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

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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Abstract

The estimation of gait temporal parameters with inertial measurement units (IMU) is a research topic of interest in clinical gait analysis. Several methods, based on the use of a single IMU mounted at waist level, have been proposed for the estimate of these parameters showing satisfactory 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 conditions was not systematically explored. We tested the three best performing methods found in a previous comparative study on data acquired from ten older adults, ten hemiparetic, ten Parkinson's disease and ten Huntington's disease subjects. An instrumented gait mat was used as gold standard. When pathological populations were analyzed, missed or extra events were found for all methods and a global decrease of their performance was observed to different extents depending on the specific group analyzed. The results revealed that none of the tested methods outperformed the others in terms of accuracy of the gait parameters determination for all the populations except the Parkinson's disease subjects group for which one of the methods performed better than others. The hemiparetic 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 estimates of the stance and swing durations which however should be interpreted with caution in pathological populations (stance duration errors between 6-14 %, swing duration errors between 10-32 % of the actual values across populations).

1. Introduction

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 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 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 consumption. The use of IMU technology is particular promising for the evaluation of gait parameters while monitoring daily life activities [1–3]. In the latter context, the instrumental setup 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 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 general, the farther from the ground the IMU location, the more difficult the parameters determination is.

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

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

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

2. Materials and Methods

2.1 Tested methods

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

TABLE 1 ABOUT HERE

2.2. Data collection protocol

Instrumentation

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

Subjects

Ten hemiparetic subjects (HE) (two females, eight males; mean (*sd*) age: 58.6 (*12.1*) y.o., height: 1.72 (*0.06*) m, mass: 82.5 (*15.9*) kg), ten subjects with Parkinson's disease (PD) (five females, five 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 Huntington's disease (HD) (five females, five males; mean (*sd*) age: 50.3 (*13.3*) y.o., height: 1.63 (*0.05*) m, mass: 60.6 (12.2) kg), and ten healthy elderly (EL) (six females, four males; mean (*sd*) 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 Movement Disorders Clinic of the University of Genoa. Disease severity was determined by means of the Functional Ambulatory Category (FAC) [27] for the HE subjects (3.3±1.5), the Unified Huntington's Disease Rating Scale (UHDRS) [28] for the HD subjects (62.7±19.1) and the Unified Parkinson's Disease Rating Scale (UPDRS) [29] for the PD subjects (34.9±16.9). The Declaration of Helsinki was respected, all subjects provided informed written consent, and local ethic committee approval was obtained.

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 self-selected, 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.

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.

Number of missed and extra GEs

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

$$0 \leq N_{det\text{-}GE} \leq N_{act\text{-}GE};$$
$$0 \leq N_{mis\text{-}GE} \leq N_{act\text{-}GE}; \quad (1)$$
$$N_{est\text{-}GE} = N_{det\text{-}GE} + N_{ext\text{-}GE};$$

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

Accuracy of the temporal parameters estimates

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 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. For each subject and each tested method, the errors (*e*) of the estimated GEs and gait temporal 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 percent error (*mae%*) were then computed.

Statistical analysis

<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.

Comparative evaluations within methods for the different populations

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.

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.

TABLE 2 ABOUT HERE

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.

TABLE 3 ABOUT HERE

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.

TABLE 4 ABOUT HERE

FIGURE 1 ABOUT HERE

Statistical analysis

Comparative evaluations across methods within populations

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.

Comparative evaluations within methods for the different populations

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.

4. Discussion

In the healthy elderly group, no missed or extra events were found for any of the tested methods, 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, 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 signal offset. In healthy elderly, no significant differences were found for IC timings estimate errors across methods. All methods showed a good accuracy level when estimating the stride duration (mae% values < 2%) and an acceptable accuracy level for the step duration (mae% values < 4%). Slightly larger errors were observed for the swing duration estimates provided by the M-method (mae% values < 5%).

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

242 the Z- and M- methods were applied (respectively 6% and 5% of the act-ICs), and a high number of
243 extra ICs when the S- and M methods was applied (30% and 11% of the est-ICs). The M-method also
244 returned a high number of extra FCs (13% of the det-FCs). Conversely, all methods perform very
245 well in terms of ICs detection when applied to the Parkinson's disease and Huntington's disease
246 subjects groups with the only exception of the S-method which found a moderate number of extra
247 ICs (respectively 6% and 8% of the Est-ICs). The presence of the significantly high number of
248 missed and extra events in the hemiparetic subjects can be explained by trunk acceleration patterns
249 that are much more irregular compared to normal gait also due to the use of walking aids and by the
250 lowest gait speed which causes a signal attenuation (mean gait speed of 0.6 m/s). On the contrary,
251 Parkinson's disease subjects group showed the most similar performances for all the tested methods
252 with respect to the healthy elderly group. It is worth to notice that the presence of missed or extra
253 GEs could greatly affect the validity of the gait temporal parameters estimates. In fact, since the gait
254 cycle and each sub-phase (i.e. step, stance and swing durations) are identified starting from the IC
255 and FC timings, if any missed or extra event is present in the data, the gait parameters estimation will
256 be incorrect (i.e., longer or shorter stride/step/stance/swing time or higher or smaller number of gait
257 cycles). This would potentially weaken the clinical applicability. Furthermore, the presence of extra
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].
260 None of the tested methods outperformed the others in terms of accuracy of the gait parameters
261 determination for all the populations except the Parkinson's disease subjects group. A general
262 decrease of the methods accuracy was observed when they were applied to pathological groups with
263 respect to healthy elderly. The accuracy analysis confirmed that the hemiparetic subjects group was
264 the most critical one for all methods and the largest errors were found for the affected side (mae%
265 between 4% and 5% for the stride time and between 8% and 13 % for the step time). The errors were
266 even larger for the estimates of the stance and swing durations provided by the M-method (mae%
267 between 10% and 32%).
268 For the Parkinson's disease subjects group, the Z-method performed relatively better than the other
269 methods, reporting absolute errors comparable with those obtained in the healthy elderly group. No
270 clear trends emerged for the Huntington's disease subjects group. The errors, affecting the estimates
271 of the stance and swing durations provided by the M-method, were found to be significantly larger in
272 the pathological groups with respect to the healthy elderly group.
273 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.

