Comparative assessment of different methods for the estimation of gait temporal parameters using a single inertial sensor: application to elderly, post-stroke, Parkinson's disease and Huntington's disease subjects

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1 Title:

Comparative assessment of different methods for the estimation of gait temporal parameters
using a single inertial sensor: application to elderly, hemiparetic, parkinsonian and choreic gait

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34 Abstract

The estimation of gait temporal parameters with inertial measurement units (IMU) is a research topic 35 of interest in clinical gait analysis. Several methods, based on the use of a single IMU mounted at 36 waist level, have been proposed for the estimate of these parameters showing satisfactory 37 38 performance when applied to the gait of healthy subjects. However, the above mentioned methods were developed and validated on healthy subjects and their applicability in pathological gait 39 conditions was not systematically explored. We tested the three best performing methods found in a 40 previous comparative study on data acquired from ten older adults, ten hemiparetic, ten Parkinson's 41 disease and ten Huntington's disease subjects. An instrumented gait mat was used as gold standard. 42 When pathological populations were analyzed, missed or extra events were found for all methods and 43 a global decrease of their performance was observed to different extents depending on the specific 44 group analyzed. The results revealed that none of the tested methods outperformed the others in 45 terms of accuracy of the gait parameters determination for all the populations except the Parkinson's 46 disease subjects group for which one of the methods performed better than others. The hemiparetic 47 48 subjects group was the most critical group to analyze (stride duration errors between 4-5 % and step duration errors between 8-13 % of the actual values across methods). Only one method provides 49 estimates of the stance and swing durations which however should be interpreted with caution in 50 pathological populations (stance duration errors between 6-14 %, swing duration errors between 10-51 32 % of the actual values across populations). 52

54 **1. Introduction**

55 The assessment of the temporal and spatial parameters of gait is commonly considered of primary importance in clinical gait analysis since it contributes to the quantitative characterization of many 56 57 common gait abnormalities. The determination of these parameters requires the detection of the initial and final foot contacts (IC and FC), usually referred to as gait events (GEs). Inertial 58 59 measurement units (IMUs), including miniature gyroscopes and accelerometers, have been increasingly employed to this purpose thanks to their high wearability, reduced cost and low power 60 consumption. The use of IMU technology is particular promising for the evaluation of gait 61 parameters while monitoring daily life activities [1-3]. In the latter context, the instrumental setup 62 63 should be even less invasive and cumbersome than in the laboratory setting, directing researchers and developers towards the use of a single IMU. To minimally alter the subject's gait, a single IMU is 64 65 often attached at the waist level so that the impact of both feet could be detected [4]. A downside of this solution is the difficulty to implement a robust and accurate method for identifying GEs, since in 66 general, the farther from the ground the IMU location, the more difficult the parameters 67 determination is. 68

In normal gait, some features of the lower trunk acceleration patterns (e.g., peaks, zero crossings) 69 were consistently associated with the occurrences of ICs and FCs [4-8]. These observations have led 70 several authors to propose methods for the detection of GEs and/or the estimate of temporal gait 71 parameters from the acceleration signals of a single IMU mounted at the waist level [9–15]. In a 72 previous study [16], we evaluated the performance of five selected methods employing a single IMU 73 74 [17,10–13] for detecting GEs and estimating gait temporal parameters on a group of healthy young 75 subjects. The comparison was carried out in terms of sensitivity and positive predicted values in 76 detecting GEs, accuracy in estimating gait temporal parameters, and robustness with respect to the 77 IMU positioning. The results reported in [16] showed an acceptable accuracy, sensitivity and 78 robustness of all the evaluated methods in determining those gait temporal parameters based on the identification of ICs (e.g., stride duration), while a lower accuracy in determining the temporal 79 parameters which also require the FCs identification (e.g., stance duration) was found. 80

The above mentioned methods were developed and validated on healthy young or elderly subjects and their applicability in pathological gait conditions was not systematically explored. The only exception is the method proposed by [9] which was later applied to pathological groups, such as amputees [18], various neurological patients [19], or patients with Parkinson's disease [20]. In most cases, only average values of the gait parameters were analyzed and caution in interpreting gait parameters was often recommended [18,19]. It seems that these methods cannot simply be extended to the analysis of pathological gaits.

