et al.* 2013) to describe changes in movement biomechanics. These changes are often illustrated by measuring the differences in selected spatio-temporal parameters such as walking speed, stride time (or cycle time) and stance time. In order to compare the results of investigations which were obtained using different detection algorithms, it is important to compare the performance of the algorithms and the effect they have on the calculation of spatio-temporal parameters.

In this respect, pressure matrices such as the GaitRite® walkway have been evaluated against kinematic data for the determination of spatio-temporal parameters (Webster *et al*. 2005, Stokic *et al*. 2009). The results of these investigations showed that the mean differences between the two methods measured 1.5% or less of the parameter mean value (Stokic *et al*. 2009) and that the individual step values were within 1.5 cm and 0.02 s on the majority (80−94%) of the steps (Webster *et al*. 2005). With these results, the authors conclude that the systems may be used interchangeably.

A method using data from pressure measurements insoles (AD) has been previously proposed and evaluated against force platforms (Catalfamo *et al*. 2008). The absolute mean differences between the gold standard (KN) and AD were 22 ± 9 ms for IC and 10 ± 4 ms for FO. Given these results, the authors concluded that the pressure measurement system could be considered an option for detection of gait events and presents advantages in terms of portability, number of steps analysed per trial and practicality.

However, a direct comparison between pressure measurement insoles, commonly used for footwear evaluation (Bus *et al*. 2009, Kavros *et al*. 2011, Bennetts *et al*. 2013), and kinematic systems is still pending.

A comparison of algorithms already proposed in the literature through analysis of the published results would be possible only if all the conditions used in the original studies were relatively consistent. This was not the case for the algorithms chosen for evaluation, hence a direct and simultaneous comparison of the methods was proposed for this study.

The objective of this work was to compare the differences between the AD method and selected kinematic based approaches for gait event detection and determination of a basic set of spatio-temporal parameters using the same volunteer dataset and test conditions.

2. Methods

2.1 Subjects

Ten subjects without discernible gait abnormalities participated in the study: nine males, one female, age 29 ± 6 years and mass 82.6 ± 18.9 kg (mean ± standard deviation). The purpose of the study was explained to each subject before they were asked to give their consent to take part. All experimental procedures were approved by the University Ethics Committee.

2.2 Protocol

Pressure distribution under the feet was measured using an F-Scan® Mobile system (V 6.30 Tekscan, Inc. South Boston, MA, USA). The subjects wore their own training shoes and were fitted with the portable equipment and the insoles (F-Scan® Mobile system), which were trimmed to their shoe size. The protocol included 10 minutes of walking before the study, to ensure equilibration in the temperature of the insoles and familiarity with the equipment.

Figure 1. Equipment used for data collection in one of the subjects who participated in this study. The subjects were fitted with markers on heels and toes, and with insoles inside the shoes and a portable datalogger on their waist for capturing and storage of pressure measurement data.

During this time, subjects walked on level ground on a path that included the walkway used for the data collection. The calibration of the insoles was performed using the ‘Step Calibration’ procedure, according to the instructions in the Tekscan user manual.

Kinematic data were obtained using seven digital infrared cameras (ProReflex, Qualisys Medical AB, Gothenburg, Sweden). Retroreflective markers were placed on both feet at the heel (posterior aspect of the calcaneus) and toe (between the second and third metatarsal head) as shown in Figure 1.

Each subject was asked to walk six times at their self-selected normal speed along a 10 m walkway. Two AMTI force platforms (Advanced Mechanical Technology, Inc., Watertown, Massachusetts, USA, model 400600HF-2000) were in the middle of this walkway.

F-Scan®, kinematic and the force platform data were synchronised and sampled at 200 Hz.

The IC and FO events were detected off line through routines written using Matlab® (Version 7.0 R14, MathWorks Inc, Natick, MA, USA). Three different methods were used for determination of events: Contact Area Detection (AD) algorithm using data from the F-Scan system, Kinematic Detection using a fixed threshold based on the algorithm proposed by Ghoussayni (2004) (KM), and Kinematic Detection using high pass-filtering as proposed by Desailly (2009) (HPA). Given that some modifications were necessary in this study with respect to the conditions with which the algorithms were originally evaluated, a gold standard detection in the form of Kinetic Detection (KN) was also included. Differences in the results between the methods and KN in our study with those reported previously would then be an indication that the change in the study conditions affected the performance of the algorithms.

