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Comparison of different methods for the estimation of gait temporal parameters using a single inertial sensor mounted on the lower trunk: application to elderly and hemiparetic subjects.

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Abstract – **The estimation of gait temporal parameters with wearable inertial measurement units (IMU) has been a research topic of interest in clinical gait analysis. Several methods, based on the use of a single IMU, have been proposed for their estimate, showing in most cases a sufficiently low number of missed and extra events and a satisfactory accuracy when applied to the gait of healthy subjects. In this study, we hypothesized that the same does not hold for abnormal gait. Some of the methods were applied to the gait of a group of hemiparetic subjects and to a group of healthy elderly. The results confirmed the hypothesis since, when applied to the hemiparetic subjects gait, all methods showed a) a higher number of missed and extra gait events detected by all tested methods, b) a significantly lower accuracy in estimating both gait events and temporal parameters. Errors in estimating gait temporal parameters were not significantly different among methods.**

I. INTRODUCTION

Temporal and spatial gait parameters, such as stride, stance and swing durations and stride and step length, are commonly considered of primary importance in clinical gait analysis since they reflect some of the most common gait abnormalities. Their determination requires the preliminary detection of the initial and final foot contacts (IC and FC), usually referred as gait events (GEs). Among the technologies that could be used to detect the GEs, inertial measurement units (IMU), a combination of miniature gyroscopes and accelerometers, have been increasingly employed. The development of miniaturized sensing technology has progressively improved their wearability, reduced their cost and power consumption.

The use of IMU technology for the estimation of temporal gait parameters has been investigated by numerous authors [1-3], in some cases with the goal of extending its use to the evaluation of gait parameters while monitoring daily life activities [4]. In the latter context, the instrumental setup should be even less invasive and cumbersome than in a laboratory setting, directing researchers and developers towards the use of a single wearable 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 [5]. A downside of such solution is the difficulty in implementing a robust and accurate method for identifying GEs, and thus determining gait temporal parameters.

In normal gait some features of the lower trunk acceleration patterns (i.e. peaks, zero crossings etc.) were found to be consistently associated with the occurrences of ICs and FCs. 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 [6-10]. However, all the above mentioned methods were validated on healthy subjects (including healthy elderly). Only the method proposed by [7] was later applied to pathological groups, such as amputees, neurological patients, or affected by Parkinson disease. In most cases, only mean values of gait parameters were analyzed and caution in interpreting gait parameters was often recommended [11].

In a previous study [12], we evaluated the performance of five methods employing a single IMU [6-10] for detecting GEs and estimating gait temporal parameters on a group of healthy subjects. The comparison was carried out in terms of sensitivity in detecting GEs, accuracy in estimating gait temporal parameters and robustness with respect to the IMU positioning.

However, the results obtained in that study could not be directly translated to pathological subjects given the high

variability of the lower trunk acceleration patterns in abnormal gait [13].

The aim of this preliminary work was to extend the analysis of the previous study to a selected pathological gait condition. To this purpose, a subset of the previously tested methods [7-9] was applied to the gait of ten hemiparetic subjects and ten healthy elderly. We hypothesized that errors associated to any of the tested methods on the gait of the hemiparetic group were larger than those obtained on the gait of the elderly group. We also investigated if the errors obtained from the different methods were significantly different from each other in both elderly and hemiparetic gait. Since for most methods the robustness to the IMU positioning along the trunk was found not to be a critical factor, in this study we placed the IMU in a single position on the lower trunk. One of the previously tested methods [10] was excluded for the asymmetric position of the IMU. A second method [6] was excluded due to its poor sensitivity [12].

For each method, the number of missed and extra GEs, along with the total number of GEs as detected by an instrumented gait mat used as gold standard was considered. The accuracy of the determination of GEs and temporal gait parameters was evaluated against reference data provided by the gold standard for all the methods and for both elderly and hemiparetic subjects.

II. MATERIALS AND METHODS

A. Tested methods

A brief description of the three methods M1 [7], M2 [8] and M3 [9] is provided in Table 1; additional details can be found in the literature [7-9].

B. Instrumentation

One IMU (Opal, APDM, Inc) was positioned over the subject's lumbar spine, between L4 and S2, using a semi-elastic waist belt (Fig. 1). Three-axial proper accelerations and angular velocities were sampled at 128 Hz. 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
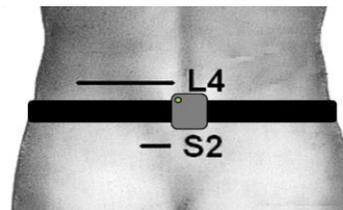

Fig. 1. IMU positioning.

parameters analyzed. The IMU and the instrumented mat were synchronized (±1 sample).