2) The Z-method, including a preliminary filtering of the acceleration signals, should be preferred 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.

Conflict of interests

The authors declare that they have no conflict of interests.

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Table 1: Description of the tested gait event detection methods

	sensor type	**sampling rate [Hz]**	**sensor position**	**estimated GEs**	**evaluated signals**	**alghoritm features**	**estimated parameters**
Z-method* [9]	3-axis acc	100	S2	IC	antero-posterior acceleration	zero crossing, peak 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

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

Table 2: Number of gait cycles and mean (*sd*) of gait velocities, stride time, step time, stance time and 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).

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

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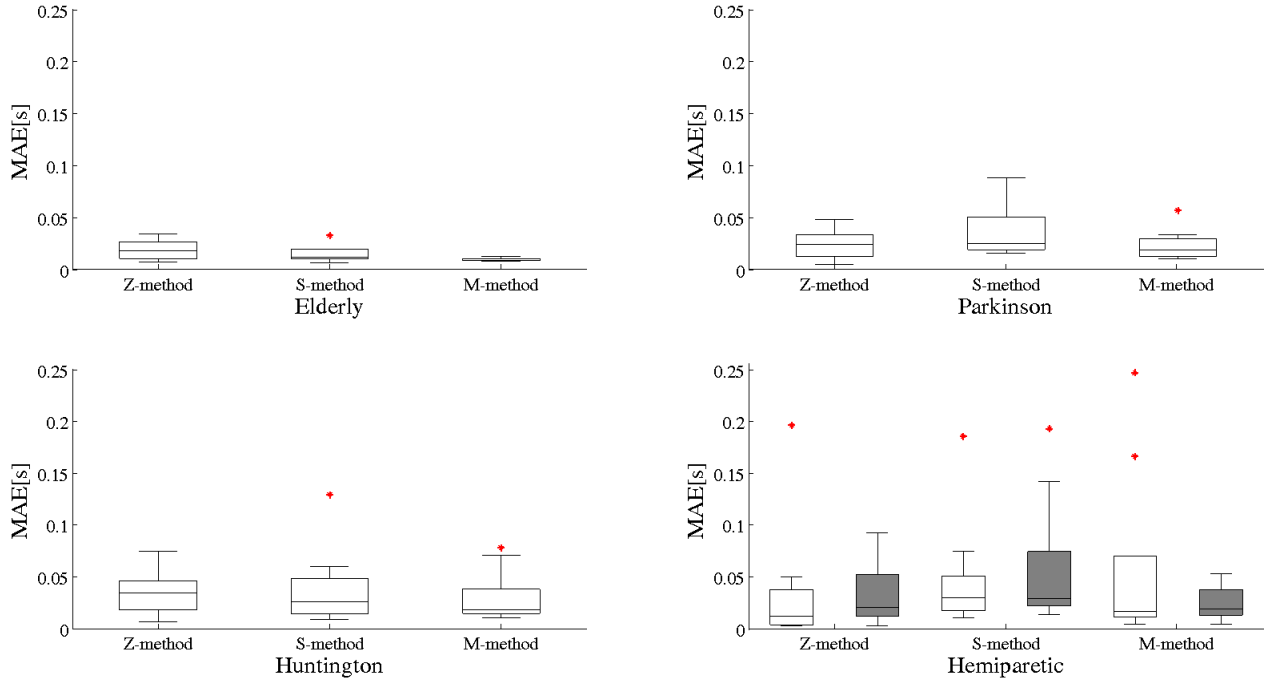
Method		IC		stride time			step time			FC		stance time			swing time		
		μ (sd)	MAE	μ (sd)	MAE	MAE%	μ (sd)	MAE	MAE%	μ (sd)	MAE	μ (sd)	MAE	MAE%	μ (sd)	MAE	MAE%
Z-method	EL	-7 *(30)*	21	0 *(33)*	20	2%	0 *(36)*	23	4%	-	-	-	-	-	-	-	-
	HE	-11 *(47)*	33	1 *(50)*	22	2%	29 *(138)*	59	9%	-	-	-	-	-	-	-	-
		-84 *(177)*	**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%	-	-	-	-	-	-	-	-
S-method	EL	137 *(51)*	137	0 *(23)*	14	1%	0 *(25)*	17	3%	-	-	-	-	-	-	-	-
	HE	157 *(86)*	162	-4 *(100)*	42	3%	21 *(121)*	80	12%	-	-	-	-	-	-	-	-
		131 *(114)*	**155**	**-1 *(140)***	**73**	**5%**	**-26 *(139)***	**84**	**12%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	PD	183 *(65)*	186	1 *(69)*	36	3%	1 *(83)*	49	9%	-	-	-	-	-	-	-	-
	HD	138 *(75)*	146	0 *(80)*	37	3%	1 *(109)*	57	10%	-	-	-	-	-	-	-	-
M-method	EL	42 *(23)*	43	0 *(13)*	10	1%	0 *(16)*	13	2%	36 *(29)*	42	-6 *(29)*	21	3%	7 *(28)*	20	5%
	HE	72 *(62)*	81	4 *(78)*	26	2%	66 *(170)*	89	13%	-4 *(78)*	58	-75 *(103)*	94	10%	79 *(99)*	94	23%
		-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 *(33)*	40	-31 *(70)*	47	6%	32 *(68)*	46	12%
	HD	57 *(62)*	68	0 *(73)*	29	3%	-2 *(66)*	31	5%	50 *(40)*	56	-10 *(68)*	39	6%	10 *(68)*	38	10%