The rationale behind the selection of the kinematic methods was that: a) they were automatic methods using a minimum set of markers data; b) they were kinematic-based only algorithms; c) their performance has been evaluated in the literature for gait event detection during walking and the results compared favourably to alternative algorithms based on the same type of data; and d) one of the methods would be a threshold-based algorithm and the other would not use thresholds.

2.3 *Kinetic detection algorithm*

A 5 N threshold applied to the vertical component of the ground reaction force (Desailly *et al*. 2009, Hanlon and Anderson 2009) was considered to be low enough to detect both the time for initial contact and foot off and appropriate to compare results with the literature (Figure 2A).

2.4 *Area detection algorithm*

The Contact Area method (AD) was implemented as described in its original publication (Catalfamo *et al*. 2008). The algorithm first estimates the total area of the foot which is loaded when the foot is not in contact with the floor (area loaded during swing phase, ALSw) and the total area of the foot loaded during stance, ALSt. Then, a threshold of 5% is applied to the difference between ALSt and ALSw and used for detection of IC and FO. IC is determined as the first sample for which the area signal exceeded the threshold and FO is determined as the first sample, after stance, when the area signal fell below the threshold (Figure 2B).

2.5 *Kinematic detection algorithm using a fixed threshold*

As proposed in Ghoussayni *et al*. (2004), the velocity of the heel and toe markers was used and a fixed threshold was applied to the velocity. For this study, the velocity of markers in the x-axis of the laboratory coordinate system was utilised (in the Gait Laboratory used, this corresponds nominally to the velocity in the direction of progression).

First the signals were low-pass filtered at 20 Hz (zero-lag fourth-order Butterworth filter). This is higher than the cut-off of 10 Hz used in the original work. This revised cut-off frequency was selected based on the work by Antonsson and Mann (1985). They used force platform data to evaluate the ‘portion of the gait cycle where the