Indeed, in some gait pathologies, deviations of the acceleration patterns (e.g., smaller amplitudes, 88 higher variability) from those typically observed in normal gait are not negligible [21,22]. Such 89 deviations are often due to impairments and consequent compensatory strategies. For example, 90 hemiparetic gait is often characterized by an increased lateral displacement of the foot during swing 91 in the paretic limb, consistently with limb vaulting to further assist limb clearance [23]. Other gait 92 abnormalities, such as choreiform gait, also known as "drunken gait", are characterized by staggering 93 from side to side, with lateral swaying, and stride-by-stride lateral deviations from forward direction 94 during walking [24], while parkinsonian gait is generally characterized by small shuffling steps and a 95 96 stooped posture [25].

97 The gait abnormalities described above reflect in changes of the trunk acceleration waveforms 98 which can potentially affect the performances of the single IMU based methods, thus limiting their 99 applicability in the clinical setting. The aim of this work was to propose a comparative analysis of 100 selected single IMU based methods for estimating gait temporal parameters in different pathological 101 gait conditions. To this purpose, based on the findings reported in [16], the three best performing 102 previously tested methods [9,11,12] were applied to the gait data of ten patients with hemiparesis, ten 103 patients with Parkinson's disease, ten patients with Huntington's disease, and ten healthy elderly.

For each method, we evaluated the number of missed and extra GEs, along with the total number of GEs as detected by an instrumented gait mat, used here as a gold standard. The accuracy, associated with the GEs and temporal gait parameters determination, was evaluated against reference data provided by the instrumented mat. Comparative evaluations across methods within populations (Which is best performing algorithm for a given population?) and within methods for the different populations (Does a specific algorithm perform better for a given population?) were also performed.

110

111 2. Materials and Methods

112 2.1 Tested methods

113 Schematic descriptions of the Z-method [9], S-method [11] and M-method [12] are reported in 114 Table 1; additional details can be found in the literature.

115

TABLE 1 ABOUT HERE

116 2.2. Data collection protocol

117 Instrumentation

A single IMU (OpalTM, APDM) featuring a 3-axis accelerometer and 3-axis gyroscope (unit weight 118 22 g, unit size 48.5×36.5×13.5 mm) was positioned over the subject's lumbar spine, between L4 and 119 S2, using a semi-elastic waist belt. For the selected methods, the robustness to the IMU positioning 120 along the lower trunk was found not to be a critical factor [16]. Sampling frequency was set at 128 121 Hz and accelerometer range at ± 6 g. A spot check of the MIMU performance was performed 122 according to the guidelines proposed by [26]. An instrumented gait pressure mat (GAITRiteTM 123 Electronic Walkway, CIR System Inc) acquiring at 120 Hz (spatial resolution accuracy: ±12.7 mm: 124 time accuracy: ±1 sample) was used to acquire reference data. The instrumented mat returned all GEs 125 126 and temporal parameters analyzed. The IMU and the instrumented mat were synchronized (±1 sample). 127

128 Subjects

Ten hemiparetic subjects (HE) (two females, eight males; mean (sd) age: 58.6 (12.1) v.o., height: 129 1.72 (0.06) m, mass: 82.5 (15.9) kg), ten subjects with Parkinson's disease (PD) (five females, five 130 males; mean (sd) age: 73.8 (5.7) y.o., height: 1.66 (0.10) m, mass: 67.7 (9.3) kg), ten subjects with 131 Huntington's disease (HD) (five females, five males; mean (sd) age: 50.3 (13.3) y.o., height: 1.63 132 (0.05) m, mass: 60.6 (12.2) kg), and ten healthy elderly (EL) (six females, four males; mean (sd) 133 age: 69.7 (5.8) y.o., height: 1.62 (0.08) m, mass: 63.6 (5.7) kg) were enrolled from the out-patient 134 Movement Disorders Clinic of the University of Genoa. Disease severity was determined by means 135 of the Functional Ambulatory Category (FAC) [27] for the HE subjects (3.3±1.5), the Unified 136 Huntington's Disease Rating Scale (UHDRS) [28] for the HD subjects (62.7±19.1) and the Unified 137 Parkinson's Disease Rating Scale (UPDRS) [29] for the PD subjects (34.9±16.9). The Declaration of 138 Helsinki was respected, all subjects provided informed written consent, and local ethic committee 139 140 approval was obtained.

