Comparison between Defined and Total Areas of the Foot for Detection of Gait Events

J.M. Völker[1], A. Shaheen[2], D. Ewins[2], R. Acevedo[1], and P. Catalfamo[1,2,3]

[1] LIRINS, Facultad de Ingeniería, Universidad Nacional de Entre Ríos, Argentina
[2] Centre for Biomedical Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, GU2 7TE, UK
[3] Con-sejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
jmvolker@hotmail.com, {pcatalfamo,racevedo}@bioingenieria.edu.ar,
{a.shaheen,d.ewins}@surrey.ac.uk

Abstract—**The detection of the initial contact (IC) of the foot with the floor and the end of contact or foot off (FO) supports the determination of a number of spatio-temporal parameters during gait. Methods using pressure measurement systems have been proposed for detection of gait events, either using the entire area of the sole of the foot or a limited number of defined areas. Selecting the appropriate placement for the defined areas within the foot may represent a challenge for which further information is often required. The purpose of this work was to compare the detection of IC and FO using both approaches. Five healthy subjects walking on level ground were evaluated. The average mean difference between the methods was less than 10 ms for IC and less than 35 ms for FO. Also, the results showed that the number and position of the defined areas used for detection should be evaluated with care as different contact and unloading strategies were used by the participants.**

Keywords— **Analysis of human movement, gait detection, pressure measurement, insole sensors, initial contact, foot off.**

I. Introduction

Gait analysis is the systematic study of human locomotion and it is often used in sports, rehabilitation, and health diagnostics [1]. The analysis often involves the measurement, description, and assessments of temporal and spatial characteristics of human gait, known as spatio-temporal parameters [2, 3, 4].

The detection of the initial contact of the foot with the floor (IC) and the end of contact or foot off (FO) are required to calculate some of the parameters, such as cycle time, step frequency, and single and double support phases.

Force plates are the gold standard for determining IC and FO during gait. Despite their accuracy, force plates are a relatively expensive piece of equipment and the number of force platforms available (often two per gait laboratory) limits the number of steps per trial that can be recorded. These limitations and the need for portable, simple to use and relative low cost systems that could be easily included in the clinical setting have led to the development of new approaches.

Methods using pressure measurement systems have been proposed for detection of gait events [4,5]. Catalfamo et al [5] proposed a method which uses data from the entire area of the sole of the foot at any instant in time. Other researchers [6,7] have proposed the use of foot switches for detection. For this approach, only limited areas of the sole of the foot are involved in detection. The size and number of foot switches used varies depending on the investigation and the applications. For example, Popovic et al. [6] proposed the use of three foot switches placed under the heel, and the first and fifth metatarsal heads, whereas Balbinot et al [7] proposed the use of only two, placed under the heel and toe.

Selecting the appropriate area where to place the foot switches may represent a challenge for which further information may be required, especially in pathological gait [1] and also when walking on different terrains (for example, stairs) for which the pattern of contact and break of contact may change.

The purpose of this work was to compare the detection of IC and FO using a limited number of defined (sub) areas of the foot, with respect to the detection using the entire area of the foot.

II. Methods

A. Subjects

Five subjects (2 males, 3 females, 30 ± 8 years, 62.4 ± 8.6 kg, 1.68 ± 0.14 m and all right foot dominant) without discernible gait abnormalities participated in the study. The purpose of the study was explained to each subject before they were invited to give consent. The study protocol was approved by the local Ethics Committee.

B. Protocol

The subjects wore their own training shoes and were fitted with the F-Scan® Mobile portable equipment, including the insoles (Tekscan, Inc., MA. USA). New insoles were used for each participant and trimmed to the appropriate shoe size. Then the subjects were asked to walk for at least ten minutes, to ensure equilibration in the temperature of the insoles, as recommended in [8], and familiarity with the equipment.

The calibration of the insoles was performed according to the instructions in the Tekscan user manual [9], using a Step Calibration procedure.

After calibration, each subject was asked to walk at their self-selected normal speed (SS) for one minute along a 10 m

A. Braidot and A. Hadad (eds.), *VI Latin American Congress on Biomedical Engineering CLAIB 2014, Paraná, Argentina 29, 30 & 31 October 2014,*
IFMBE Proceedings 49, DOI: 10.1007/978-3-319-13117-7_62

walkway (in both directions). Then the procedure was repeated for a self selected fast speed (SSF) and self selected slow speed (SSS). The data was sampled at 200 Hz.

From the F-Scan® software the data of the total area loaded of each foot for each trial was exported.