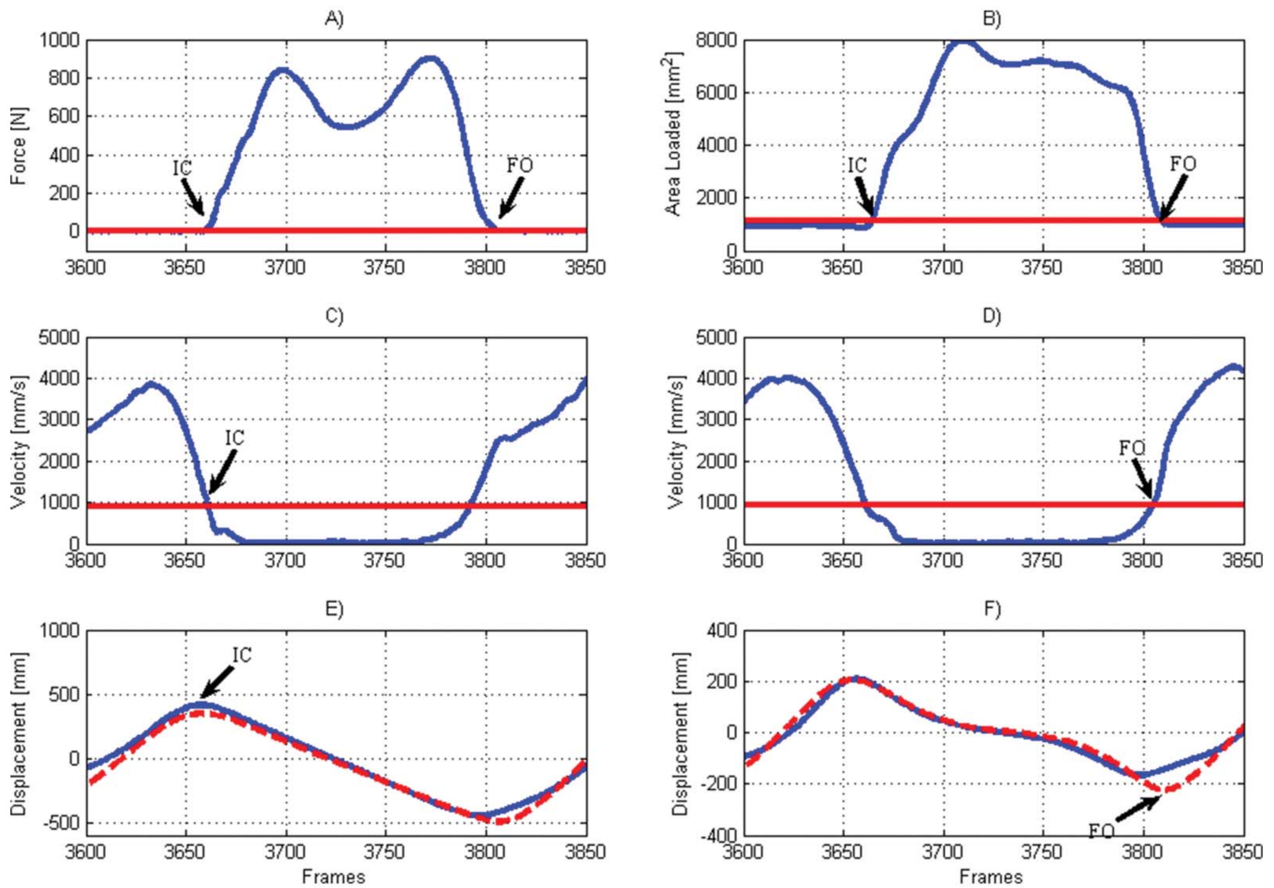

Figure 2. Methods used for detection of IC and FO. (A) Kinetic Detection Algorithm using a 5 N threshold for both events. (B) Area Detection Algorithm, using the area loaded of the foot and a 5% threshold over the range of area loaded. (C and D) Kinematic Detection Algorithm using a fixed threshold: velocity of the heel marker in the direction of progression for the detection of IC (C) and velocity of the toe marker in the direction of progression for the detection of FO (D). (E and F) HPA, High Passed Filtered Displacement of the heel (solid line) and toe marker (dashed line), with cut off frequency of 0.5 of the 'gait frequency' for detection of IC (E), and displacement of the heel and toe marker, with cut off frequency of 1.1 of the 'gait frequency' for detection of FO (F).

most abrupt and rapid position changes with time occur, thereby encompassing the worst case accelerations in the biomechanical system'. Those accelerations occur at the foot during heel strike. Their results showed that 98% of the total power of the signal is contained below 10 Hz and 99% below 15 Hz. This suggests that a 15 Hz cut-off frequency would be appropriate for an ideal filter. However, because of the characteristics of signal attenuation of a non-ideal Butterworth filter, and in order to maintain any components of the signal at or below 15 Hz, the cut-off frequency used was 20 Hz.

In the study by Ghoussayni et al. (2004), the threshold values were selected so that they would accommodate low-level movement of the markers during contact periods and errors due to the inherent noise of the measurement system. When analysing data from two randomly selected subjects who participated in the present study, it was clear that the proposed thresholds were too low to meet the above condition. Hence new thresholds had to be applied.

A fixed threshold was empirically set by visually inspecting data from these two subjects. The events were visually detected (from within the Qualisys Track Manager software, V 2.6 build 682, which shows the marker movement) and for that particular frame, the velocity was noted. For both subjects analysed, the velocity that corresponded to the visual detection was 20% of the maximum velocity of the marker in the direction of progression. IC was defined as the first sample when the velocity of the heel marker dropped below this threshold (Figure 2C). FO was defined as the first sample when the velocity of the toe marker exceeded this threshold (Figure 2D).

