



Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost



Foot contact event detection using kinematic data in cerebral palsy children and normal adults gait

Eric Desailly^{a,b,*}, Yepremian Daniel^b, Philippe Sardain^a, Patrick Lacouture^a

^a Laboratoire de Mécanique des Solides, Université de Poitiers, UMR-6610, CNRS, SP2MI, BP-30179, 86962 Futuroscope Cedex, France
^b Fondation Ellen Poidatz, 77310 St Fargeau-Ponthierry, France

ARTICLE INFO

Article history:

Received 31 August 2007
Received in revised form 17 June 2008
Accepted 24 June 2008

Keywords:

Gait events
Kinematic detection
Initial contact
Toe off
Algorithm

ABSTRACT

Initial contact (IC) and toe off (TO) times are essential measurements in the analysis of temporal gait parameters, especially in cerebral palsy (CP) gait analysis. A new gait event detection algorithm, called the high pass algorithm (HPA) has been developed and is discussed in this paper. Kinematics of markers on the heel and metatarsal are used. Their forward components are high pass filtered, to amplify the contact discontinuities, thus the local extrema of the processed signal correspond to IC and TO. The accuracy and precision of HPA are compared with the gold standard of foot contact event detection, that is, force plate measurements. Furthermore HPA is compared with two other kinematics methods. This study has been conducted on 20 CP children and on eight normal adults. For normal subjects all the methods performed equally well. True errors in HPA (mean \pm standard deviation) were found to be 1 ± 23 ms for IC and 2 ± 25 ms for TO in CP children. These results were significantly ($p < 0.05$) more accurate and precise than those obtained using the other algorithms. Moreover, in the case of pathological gaits, the other methods are not suitable for IC detection when IC is flatfoot or forefoot. In conclusion, the HPA is a simple and robust algorithm, which performs equally well for adults and actually performs better when applied to the gait of CP children. It is therefore recommended as the method of choice.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

In gait analysis, a gait cycle is determined from initial contact (IC) and toe off (TO) times. Those temporal measurements are essential in cerebral palsy clinical gait analysis. They allow normalization of gait kinematics and/or kinetics, which in turn facilitates comparisons between different subjects and conditions. The reference method to determine those events is that using force plates if “clean hits” are recorded for each stance phase. This condition is not systematically satisfied and, furthermore, the number of force plates able to be used in a laboratory is limited. Other methods, such as using foot-switches or attaching accelerometers to the body are used for detecting gait events with some success. Nevertheless, they need to be accompanied by additional devices, which complicate the experimental procedure. In many situations, including the case of clinical gait analysis in children, a method of detection of those events based on kinematic data is often necessary. Different detection methods have been described

[1–5], amongst which only three use exclusively kinematic data. These are the Hreljac and Marshall method (HMA) [3], the O'Connor et al. method (FVA, standing for foot velocity algorithm) [5] and the Ghousayni et al. method [1]. The HMA and the FVA are the only ones using neither arbitrary contact detection threshold nor video frames and force plates at any stage of their detection algorithm. The Ghousayni et al. method [1] has not been included in this study since, to use it, threshold values need to be defined. That restriction renders this algorithm not completely automatic.

The HMA is established on the hypothesis that the vertical acceleration peak of the heel marker takes place at IC and that the forward acceleration peak of the metatarsal marker occurs at TO. The FVA relies on the identification of peaks and troughs in the vertical velocity signal from the midpoint of the heel and toe marker locations.

The HMA and FVA have only been tested on three cerebral palsy children [5]. The aim of the pre-test was to choose a method and it appeared that both methods presented a lack of precision regarding a population of cerebral palsy children. A new method of gait event detection was thus developed, the high pass algorithm (HPA). It is based on a high pass frequency filtering of the forward displacement signals from the foot markers. The present study evaluates the accuracy and precision of this method against the two others in pathological gait event analysis. Their applicability to

* Corresponding author at: Laboratoire de Mécanique des Solides, Université de Poitiers, UMR-6610, CNRS, SP2MI, BP-30179, 86962 Futuroscope Cedex, France. Tel.: +33 549496686; fax: +33 549496504.