141 *Acquisition protocol*

Subjects were asked to walk back and forth for about one minute along a 12-meter walkway with the instrumented mat placed two meters from the starting line where they stood with their feet together for a few seconds after the beginning of the IMU acquisition. Subjects walked at selfselected, comfortable speed, wearing their own shoes. Walking aids such as canes or tripods were allowed if used in daily life. A single trial including several gait cycles was recorded for each subject.

147 2.3 Data analysis

All the methods analyzed provided an estimate of the stride and step durations. In particular, the Z-method and M-method define the gait cycle from the IC timing, conversely, the S-method identifies the zero-crossing instants of the acceleration norm (these instants occur in the proximity of
the IC). Since only M-method provides FC timing estimates, stance and swing duration were
estimated only for this method.

153 Number of missed and extra GEs

The number of actual GEs (*act*-GE) were provided by the gold standard (N_{act-GE}). They could either be detected (*det-GE*) or missed (*mis-GE*) by each of the methods (N_{det-GE} , N_{mis-GE}). The GEs estimated (*est-GE*) by each method (N_{est-GE}) could be either detected or extra GEs (*ext-GE*) (N_{ext-GE}). The following relationships exist:

161 When neither mis-GEs nor ext-GE are present, the estimated GEs coincide with the act-GEs.

162 *Accuracy of the temporal parameters estimates*

163 For each method, the differences between the IC timing, stride and step duration estimates (plus FC timing, stance and swing duration for M-method) and the relevant gold standard values were 164 165 calculated. In the EL, HD and PD subjects left and right sides were not differentiated, conversely for the HE subjects, the results relative to the affected and non-affected sides were considered separately. 166 167 For each subject and each tested method, the errors (e) of the estimated GEs and gait temporal 168 parameters were computed as the averages of the above mentioned differences over the recorded gait cycles. Their group mean (μ), standard deviation (sd), mean absolute error (mae) and the relevant 169 170 percent error (mae%) were then computed.

- 171 *Statistical analysis*
- 172

173 <u>Comparative evaluations across methods within populations</u>

To verify if differences among methods were present, the following statistical tests were performed (affected and non-affected side for the HE group were dealt with separately).

A Wilcoxon signed-rank test was used to compare the *mae* values of the IC timings obtained with Z-method and M-method. Differences were considered significant if the p-value was less than 0.05. A Friedman test for non-normal distribution was used to compare the *mae* values obtained for the stride and step duration estimates across all methods for each subject group. A post-hoc analysis (Wilcoxon signed-rank test) was then performed. A Bonferroni Holm's correction for multiple comparisons was also applied.

<u>Comparative evaluations within methods for the different populations</u>
 To verify if errors obtained for each of the pathological groups were larger than those obtained for
 the EL group, for each method a Wilcoxon rank sum test was performed on the *mae* values found for
 the GEs and the gait temporal parameters. A Wilcoxon signed rank test was also performed to reveal
 differences between the mae values obtained for the affected and unaffected side in the HE subjects.
 Differences were considered significant if the p-value was less than 0.05.

189

190 **3. Results**

Over 2,253 gait cycles were obtained with the instrumented mat and used for the comparative analysis. The total number of gait cycles analyzed for each subject group along with the descriptive statistics (μ and *sd*) values of the temporal parameters (gait velocity, stride time, step time, stance time, swing time) as determined by the instrumented mat are reported in Table 2.

195

TABLE 2 ABOUT HERE

196 Number of missed and extra GEs

In Table 3 the number of mis-GEs and ext-GEs along with their percentage with respect to *act* GEs and *est*-GEs for each subjects group and each method has been reported.

199

TABLE 3 ABOUT HERE

200 Accuracy of the temporal parameters estimates

Descriptive statistics (μ and sd) of e and mae for IC timings, stride duration and step duration (for all methods) and FC timings, stance and swing time (for M-method) for all the subjects groups are reported in Table 4. The *mae*% values for stride and step durations are also reported for all the methods while *mae*% values for stance and swing durations are reported only for M-method. In Fig.1 a five number summary statistics was used to represent the *mae* values in estimating stride and step durations for each subjects group and each method.