2.6 Kinematic detection using the high pass algorithm

The High Pass Algorithm (HPA) was implemented as described in its original publication (Desailly *et al*. 2009). The algorithm uses the heel and toe marker data that were low pass filtered at 7 Hz (zero-lag Butterworth fourth-order filter). The main component of the spectrum of the vertical displacement of the heel marker was calculated (this frequency value was called 'gait frequency' in the original publication (Desailly *et al*. 2009)). Then, the horizontal displacement of both markers was high pass filtered at 0.5 times the 'gait frequency'. IC was defined as the first maximum of these processed signals (Figure 2E). The horizontal displacement of both markers was also high pass filtered at 1.1 times the 'gait frequency' and FO was defined as the last minimum of these signals (Figure 2F).

The HPA method was originally evaluated against the gold standard (KN) for a group of healthy adults and a group of children with cerebral palsy (CP) walking barefoot at their self-selected speed. The results of the present study were compared to those obtained with the healthy adults group of the original publication.

2.7 Data processing

The steps for which each foot landed completely on one force platform, without touching the other were regarded as acceptable. The corresponding IC and FO events were then determined using the four methods. For the present analysis the KN method is considered the gold standard, while AD, KM and HPA are considered reference methods.

Initially, the differences in detection timing between the reference methods and the gold standard were calculated as:

KN − KM = kinetic detection (KN) − kinematic detection using the fixed threshold (KM)
KN − HPA = kinetic detection (KN) − kinematic detection using the high-pass filtered algorithm (HPA)
KN − AD = kinetic detection (KN) − area detection (AD)
Then the differences between the reference methods themselves were calculated as:
KM − HPA;
KM − AD;
HPA − AD.

The mean difference (MD) and also the absolute values of the differences (AMD) were calculated and used in averaging to avoid misleading results due to cancellation of positive and negative values. The differences for all the events were averaged for the 10 subjects. The 95% confidence interval (CI) was also calculated.

The distribution of the differences was plotted in histogram form. For each event (IC and FO), the number of detections versus the time difference expressed in milliseconds (calculated in the range between −100 to 100 ms, divided in 5 ms intervals) was calculated.

Walking speed, stance phase duration, step time and time of double support were calculated using the reference methods and the gold standard. For calculation of walking speed, the distance travelled during the step was obtained from kinematic data. The parameters were averaged for each subject (i.e. each set of steps from one subject was used to produce a single mean), reducing the data points to 10 for each method and compared statistically. For the statistical comparison a Friedman test with a Dunn post-test was performed using the GraphPad InStat Software version 3.05 (GraphPad Software, USA).

Also, gait cycle time and time of single support were calculated for the reference methods. In this case, it was necessary to detect two consecutive ipsilateral IC events. Given the number of force platforms available in the Gait Laboratory (two), it was not possible to calculate these parameters using the KN detection method. These parameters were calculated using the KM, HPA and AD methods, averaged for each subject and compared statistically. For the statistical comparison again a Friedman test with a Dunn post-test was performed using the GraphPad InStat Software.

3. Results

3.1 Gait event detection

A total of 18 steps (9 with the right foot and 9 with the left foot) were used for each subject. A total of 180 steps were therefore considered for the analysis. The walking speed of the subjects (calculated using the KN method) was 1.23 ± 0.15 m/s (mean ± std), with a minimum of 1.11 m/s and a maximum of 1.37 m/s.

Table 1 shows the mean difference, the absolute mean differences and the 95% confidence interval in detection of gait events between the reference methods (KM, HPA and AD) and the gold standard (KN) and between the reference methods themselves.

Figure 3 shows the distribution of the differences for the detection of IC and FO between the KN method and each of the reference methods (KM, HPA and AD). Positive differences indicate that the reference method detected the event earlier than the gold standard. Figure 4 shows the distribution of the differences for the detection of IC and FO between the reference methods (KM − HPA, KM − AD and HPA − AD).

Table 2 shows the mean ± one standard deviation of the spatio-temporal parameters calculated by the gold standard and the reference methods: walking speed, stance time, double support time and step time (calculated for all methods) and single support time and cycle time (calculated for the reference methods only). Table 2 also shows the results of the statistical tests performed.