C. Subjects

The study included ten hemiparetic (H) (two females, eight males; mean (sd) age: 62 (11.8) y.o., height: 1.71 (0.06) m, mass: 79.8 (16.3) kg) and ten healthy age-matched elderly (E) (six females, four males; mean (sd) age: 69.7 (5.8) y.o., height: 1.61 (0.07) m, mass: 64 (5.7) kg) enrolled from the out-patient Movement Disorders Clinic of the University of Genoa. The H subjects were included if their Functional Ambulatory Category score, evaluating ambulation ability on a six-point scale, was greater than zero. The local ethics committee approval was obtained.

D. Acquisition protocol

Subjects were asked to walk along a 12-meter walkway with the instrumented mat placed two meters from the starting line where they stood with parallel feet for a few seconds after the beginning of the IMU acquisition. Subjects walked at self-selected comfortable speed, wearing their own shoes. Walking aids (canes or tripods) were allowed if used in daily life. A single trial including several gait cycles was recorded.

E. Data analysis

The estimates of the timing of the GE defining the gait cycle were obtained for all methods: IC timing for M1 and M3 and a peculiar GE occurring in the proximity of the IC for M2 [8]. Therefore, strides duration could be estimated for all methods.

Since only M3 provides FC timing estimates, stance and swing duration were estimated only for that method.

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
M1 [7]	3-axis acc	100	S2	IC	antero-posterior acceleration	zero crossing, peak detection	GEs detection; mean step length estimate
M2 [8]	3-axis acc	50	waist	IC (*)	acceleration norm	sliding window summation, zero crossing	step length estimate
M3 [9]	IMU	100	L5	IC; FC	vertical acceleration	gaussian CWT, minima and maxima	GEs detection

Table 2. Missed and extra GEs for all methods and their percentage with respect to the number of actual and detected GEs obtained for both the elderly (E) and hemiparetic (H) groups.

Method/GE		mis-GE	% of act-GE	det-GE	ext-GE	% of act-GE	det-GE
M1/IC	E	9	9.5	10.5	0	0	0
	H	40	27.8	38.5	0	0	0
M2/IC	E	0	0	0	0	0	0
	H	23	16.0	15.2	30	20.8	19.8
M3/IC	E	0	0	0	0	0	0
	H	19	13.2	15.2	0	0	0
M3/FC	E	0	0	0	0	0	0
	H	12	8.4	7.1	37	25.9	22

Number of missed and extra GEs

The actual GEs (*act*-GE) were provided by the gold standard. They could either be detected (*det*-GE) or missed (*mis*-GE) by each of the methods. The detected GEs could be either true or extra GEs (*ext*-GE).

Accuracy

For each method, the differences between the IC timing and stride duration estimates (plus FC timing, stance and swing duration for M3) and the relevant gold standard values were calculated. Whereas for the E subjects left and right side were not differentiated, for the H subjects, the results relative to the affected and non-affected side were considered separately. For each subject, the errors (*Err*) of the estimated GEs and gait temporal parameters was computed as the averages of the above mentioned differences over the recorded gait cycles. Their group mean, standard deviation, mean absolute error (*MAE*) and the relevant percent error (*MAE%*) were then computed.

Statistical analysis

A normality test (Shapiro-Wilk test) was performed.

To verify if errors obtained for the H group were larger than those obtained for the E group, a Wilcoxon rank sum test was performed on the MAE values obtained for all methods and all GEs and temporal gait parameters.

To verify if differences among methods were present, the following statistical tests were performed for both E and H groups (affected and non-affected side for the H group were dealt with separately). A Wilcoxon signed-rank test was used to compare the MAE values of the IC timings obtained with M1 and M3 (GEs detected by M2 are not coincident with IC timings). A Friedman test for non-normal distribution was used to compare the MAE values obtained for the stride duration estimates among all methods. A post-hoc analysis (Wilcoxon signed-rank test) was then performed. A Bonferroni Holm's correction for multiple comparisons was also applied.
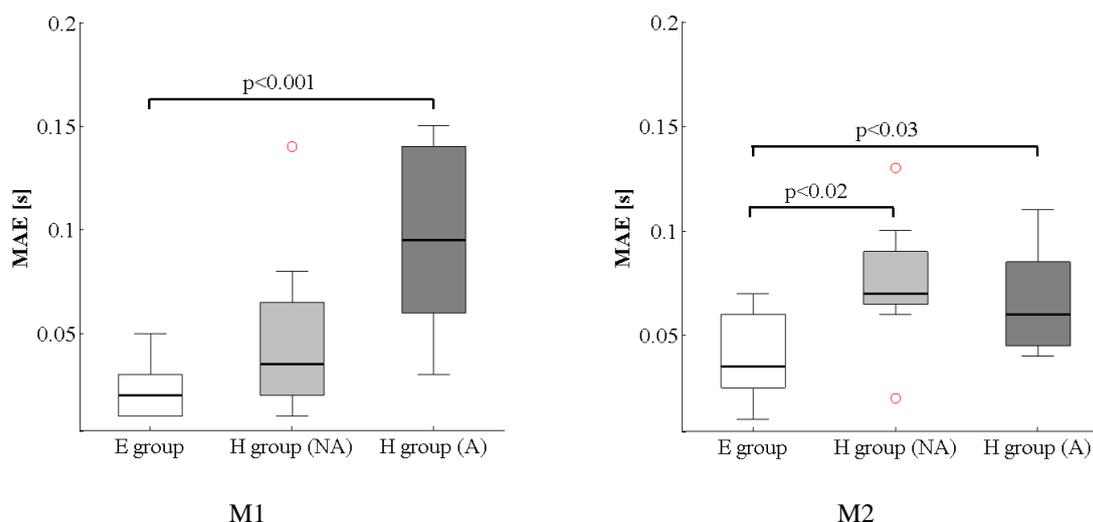