E-mail address: desailly@lms.univ-poitiers.fr (E. Desailly).

normal gait analysis is also addressed. The hypothesis underlying this study is that the HPA is superior to HMA and FVA with respect to both accuracy and precision.

2. Methods

All subjects walked barefoot at a self-selected speed and only trials containing clean force plate hits on both sides were studied. Cerebral palsy children and healthy adults formed the two groups. The first group was composed of 20 patients (age 6–19 years, average 13.5 years). All of them had spastic cerebral palsy, their initial foot contacts were classified according to three categories by a rehabilitation physician: heel contact, flat contact and fore foot contact. Ten of the children had a GMFCFS level [6] of I; six were at level II and four at level III. The second group, consisting of eight healthy adults, walked normally with a heel first rocker. All experimental procedures were conducted in accordance with the declaration of Helsinki and were approved by the local ethics committee. Subjects had given their informed consent.

Kinematic data were acquired (Saga3^{RT}) simultaneously with dynamic data measured by two force plates (Kistler 9286 A) operating at frequencies of 50 Hz and 400 Hz. A set of classical clinical-purpose Helen Hayes markers was used to collect kinematic data [7]. Pelvis markers were used to calculate mean walking speed by finite differentiation. For event detection, only second metatarsal head and heel markers were used. Event detection was accomplished using the “gold standard” force plate method and the three algorithms based on kinematic data. The force plate algorithm used is a threshold method. IC is detected as the first point above 5 N before the maximum value of the ground reaction force is attained. TO is then the first point under 5 N after this maximum [2].

2.1. The Hreljac and Marshall's algorithm (HMA)

The HMA was computed as follows. The raw positions of the markers were low-pass filtered with optimal cutoff frequencies for each marker using the residual method of Winter [8] as recommended by the authors [3]. This method was repeated by Tirosh and Sparrow [9]. IC detection needs the vertical displacement and the jerk of the heel marker. IC is detected after the maximum vertical displacement of the heel marker when its jerk signal first crosses zero as it

decreases. Detection of the TO uses the horizontal displacement and the jerk of the second metatarsal head marker. Similarly, TO is detected before the maximum horizontal displacement of the second metatarsal head marker when its jerk first crosses zero as it decreases.

2.2. The foot velocity algorithm (FVA)

The FVA was not fully processed in terms of its initial description [5]. Heel and metatarsal markers were used in this algorithm. Their raw positions were low-pass filtered with a cutoff frequency of 7 Hz (zero-lag Butterworth fourth-order filters). The vertical velocity of their middle point was used. TO is still detected at the local maximum peaks of the foot middle point velocity curves. But for IC detection, the processed signal only contains a single trough in the case of equinus gait, as shown in Fig. 1, referring to the equinus column and FVA row. Therefore, the threshold level proposed by the authors in IC identification is not relevant for the above population. This threshold was initially used to eliminate the major troughs occurring during the swing phase in order to detect only the second ones after TO. To keep the FVA applicable to normal gait, this threshold method was replaced by a “retrograde” method: IC is detected at the first trough before the following TO. This “retrograde” method makes the FVA relevant for both populations. Smaller troughs during stance phase are disregarded. The “retrograde” method has been validated by a systematic visual inspection of the detected time events on the foot velocity graphics.

2.3. The high pass algorithm (HPA)

HPA is a signal process that combines elements of signal processing from the time and frequency domains. The forward displacement signal is high pass filtered (zero-lag Butterworth fourth-order filter) in order to eliminate the static offset of the signal. Maxima and minima of this processed signal correspond to the high frequencies contained in the signal. They are induced by IC and TO and therefore permit the detection of those events. The algorithm is as follows:

- The heel and metatarsal markers were used.
- All signals were low pass filtered at 7 Hz (zero-lag Butterworth fourth-order filter).