Figure 3 illustrates that there is a tendency for KM to detect both events earlier than KN and for AD to detect IC later than KN. In the case of HPA, the detection of IC was performed earlier than the KN method while the

Table 1. Mean difference (MD) ± one standard deviation, absolute mean difference (AMD) ± one standard deviation, and 95% confidence interval (CI) of MD, all expressed in milliseconds, for the detection of initial contact (IC) and foot off (FO) between the methods. KN: Kinetic detection algorithm; KM: Kimematic detection algorithm using the fixed threshold; HPA: Kinematic detection using the high-pass filtered algorithm; AD: Area detection algorithm. N = 180.

	IC			FO		
	MD	AMD	CI	MD	AMD	CI
KN − KM	9 ± 12	12 ± 9	[8; 11]	13 ± 12	15 ± 9	[12; 15]
KN − HPA	24 ± 14	25 ± 13	[22; 26]	−20 ± 9	20 ± 11	[−21; −17]
KN − AD	−24 ± 11	23 ± 11	[−25; −22]	−1 ± 15	11 ± 11	[−4; 1]
KM − HPA	15 ± 6	14 ± 6	[14; 15]	−33 ± 11	34 ± 11	[−34; −31]
KM − AD	−33 ± 15	33 ± 15	[−35; −30]	−14 ± 14	17 ± 13	[−17; −13]
HPA − AD	−47 ± 17	47 ± 17	[−49; −44]	19 ± 13	20 ± 13	[15; 20]

detection of FO was performed later. These tendencies affected the differences between the methods themselves.

Figure 4 shows that KM detected IC later than HPA and earlier than AD, and it detected FO earlier than HPA and AD. HPA detected IC earlier than AD and FO later than AD.

4. Discussion

The choice of the system used for detection will depend on a number of factors, for example the characteristics of the study itself and the evaluation requirements (indoors, outdoors, type of terrain, shod condition). For different evaluations, alternative systems may be required. Methods that automatically detect the events, such as the ones shown here, are often preferred over those that use visual inspection mainly due to the time used to visually inspect data and a reduction in subjectivity. The software associated with biomechanical systems (for example, the software included with the F-Scan measurement system, or those that determine kinematic data from motion analysis systems) normally includes routines for gait event detection. These are then used, for example, for the normalisation of data. Often the software allows the users to include personalised routines. In those cases, it could be possible to select or include a new algorithm, if it is considered more appropriate for the application.

However, in order to compare the results of research it is important to understand the impact that the method has