207 **TABLE 4 ABOUT HERE**

FIGURE 1 ABOUT HERE

210

211 <u>Comparative evaluations across methods within populations</u>

No significant differences were found in the *mae* values obtained for all the gait parameters between the tested methods for all the subject groups (p>0.017) except for the PD group for which (a) IC timing errors for the Z-method were smaller than the M-methods; (b) stride time errors for the M-method were smaller than the S-method; and (c) step time errors for the Z-method were smaller than the S-method.

217

218 <u>Comparative evaluations within methods for the different populations</u>

For the Z-method, the IC timing errors, the stride time and step time errors for the HD group resulted significantly larger than those obtained for the EL group.

For the S-method, the stride time and step time errors for the HE (both affected and non affected side) and PD groups resulted significantly larger than those obtained for the EL group.

For the M-method, the IC timing errors, the stride time and step time errors for all the pathological groups (HE, PD and HD) were significantly larger than those obtained for the EL group. In addition, both stance and swing duration errors were significantly larger for the pathological groups.

226

227 4. Discussion

In the healthy elderly group, no missed or extra events were found for any of the tested methods, 228 229 confirming previous results in healthy young adults [16]. It should be noticed that in the present study, the acceleration signals were filtered before processed using the Z-method (high pass filter, 230 231 cut-off frequency 1 Hz [30]). This simple solution is extremely helpful when using the Z-method since it prevents from extra events detection associated to erroneous zero-crossing values due to the 232 signal offset. In healthy elderly, no significant differences were found for IC timings estimate errors 233 across methods. All methods showed a good accuracy level when estimating the stride duration 234 (mae% values < 2%) and an acceptable accuracy level for the step duration (mae% values < 4%). 235 Slightly larger errors were observed for the swing duration estimates provided by the M-method 236 (mae% values < 5%). 237

Conversely, when pathological populations were analyzed, missed or extra events were found and a global decrease of performance was observed to different extents depending on the specific group analyzed. The results revealed that the hemiparetic subjects group is the most critical group to analyze. In particular, the hemiparetic subjects group showed a moderate number of missed ICs when

the Z- and M- methods were applied (respectively 6% and 5% of the act-ICs), and a high number of 242 extra ICs when the S- and M methods was applied (30% and 11% of the est-ICs). The M-method also 243 returned a high number of extra FCs (13% of the det-FCs). Conversely, all methods perform very 244 well in terms of ICs detection when applied to the Parkinson's disease and Huntington's disease 245 subjects groups with the only exception of the S-method which found a moderate number of extra 246 ICs (respectively 6% and 8% of the Est-ICs). The presence of the significantly high number of 247 missed and extra events in the hemiparetic subjects can be explained by trunk acceleration patterns 248 that are much more irregular compared to normal gait also due to the use of walking aids and by the 249 250 lowest gait speed which causes a signal attenuation (mean gait speed of 0.6 m/s). On the contrary, Parkinson's disease subjects group showed the most similar performances for all the tested methods 251 252 with respect to the healthy elderly group. It is worth to notice that the presence of missed or extra GEs could greatly affect the validity of the gait temporal parameters estimates. In fact, since the gait 253 254 cycle and each sub-phase (i.e. step, stance and swing durations) are identified starting from the IC and FC timings, if any missed or extra event is present in the data, the gait parameters estimation will 255 256 be incorrect (i.e., longer or shorter stride/step/stance/swing time or higher or smaller number of gait cycles). This would potentially weaken the clinical applicability. Furthermore, the presence of extra 257 258 or missed events can be especially critical when functional electrical stimulation is adopted for a 259 proper and timely dispensing of the electrical stimuli during walking, for example [6,31].

None of the tested methods outperformed the others in terms of accuracy of the gait parameters 260 determination for all the populations except the Parkinson's disease subjects group. A general 261 decrease of the methods accuracy was observed when they were applied to pathological groups with 262 respect to healthy elderly. The accuracy analysis confirmed that the hemiparetic subjects group was 263 the most critical one for all methods and the largest errors were found for the affected side (mae%) 264 between 4% and 5% for the stride time and between 8% and 13% for the step time). The errors were 265 even larger for the estimates of the stance and swing durations provided by the M-method (mae% 266 267 between 10% and 32%).