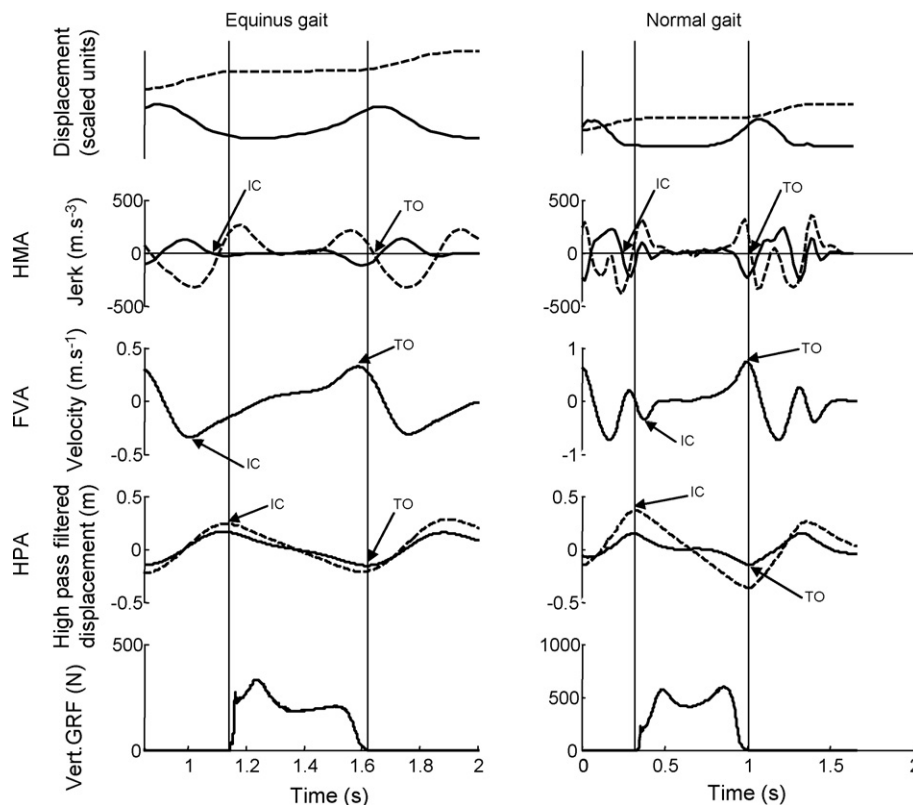


Fig. 1. Signals used in HMA, FVA, and HPA to detect IC and TO in the case of the equinus gait and the normal gait. In the first row the vertical (solid) and horizontal (dashed) raw displacements do not give clear identification of gait events. The HMA row shows the jerk of those displacements with the corresponding IC and TO detection. The FVA row shows the vertical velocity of the middle point of the foot markers and the corresponding events detection. The HPA row shows the horizontal displacement of one marker high pass filtered at 0.5 (dashed) and 1.1 (solid) of the gait frequency with the detected IC and TO. The vertical component (last row) of the ground reaction forces indicates the true times of IC and TO.

- The gait frequency was determined from the vertical component of the heel marker.
- The horizontal displacement of both markers was high pass filtered at 0.5 times the gait frequency.
- Cubic spline interpolation at the same frequency as that of the force plates was applied.
- IC was defined as the first maximum of these high passed signals.
- The horizontal displacement of both markers was then high pass filtered at 1.1 times the gait frequency.
- Cubic spline interpolation again.
- TO was defined as the last maximum of these high passed signals.

After filtering, the signals were interpolated with a spline function at the frequency of the force plates, in order to enhance the accuracy of detection.

2.4. Computations and statistical analysis

The algorithms were developed in MATLAB™. For each trial, IC and TO event times were determined using the force plate data and estimated using the kinematic methods. The true errors (TE) and absolute errors (AE) were calculated for each of the algorithms by the net or absolute differences between estimated times and event times. The number of frame errors was calculated through normalizing the AE by frame duration (20 ms). The accuracy is equivalent to the mean of the TE. The precision is the mean of the AE. The TE data were tested for normal distribution using the Kolmogorov–Smirnov test. If distributions of the data are normal, then the TE and AE can be expressed by mean and standard deviation. If not, the data are compared by median and range. The statistical differences of accuracy between the methods were tested by an ANOVA for repeated measures with a post hoc paired *t*-test after a Bonferroni correction. The statistical differences of precision between the methods were tested with a non-parametric Wilcoxon test. The significance threshold in all tests is $p < 0.05$. Data analysis was completed using the statistical program R.