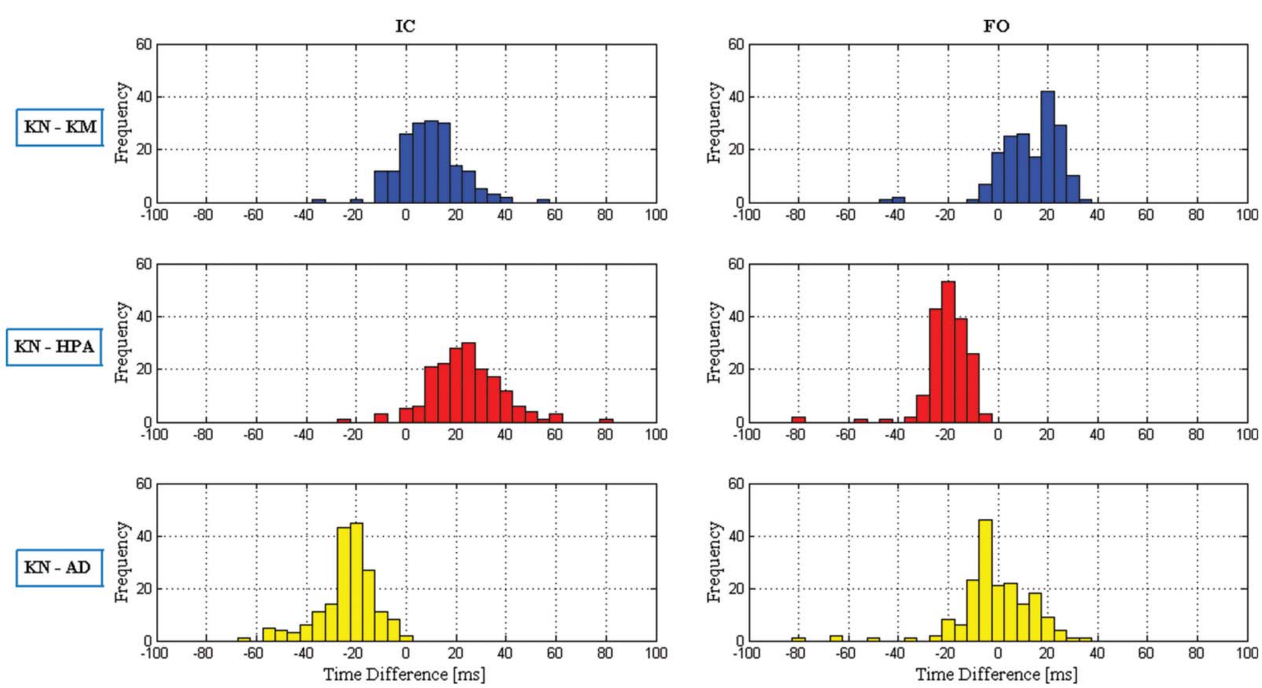

Figure 3. Frequency distribution of the time differences between the reference methods and the gold standard (KN) for IC and FO event detection. Positive differences indicate that the reference method detected the event earlier than the gold standard. N = 180.