For the Parkinson's disease subjects group, the Z-method performed relatively better than the other methods, reporting absolute errors comparable with those obtained in the healthy elderly group. No clear trends emerged for the Huntington's disease subjects group. The errors, affecting the estimates of the stance and swing durations provided by the M-method, were found to be significantly larger in the pathological groups with respect to the healthy elderly group.

In summary, on the basis of the results of this study, the following remarks can be drawn:

1) The analysis of the gait of hemiparetic subjects using a single inertial unit worn on the lower
back can be critical both in terms of missed/extra gait events and temporal parameters accuracy
irrespective of the method employed.

277 2) The Z-method, including a preliminary filtering of the acceleration signals, should be preferred278 when analyzing Parkinson's disease population.

3) The estimate of the stride duration is more reliable and valid than the step duration.

4) The estimates of the stance and swing durations in pathological population are not be reliable.

It is important to note that the results reported in the present study are referred to a straight level walking. During daily life when the subject varies the direction of progression and keeps stopping and starting, the methods performance are expected to decrease.

In conclusion, when highly impaired gait is analyzed (e.g. hemiparetic subjects), methods employing two inertial units on each leg should be preferred, at least for those gait parameters related to the accurate detection of both the ICs and FCs (e.g. stance time). In this regard, it has been recently shown [32] on similar pathological populations, that by exploiting some lower limb invariant kinematic characteristics, both missed and extra events can be avoided and that the errors can be reduced to 1% for the stride duration, 2-3 % for the step and stance durations and 6-7% for the swing.

291 Conflict of interests

292 The authors declare that they have no conflict of interests.

293

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	sensor type	sampling rate [Hz]	sensor position	estimated GEs	evaluated signals	evaluated alghoritm signals features		
Z-method* [9]	3-axis acc	100	S2	IC	antero-posterior zero crossing, j acceleration detection		GEs detection; mean step length estimate	
S-method [11]	3-axis acc	50	waist	IC	acceleration norm	sliding window summation, zero crossing	step length estimate	
M-method [12]	IMU	100	L5	IC; FC	vertical acceleration	Gaussian CWT, minima and maxima	GEs detection	

Table 1: Description of the tested gait event detection methods

(*) The acceleration signals were filtered before processed (high pass filter, cut-off frequency 1 Hz [30]).

Table 2: N	Number of gait cycles and mean (sd) of gait velocities, stride time, step time, stance time
an	nd swing time for all groups (healthy elderly – EL, hemiparetic – HE, Parkinson's disease
-]	PD and Huntington's disease – HD).

Group	gait cycles	gait velocity [m/s]	Stride time [s]	Step time [s]	Stance time [s]	Swing time [s]
EL	574	1.17 (0.16)	1.05 (0.10)	0.53 (0.05)	0.68 (0.07)	0.38 (0.03)
HE *	576	0.61 (0.24)	1.35 (0.24)	0.67 (0.12)	0.94 (0.17)	0.41 (0.10)
PD	532	0.85 (0.14)	1.14 (0.09)	0.57 (0.05)	0.76 (0.07)	0.38 (0.03)
HD	567	1.08 (0.30)	1.11 (0.14)	0.56 (0.07)	0.71 (0.10)	0.40 (0.05)

(*) Six hemiparetic subjects used a walking aid during the data acquisition sessions

- Table 3: Missed and extra GEs for all methods and their percentage (light gray: 1-3%; medium gray: 4-8%; dark gray: >9%) with respect to the number of actual and estimated GEs obtained for all groups (healthy elderly EL, hemiparetic HE, Parkinson's disease PD and Huntington's disease HD).