3. Results

Table 1 presents statistical results for the TE and AE with respect to the three methods and the two populations studied. Mean, standard deviation, median, and range of the data are expressed.

3.1. Clinical data

In the studied population the analyzed steps are composed of 23 fore foot, 13 flat foot and four heel first contacts. Their mean speed was 0.96 ± 0.17 m/s with a range from 0.67 to 1.23 m/s.

Considering TE, the Kolmogorov–Smirnov test accepted the normalcy hypothesis in most of the conditions, the exception being IC detection in CP children using the FVA. ANOVA for repeated measures shows an effect of the algorithm variable. The post hoc paired *t*-test after a Bonferroni correction demonstrated that HPA was more accurate than both HMA and FVA in the detection of TO. The mean TE and standard deviations are presented in Fig. 2. The

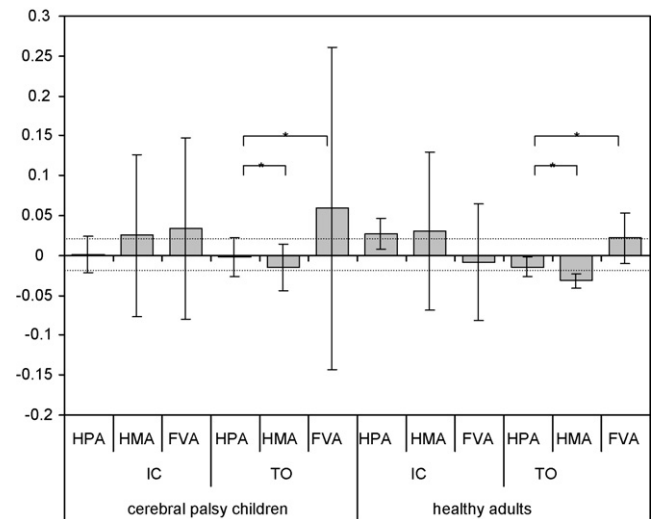


Fig. 2. Means and standard deviations of the true errors in the estimated gait event times (IC and TO) for the three tested algorithms (HPA, HMA, and FVA): for cerebral palsy children's steps ($n = 40$) and healthy adults' steps ($n = 16$). Horizontal dotted lines indicate true errors of one frame (20 ms). *Indicates a statistical difference with $p < 0.05$.

velocity curves used in the FVA showed only one major trough in 32 of the 40 steps.

In relation to AE, the Wilcoxon test shows a statistical difference between the HPA and both the HMA and the FVA in both IC and TO detection. The percentage distribution of the number of frame errors for the three tested algorithms is seen in Fig. 3. This shows the greater precision of the HPA over the HMA and the FVA. The HPA identified 75% of the IC and 66% of the TO with an AE of less than one frame (<20 ms).

3.2. Data from normal adults

In the normal adult population the mean speed was 1.2 ± 0.12 m/s with a range from 1.03 to 1.36 m/s.

Concerning TE, the Kolmogorov–Smirnov test accepted the normalcy hypothesis in all conditions. ANOVA for repeated measures shows an effect of the algorithm variable. In the post hoc paired *t*-test after Bonferroni correction, again HPA proved to be more accurate than HMA and FVA in the detection of TO. The mean TE and standard deviations are presented in Fig. 2.