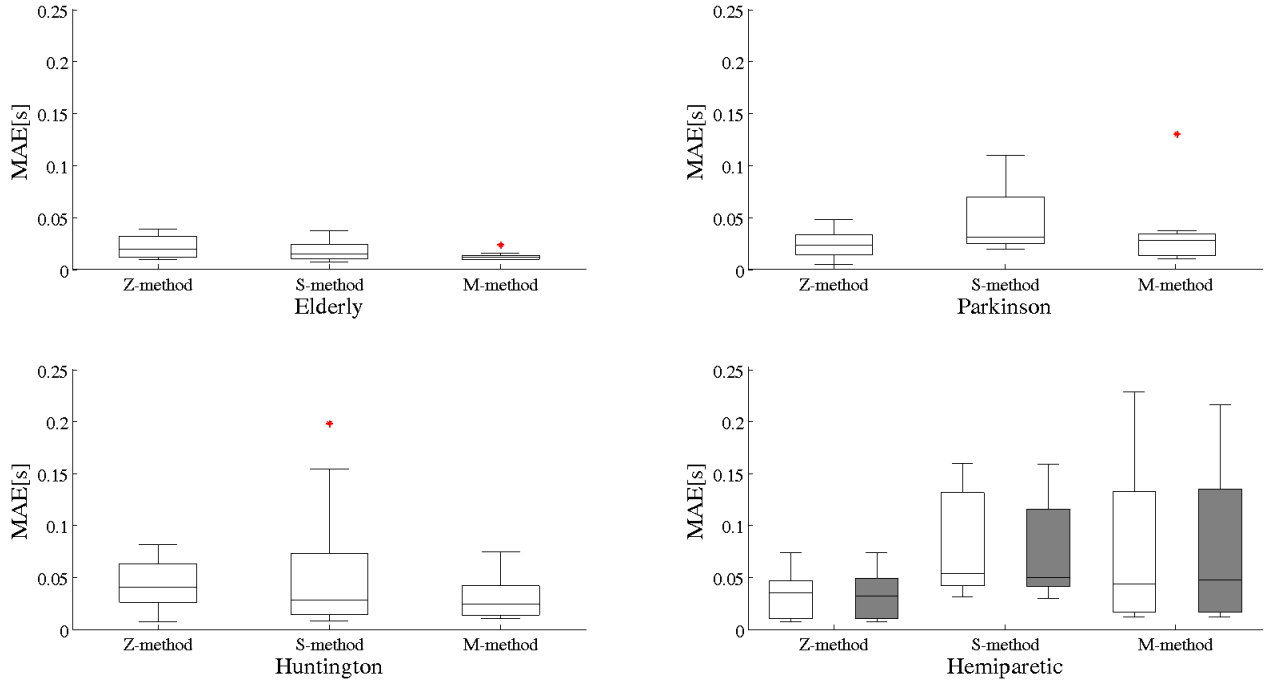
Figure 1: Minimum, first quartile (q_1), median, third quartile (q_3) and maximum values of: (a) stride time estimate mean absolute errors (*MAE*) as obtained from each of the tested methods for each subjects group (Elderly, Parkinson, Huntington, Hemiparetic); (b) step time estimate mean absolute errors (*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)


MAE[s]
0.25
0.2
0.15
0.1
0.05
0
Z-method
S-method
M-method
Elderly
Parkinson
Huntington
Hemiparetic

(b)


MAE[s]
0.25
0.2
0.15
0.1
0.05
0
Z-method
S-method
M-method
Elderly
Parkinson
Huntington
Hemiparetic