			% of		
Method/GE		mis-GE	act-GE	ext-GE	est-GE
	EL	0	0.0%	0	0.0%
7 mothed/IC	HE	37	6.4%	5	0.9%
Z-method/IC	PD	0	0.0%	1	0.2%
	HD	5	0.9%	5	0.9%
	EL	0	0.0%	0	0.0%
S mothod/IC	HE	3	0.5%	250	30.4%
5-method/IC	PD	2	0.4%	36	6.4%
	HD	1	0.2%	50	8.1%
	EL	0	0.0%	0	0.0%
M mathad/IC	HE	27	4.7%	13	2.3%
M-method/IC	PD	6	1.1%	0	0.0%
	HD	4	0.7%	3	0.5%
	EL	0	0.0%	0	0.0%
M mathad/EC	HE	0	0.0%	73	11.2%
M-memou/FC	PD	0	0.0%	0	0.0%
	HD	1	0.2%	5	0.9%

Table 4: Mean (μ) and standard deviation (*sd*) of the error and mean absolute error (MAE) in estimating IC timing, stride and step duration with all the methods (Z-Method, S-Method, M-Method) and FC timing, stance and swing duration with M-Method for all groups (healthy elderly - EL, hemiparetic - HE, Parkinson's disease - PD and Huntington's disease - HD). The percent mean absolute error MAE% values for stride, step, stance and swing duration estimates are also reported (light gray: 1-3%; medium gray: 4-8%; dark gray: >9%). Affected (bold) and non affected side estimate errors obtained for the H group are reported separately. Quantities are in milliseconds.

		IC		stride time		step time		FC		stance time			swing time				
Method		μ (ba)	MAE	μ (sd)	MAE	MAE%	μ (ba)	MAE	MAE%	μ (ba)	MAE	μ (sd)	MAE	MAE%	μ (sd)	MAE	MAE%
	EL	-7 (30)	21	0 (33)	20	2%	0 (36)	23	4%	-	-	-	-	-	-	-	-
thoe	HE	-11 (47)	33	1 (50)	22	2%	29 (138)	59	9%	-	-	-	-	-	-	-	-
Z-met		-84 (177)	100	2 (121)	52	4%	-29 (135)	57	8%	-	-	-	-	-	-	-	-
	PD	-7 (33)	25	0 (38)	24	2%	0 (38)	25	4%	-	-	-	-	-	-	-	-
	HD	-40 (60)	47	1 (68)	37	3%	0 (74)	46	8%	-	-	-	-	-	-	-	-
_	EL	137 <i>(51)</i>	137	0 (23)	14	1%	0 (25)	17	3%	-	-	-	-	-	-	-	-
noc	ПΕ	157 (86)	162	-4 (100)	42	3%	21 (121)	80	12%	-	-	-	-	-	-	-	-
netl	пс	131 (114)	155	-1 (140)	73	5%	-26 (139)	84	12%	-	-	-	-	-	-	-	-
S-n	PD	183 (65)	186	1 (69)	36	3%	1 (83)	49	9%	-	-	-	-	-	-	-	-
•1	HD	138 (75)	146	0 (80)	37	3%	1 (109)	57	10%	-	-	-	-	-	-	-	-
	EL	42 (23)	43	0 (13)	10	1%	0 (16)	13	2%	36 (29)	42	-6 (29)	21	3%	7 (28)	20	5%
M-method	TIE	72 (62)	81	4 (78)	26	2%	66 (170)	89	13%	-4 (78)	58	-75 (103)	94	10%	79 <i>(99)</i>	94	23%
	пе	-5 (177)	112	1 (185)	69	5%	-62 (175)	90	13%	-32 (107)	68	-27 (189)	133	14%	28 (190)	132	32%
	PD	65 (68)	75	1 (69)	24	2%	0 (91)	34	6%	34 <i>(33)</i>	40	-31 (70)	47	6%	32 (68)	46	12%
	HD	57 (62)	68	0 <i>(73)</i>	29	3%	-2 (66)	31	5%	50 (40)	56	-10 (68)	39	6%	10 (68)	38	10%

Figure 1: Minimum, first quartile (q_1) , median, third quartile (q_3) and maximum values of: (a) stride time estimate mean absolute errors (*MAE*) as obtained from each of the tested methods for each subjects group (Elderly, Parkinson, Huntington, Hemiparetic); (b) step time estimate mean absolute errors (*MAE*) as obtained from each of the tested methods for each subjects group (Elderly, Parkinson, Huntington, Hemiparetic). Errors larger than $q_1+1.5(q_3+q_1)$ or smaller than $q_1-1.5(q_3-q_1)$ are considered outliers and represented with stars. Methods are listed in the x-axis of the plots and represented by the relevant initial. Affected (gray box) and non affected side estimate errors obtained for the hemiparetic group are reported separately.

Figure 1

(a)



(b)