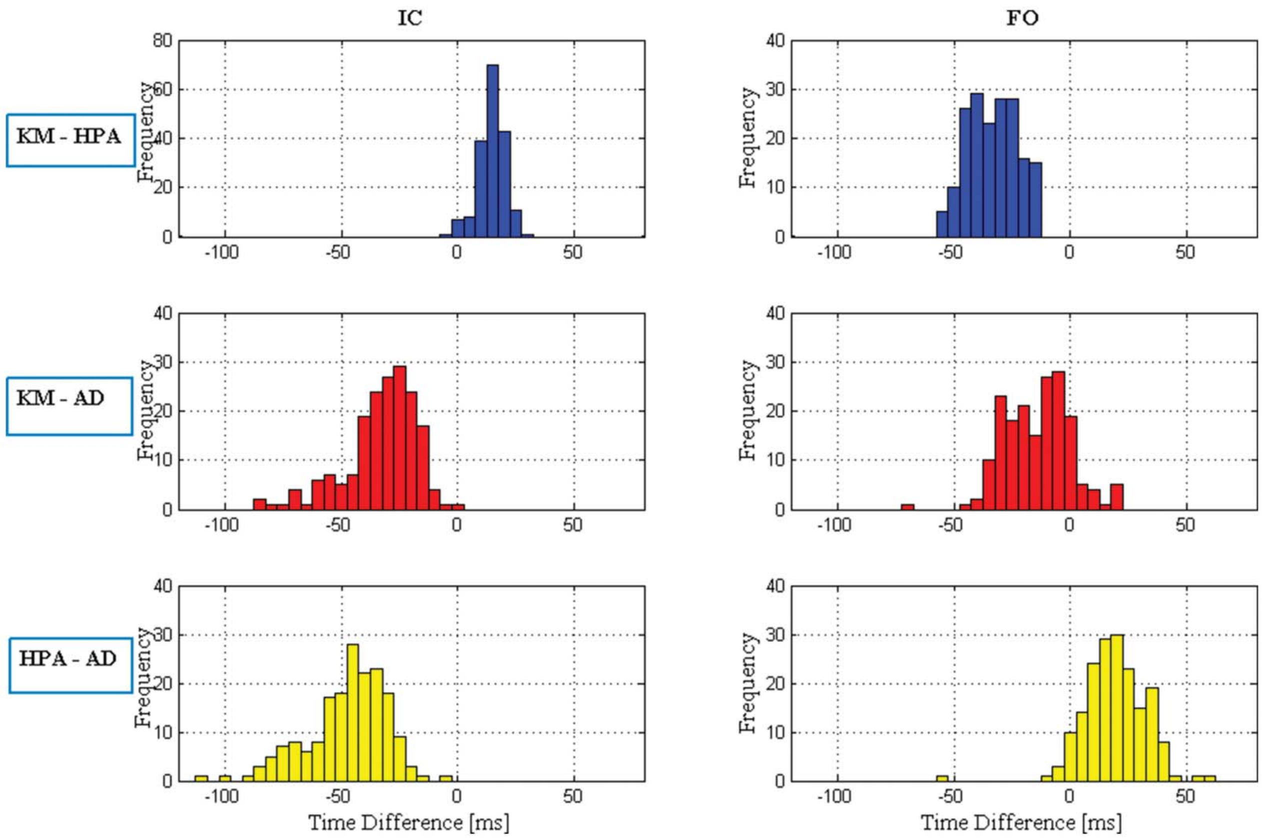

Figure 4. Frequency distribution of the time differences between the reference methods for IC and FO event detection. Positive differences indicate that the second reference method detected the event earlier than the first one: i.e. in the case of KM − HPA, positive differences indicate that the HPA method detected the event earlier than KM. N = 180.

on the evaluation of gait event detection and the calculation of spatio-temporal parameters.

The two kinematic methods selected for the present study (KM, HPA) represent only a sample of the wide variety of methods proposed in the literature, however they were considered representative enough to show trends in their comparative performance.

When comparing the reference systems used in this study (KM, HPA and AD) with the gold standard (KN), the (mean) absolute mean differences in detection of IC and FO were within 25 ms (Table 1).

Desailly *et al*. (2009) evaluated the HPA method against the gold standard (KN) for healthy adults and children with cerebral palsy (CP) walking barefoot at their self-selected speed. For healthy adults, the authors reported a mean difference between the HPA method and KN of 27 ± 19 ms for IC event detection and −14 ± 12 ms for FO. In this study, the MD between HPA and KN was 24 ± 14 for IC and -20 ± 9 for FO (Table 1), which indicates not only similar differences but also the same tendency (HPA detects IC earlier than KN and FO later than KN). The results indicate therefore that the shod

Table 2. Duration of the spatio-temporal parameters expressed in metres per second and seconds as calculated by each of the detection algorithms. N = 10.

	KN	KM	HPA	AD
Walking Speed	1.23 ± 0.15	1.23 ± 0.16	1.24 ± 0.16^{AD}	1.23 ± 0.15^{HPA}
Stance Time	0.72 ± 0.05^{HPA}	0.72 ± 0.05^{HPA}	0.77 ± 0.06$^{KN, KM, AD}$	0.70 ± 0.05^{HPA}
Double Support	0.17 ± 0.03^{HPA}	0.16 ± 0.03^{HPA}	0.21 ± 0.03$^{KN, KM, AD}$	0.14 ± 0.03^{HPA}
Step Time	0.56 ± 0.05	0.56 ± 0.05	0.56 ± 0.05^{AD}	0.56 ± 0.05^{HPA}
Single Support		0.41 ± 0.02^{HPA}	0.37 ± 0.02$^{KM, AD}$	0.43 ± 0.03 ^{HPA}
Cycle Time		1.14 ± 0.07^{HPA}	1.14 ± 0.07^{KM,AD}	1.14 ± 0.06^{HPA}

^{KN}Statistically different to KN, ^{KM} Statistically different to KM, ^{HPA} statistically different to HPA and ^{AD} statistically different to AD.

condition of the subjects has no notable effect on the performance of the algorithm (in the publication by Desailly *et al*. (2009) subjects walked barefoot while for this study subjects walked wearing footwear).

In a previous study (Catalfamo *et al*. 2008) the AD method was evaluated against the gold standard for healthy adults walking on level ground at their self-selected speed. In that study, an AMD of 22 ± 9 ms was reported for IC and 10 ± 4 ms for FO with a tendency for AD to detect IC later than KN, while the detection of FO was distributed around a difference of 0. Similar results were found in this study, with an AMD of 23 ± 11 ms for IC and 11 ± 11 for FO and similar tendencies for distribution of the events.