As for AE, the Wilcoxon test shows there to be no statistical difference between the HPA and FVA in both IC and TO detection,

Table 1

Mean, standard deviation (S.D.), median, and range of TE in the determination of gait event times (IC and TO) for the three algorithms (HPA, HMA, and FVA) applied to the steps of cerebral palsy children and healthy adults

		Cerebral palsy children's steps ($n = 40$)						Healthy adults' steps ($n = 16$)					
		HPA		HMA		FVA		HPA		HMA		FVA	
		IC	TO	IC	TO	IC	TO	IC	TO	IC	TO	IC	TO
TE (ms)	Mean	1	-2	25	-15	34	27	27	-14	31	-28	-8	21
	S.D.	23	25	101	29	113	59	19	12	100	13	73	30
	Median	3.5	-4	-14	-15	54	41	32	-16	-29	-29	-12	14
	Min	-40	-74	-109	-68	-282	-200	-10	-28	-67	-48	-115	-17
	Max	67	60	384	58	228	133	55	18	202	-2	230	77
AE (ms)	Mean	17	18	76	26	91	54	29	17	83	28	40	25
	S.D.	15	17	71	20	74	36	17	7	61	13	60	26
	Median	12	11	47	19	74	46	32	18	57	29	20	18
	Min	0	1	9	1	3	0	2	2	4	2	0	2
	Max	67	74	384	68	282	200	55	28	202	48	230	77

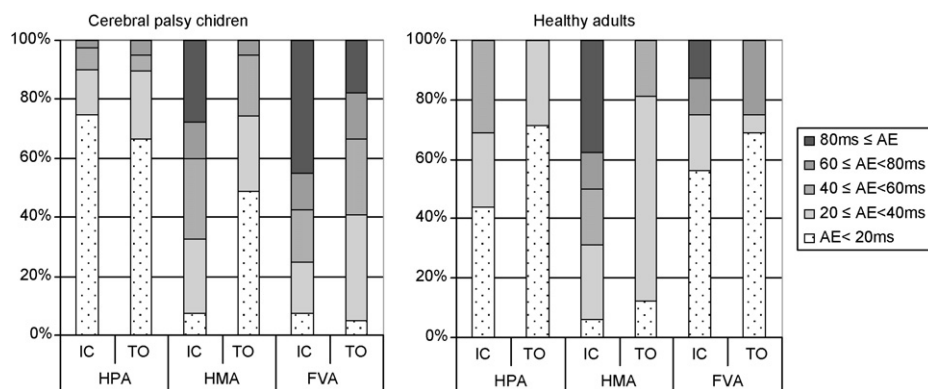


Fig. 3. Percentage distribution of number of frame errors (20 ms between each frame) in the estimated gait event times (IC and TO) for the three tested algorithms (HPA, HMA, and FVA); comparison of cerebral palsy children's steps ($n = 40$) with healthy adults' steps ($n = 16$).

while showing the greater precision of both HPA and FVA compared with HMA in IC and TO detection. The percentage distribution of the number of frame errors for the three tested algorithms is seen in Fig. 3.

4. Discussion

The determination of gait events from kinematics data is a point of importance in clinical-purpose gait studies. A detection algorithm must provide a high level of accuracy and precision for both pathological and normal gait. The HPA was developed for this purpose. The interest in this topic is confirmed by the recent publication by Zeni et al. [10] of another gait event detection algorithm. It might be productive to compare it with HPA in future research. In the present study, three algorithms, HPA, HMA and FVA, were tested on two populations.

The choice of the high pass cut off frequencies in HPA is the result of pretests, in which 0.5 and 1.1 coefficients appeared to be the best cutoff frequencies. The effect of these frequencies could be the object of another independent study. Nevertheless, one explanation for the choice of the high pass cutoff frequencies is that it corresponds to the frequency content of the signal at the detected event time. In the forward foot displacement signals, IC information contains some frequencies lower than gait frequency, while TO information contains frequencies higher than gait frequency.