The areas loaded of three defined sub areas were also exported: an octagon of 25 mm diameter and 2 octagons of 13 mm diameter. The octagons were placed using the auto templates and regions offered by the software (which automatically divides the sole of the foot in previously defined areas) so that the biggest polygon was placed under the heel (H) and the remaining two were placed under the first (M1) and fifth metatarsal (M5) head of each foot as suggested in [4] (Figure 1).

The placement of the defined areas (octagons) for each foot was performed for the first step of the SS trial in which the subject was considered to be walking comfortably, e.g. not speeding up or slowing down. These positions were replicated for the rest of the trials of each subject. Finally, the data for each specific area of every trial were exported to be used in detection.

Fig. 1 Placement of the areas defined in the foot using the F-Scan® software

C. Area detection algorithm

The Contact Area Detection method (AD) was implemented as described in [5]. 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 exceeds the threshold and FO is determined as the first sample, after stance, when the area signal falls below the threshold.

D. Defined area detection algorithm (DAD)

A routine was programmed in MatLab® to process the contact area of each specific area (heel, first and fifth metatarsal heads) of each foot.

The areas of the three polygons were added up for each sample. A threshold calculated as 5% of the maximum area in each trial was applied to the resultant signal (as seen in Figure 2).

The routine analyses the sum of the three defined areas of each foot to identify the IC as the first value that exceeds the threshold and FO as the first value that goes below the threshold. Unlike AD, having three different defined areas allows recovering information regarding the specific area of the foot involved in the event (i.e. the first of the three areas to contact the floor and the last area unloaded before the foot leaves the floor).

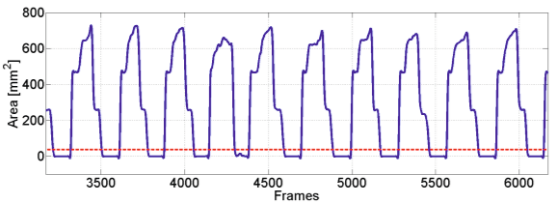

Fig 2 Total defined area (calculated as the addition of the three separately defined areas) and the 5% threshold applied to the signal

E. Data processing

One step was analysed per walk. In total, 18 IC events and 18 FO events were analysed for each subject, 3 per foot (6 per subject) per speed. The steps analysed were the ones performed in the middle of the walkway, as by then subjects should have reached a steady walking pattern [10].

The mean difference (MD) and absolute mean differences (AMD) between the methods for each event was calculated.

The absolute mean difference (AMD) between the methods for each event was calculated as:

$$\mathrm{AMD} = \sum_{i=1}^{i=N} \frac{\mathrm{Abs}\,(AD_i - DAD_i)}{\mathrm{n}}$$

Where n is the total number of steps analysed (n= 30)

The defined areas (H, M1 and/or M5) involved in the events were also analyzed. In particular, the first area loaded at IC and the last area unloaded just before FO were considered.

III. Results

A total of 90 IC and 90 FO were considered in the analysis, 30 of each for each speed condition.

The mean difference and the absolute mean difference between the AD and DAD in detection of both events, for all walking conditions (three speeds) are shown in Table 1.

Table 1 Mean difference (MD) ± standard deviation (SD) and absolute mean difference (AMD) ± standard deviation between AD and DAD, expressed in milliseconds (ms). N= 5 subjects, n=30 events per speed condition

Speed	Event	MD ± SD	AMD ± SD
SS	IC	3 ±6	6 ± 4
	FO	31 ±16	31 ± 16
SSS	IC	5 ± 7	7 ± 5
	FO	30 ± 19	30 ± 19
FSS	IC	2 ± 4	3 ± 3
	FO	27 ± 15	27 ± 15

The AMD are smaller for IC than for FO. The values are within the range of values reported in the literature when foot switches [1], wearable sensors [11] or kinematic methods [12] were used.

The AMD between AD and DAD at self-selected slow speed and self-selected fast speed were close both for IC (7 ± 5 ms and 3 ± 3 ms) and FO (30 ± 19 ms and 27 ± 15 ms) to the AMD for self-selected normal speed, suggesting that the differences between methods remain relatively unchanged with varying walking speeds.

From Table 1, the MD is always positive, indicating that the DAD method detected the events earlier than AD, particularly for FO.

Figure 3 shows the distribution of the first area loaded for IC and the last area unloaded before FO for both feet, considering a total of 90 events (45 per foot).

As can be seen in Figure 3, IC is always related to the loading of the heel of the foot in healthy participants walking on level ground. The strategy for FO however, varies between subjects and within subjects. Also a different strategy is used between feet. For more than 60% of the FO events, M1 and M5 were unloaded simultaneously for the right (dominant) foot of the participants. However, for almost 60% of the FO events for the left foot, M1 was the last area loaded.