Ghoussayni *et al*. (2004) evaluated an algorithm that used empirically-set thresholds to the sagittal plane velocity of the heel and toe markers to detect four gait events, including IC and FO. The authors reported a mean difference (MD) of approximately −1.5 frames (with a sampling frequency 60 Hz, this is approximately −25 ms) for IC, with later detection by the kinematic method than the gold standard. For FO, the difference was approximately 6 frames (or 100 ms), with the kinematic method earlier than the gold standard. The differences observed with the results of the present study (Table 1) may have been influenced by the different thresholds applied in the studies.

Even when the detection performed by the reference methods is close to the gold standard, it is important to emphasise that the tendencies in the differences (Figure 3) affect the absolute mean difference between the methods. The AMD between HPA and AD for IC detection is 47 ms (Table 1), which is reasonable since the methods detected the event earlier and later than KN, respectively (Figure 3). The difference would represent 4.1% of the mean gait cycle. Also due to these tendencies, for the kinematic methods (KM and HPA) the AMD is 34 ms for FO detection (Table 1).

The differences in gait event detection using kinematic and pressure insoles may be related to the parameter used for detection in each case, as has been noted before (Ghoussayni *et al*. 2002). When using kinematic algorithms, the parameter used for detection is the movement of the markers, whereas when using the insole detection, the parameter used is the pressure applied on the insole. In the present study kinematic algorithms detected IC earlier than the gold standard while the AD algorithm detected it later. This may be explained by the fact that the heel marker reaches the position for IC detection earlier than a substantive loading on the foot occurs. For FO, the AD method was more evenly distributed, the HPA method detected the event later than the gold standard, whereas the KM method detected it earlier (possibly due to the threshold selection as mentioned before).

Table 2 shows that mean walking speed, step time and cycle time remained close despite the method used to compute them. These parameters were calculated using data from IC events only, suggesting that the errors in IC detection tend to be systematic for each method and get cancelled when intervals between the events are determined. Stance time, double support and single support, instead, showed more variability between the methods. In this case, the parameters were calculated using both IC and FO timings; if the tendency in the errors is consistent for both events (KM, for example detected both events earlier than KN, as seen in Figure 3), the errors tend to cancel when intervals are calculated (KM remained closer to KN for stance time and double support than the other methods). On the contrary if the tendencies are opposite for both events (HPA for example detected IC earlier and FO later than KN, as shown in Figure 3) then the errors add up when calculating intervals and the differences with the gold standard increase.

The clinical relevance of the differences found between the methods would have to be evaluated for each particular application, as part of the requirements regarding the level of accuracy of the reference system. The statistical tests performed showed statistically significant differences for a number of the parameters. In particular, the AD and HPA methods have statistically significant differences for all the spatio-temporal parameters calculated. The comparison of spatio-temporal parameters calculated with the AD method with those from KM or KN did not show a statistically significant difference. The results of the statistical tests do not establish the clinical relevance of the differences found between the methods. Therefore, their value in helping to decide which method to use is limited. They do, however, provide an awareness about the possible effects of comparing results obtained from the different reference methods. The results from this study suggest that two measures of the same spatio-temporal parameter could reach statistical significance only due to the measurement system used. This emphasises the importance of understanding the impact that the detection system has when comparing results from different investigations.

AD remained closer to KM than to HPA, indicating that the kinematic detection algorithm used for detection has a clear influence on the results. The KM method is an easy method to implement and understand. It has the limitations that the selection of an appropriate threshold may vary with different populations and that the selection may affect the results.

5. Conclusion

The choice of the system used for gait event detection will depend on the research question and the requirements for the investigation.

In order to compare results from different investigations it is important to understand the impact that the detection system has on the determination of gait event detection and the calculation of spatio-temporal parameters.

The results of the present study show that an algorithm based on data from pressure sensor insoles (AD) remained closer to a threshold-based kinematic algorithm (KM), and the spatio-temporal parameters from the two methods did not show statistical differences.

It must be stated though that although the accuracies of the reference methods are in themselves arguably acceptable for detection of gait events when compared to the gold standard, the results show that comparison between reference systems can result in notable differences in event timing and statistically significant differences for spatio-temporal parameters, depending on the algorithm used. This must be considered by investigators when comparing their findings with previous results.

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