The results indicated that, in the gait of normal adults, the three methods do not give comparable results. The HPA and FVA algorithms present no significant differences and both appeared more accurate and more precise than the HMA algorithm. HPA seems slightly less accurate than FVA, at the same time appearing more precise. The statistical tests show no significant differences between those two algorithms in relation to accuracy and precision. This demonstrates their convergence in performance with respect to normal gait. For FVA, the current TE results were comparable to those obtained by the authors of the method [5] (IC 16 ± 15 ms and TO 9 ± 15 ms), whereas the populations tested were different (normal adults vs. normal children populations in their study). With the HMA algorithm, the TE and the AE emerging in the present study are superior to those reported in previous studies [3,9]. Hreljac and Marshall [3] found a mean TE of 1.2 ms in both TO and IC, with a maximum TE of 13.9 ms and 11.5 ms, respectively, and AE means of 4.7 ms and 5.6 ms. Tirosh and Sparow [9] reported AE means of 10 ms and 7.4 ms for IC and TO. O'Connor et al. obtained a TE value of -8 ($-104/109$) ms for IC and of 24 ± 15 ms for TO. Having adhered to the HMA as described by their authors and as corrected in more recent work [5], as well as using an optimal filtering frequency as

recommended in Ref. [9], no explanation for the lack of accuracy of this method in the present study emerged. It should be noted, nevertheless, that the populations of the different studies are comparable neither in number nor in age. This may be part of the explanation. Besides, the present results confirm those already described in Ref. [5], that is that it is more difficult to identify IC than TO with a kinematical algorithm. This is due to the heel first rocker, which is present in normal gait and which maintains the movement of the foot markers after IC.

In pathological gait, the superiority of HPA over the two other algorithms is well-established by experimental results. The precision of HPA is much greater and, for CP children, it has here been shown to be more accurate than both HMA and FVA. As O'Connor et al. [5] point out, Hreljac and Marshall [3] never claimed their algorithm was applicable to clinical cases and the limitations of the HMA described by O'Connor et al. are confirmed [5]. As was indicated in the introduction, the FVA is not applicable in the absence of a heel first rocker. The inaccurate results obtained with this algorithm can therefore be explained because 90% of the studied population lacked a heel first rocker. This is confirmed by the foot velocity curves showing only one major trough in 32 of the 40 analyzed steps. This is a serious drawback that leads the authors to advise against using FVA for clinical purposes.

The subjects walked barefoot at a self-selected speed, as in most clinical gait studies. We therefore have no idea of the performance of the three algorithms at speeds outside the range of 0.67–1.36 m/s. Thus, despite the good results of the HPA method compared to the others, clinicians are encouraged to use force plates to check the accuracy of data outside this walking speed range.

In conclusion, the HPA is a simple and robust algorithm which, compared to others, performs equally well for the gait of adults and better for that of cerebral palsy children. This constitutes a strong argument that HPA should therefore be recommended as the method of choice.

Conflict of interest

None.

References

- [1] Ghossein S, Stevens C, Durham S, Ewins D. Assessment and validation of a simple automated method for the detection of gait events and intervals. *Gait and Posture* 2004;20:266–72.
- [2] Hansen AH, Childress DS, Meier MR. A simple method for determination of gait events. *Journal of Biomechanics* 2002;35:135–8.
- [3] Hreljac A, Marshall RN. Algorithms to determine event timing during normal walking using kinematic data. *Journal of Biomechanics* 2000;33:783–6.

- [4] Mickelborough J, Van Der Linden ML, Richards J, Ennos AR. Validity and reliability of a kinematic protocol for determining foot contact events. *Gait and Posture* 2000;11:32–7.
- [5] O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL. Automatic detection of gait events using kinematic data. *Gait and Posture* 2007;25: 469–74.
- [6] Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Developmental Medicine and Child Neurology* 1997;39: 214–23.
- [7] Davis III RB, Öunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Human Movement Science* 1991;10:575–87.
- [8] Winter DA. *Biomechanics and motor control of human movement*, 2nd ed., New York: Wiley; 1990.
- [9] Tirosh O, Sparrow WA. Identifying heel contact and toe-off using forceplate thresholds with a range of digital-filter cutoff frequencies. *Journal of Applied Biomechanics* 2003;19:178–84.
- [10] Zeni Jr JA, Richards JG, Higginson JS. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait and Posture* 2008;27:710–4.