Figure 4 shows the last area unloaded before FO for both feet, for each of the five subjects. For the right foot, for all subjects, for the majority of the events M1 and M5 were unloaded simultaneously. For the left foot, for four subjects, for more than 50% of the events the last area unloaded was M1), while one subject unloaded predominantly M1 and M5 simultaneously (S3).

The different strategies adopted by the subjects would suggest that using only two defined areas for event detection would be insufficient, and that three areas would be needed, as used in [5].

The difference between the methods is relatively small for IC. The first area loaded at IC was the heel for all subjects.

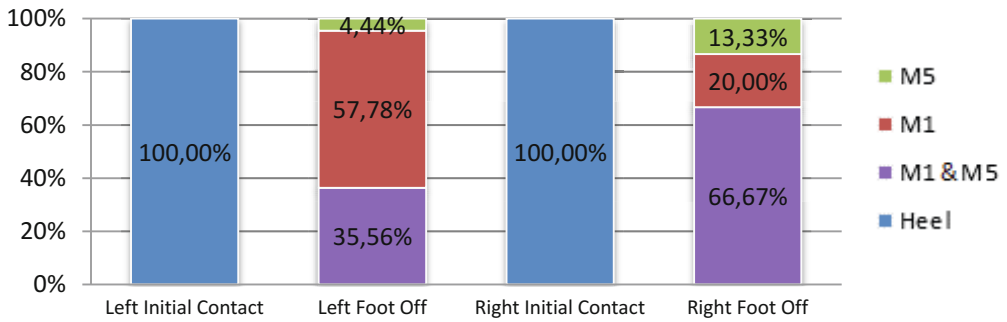

Fig. 3First area loaded at IC and last area unloaded at FO. M1: first metatarsal head, M5: fifth metatarsal head. N = 5 subjects, n = 45 events per foot

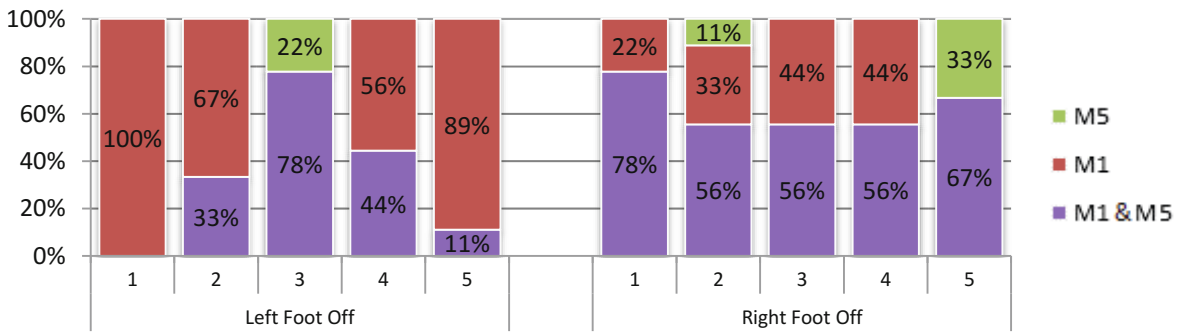

Fig. 4 Last area unloaded at FO per subject, per foot. n= 9 events per foot, per subject.

Hence, it is expected that the AD and the DAD methods remain close, given that similar areas are used for detection. In contrast, for FO, the last area unloaded varies. DAD uses only two areas, one under the first metatarsal head and one under the fifth metatarsal head. If, the last area unloaded is the toe, there will be a delay between the AD and the DAD methods (AD would detect the event later). In that case, the DAD would detect the unloading of M1 or M5, whereas the AD would detect the unloading of the toe area. It is possible that the differences in AMD between the methods for FO detection were related to this effect.

It is worth mentioning that the AD was evaluated against force platforms before [5] and showed AMD differences up to 25 ms, with a tendency to detect both events after the force platform. The results of the present study showed that DAD has a tendency to detect before the AD and is therefore likely to be closer to the values of the force platform.

IV. Conclusions

The purpose of this work was to compare the detection of IC and FO using a limited number of defined areas of the foot, with respect to the detection using the entire area of the foot.

The results of this investigation were favourable, indicating that the use of defined areas is a feasible option for gait event detection, but the minimum number of defined areas and their placement should be chosen carefully. Future work should include the study of more subjects (including both right and left foot dominant), the study of gait patterns on different terrains, e.g. stairs and ramps, and with patients with pathological gait.

Conflict of interest

The authors declare that they have no conflict of interest.

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Address of the corresponding author:

Author: Völker Juan Manuel
Institute: FI-UNER
Street: Provincial Road. 11, Km. 10
City: Oro Verde, Entre Ríos
Country: Argentina
Email: jmvolker@hotmail.com; pcatalfamo@bioingenieria.edu.ar