M1   M2

*Fig. 2. Minimum, first quartile (q1), median, third quartile (q3) and maximum values of **IC timing** estimate mean absolute errors (MAE) as obtained from M1 and M3 . Errors larger than q1+1.5(q3+q1) or smaller than q1−1.5(q3−q1) are considered outliers and are represented with circles. Subjects groups are listed in the x-axis of the plots and are represented by the relevant initial. For the H group, affected (A) and non affected (NA) side ICs timing estimate errors are reported separately.*

III. RESULTS

Number of missed and extra GEs

E group. The instrumented mat recorded 95 ICs and 95 FCs.

M1 was the only method presenting *mis*-ICs (9% of *act-ICs*). No *ext*-ICs were found in any of the tested methods.

No *mis*-FC nor *ext*-FC was found in M3 (Table 2).

H group. The instrumented mat recorded 144 ICs and 143 FCs.

All methods presented *mis*-ICs (28%, 17% and 13% of *act*-ICs for M1, M2 and M3, respectively). Only M2 presented *ext*-ICs (20% of *det*-ICs). For one subject, none of the tested methods was able to detect the ICs of the affected side, while in another subject only M2 was able to detect ICs of the affected side. Both subjects were excluded from the data analysis.

Both *mis*-FCs (8% of *act*-IC) and *ext*-FCs (22% of *det*-FC) were found for M3 (Table 2).

Accuracy

Mean and standard deviation values of *Err* and *MAE* for IC timings and stride duration (for all methods) for both E and H groups are reported in Table 3. The *MAE%* values for stride duration are also reported. In Table 4, the mean and standard deviation values of *Err* and *MAE*

Table 3. *Mean and standard deviation (sd) of the error and mean absolute error (MAE) in estimating IC timing and stride duration with the methods for E and H groups (affected side in darker gray background). The percent mean absolute error MAE% for stride duration estimates is also reported.*

			mean (*sd*)	*MAE*	
IC	M1	E	-18 (*34*)	35	
		H	-37 (*52*)	59	
			6 (*169*)	168	
	M2 (*)	E	135 (*67*)	137	
		H	130 (*216*)	188	
			132 (*136*)	178	
	M3	E	39 (*24*)	40	
		H	74 (*46*)	78	
			63 (*44*)	70	
			[*ms*]		*MAE %*
stride time	M1	E	3 (*32*)	19	2%
		H	3 (*40*)	25	2%
			3 (*56*)	42	3%
	M2	E	5 (*24*)	15	1%
		H	-38 (*239*)	53	4%
			-29 (*179*)	87	6%
	M3	E	2 (*13*)	10	1%
		H	-1 (*32*)	20	1%
			1 (*40*)	25	2%

(*) GEs in M2 are not explicitly referred to as ICs [8]

for FC timings, stance and swing time and *E%* values of stance and swing durations are reported for M3.

Statistical analysis

The H group was characterized on average by a stride duration about 50% longer (1.43 s) than the E group (1.06 s). Stance and swing durations were on average 0.99 s and 0.47 s for the H group and of 0.67 s and 0.39 s for the E group.

For both M1 and M3, the IC timing errors for the affected side of the H group resulted significantly larger than those obtained for the E group (for M3 the same holds for the non-affected side) (Fig. 2).

The errors in estimating the stride duration from the affected side of the H group were found to be significantly larger than those found in the E group for all tested methods (p<0.05) (Fig. 3).

The errors of M3 in estimating the FC timings were not significantly different between groups, while both stance and swing duration errors were significantly larger for the H group (Fig. 4).

No statistical differences were found in the MAE values for the IC timings between M1 and M3 (p>0.05). The Friedman test applied to the *MAE* values showed that only the estimate of the stride duration of the H group obtained from the three methods was significantly different (p<0.05). Stride duration errors in M2 were found significantly larger than those from M3; however, after applying the Bonferroni Holm's correction, no significant difference was found (p>0.017).

IV. DISCUSSION

The aim of the present study was to evaluate the performance of three different methods in determining gait temporal parameters, including GEs, in both elderly and hemiparetic groups.

Table 4. *Mean and standard deviation (sd) of the error and mean absolute error (MAE) in estimating FC timing, stance and swing duration with one method (M3) for E and H groups (affected side in darker gray background). The percent mean absolute error MAE% values for stance and swing duration estimates for M3 are also reported.*

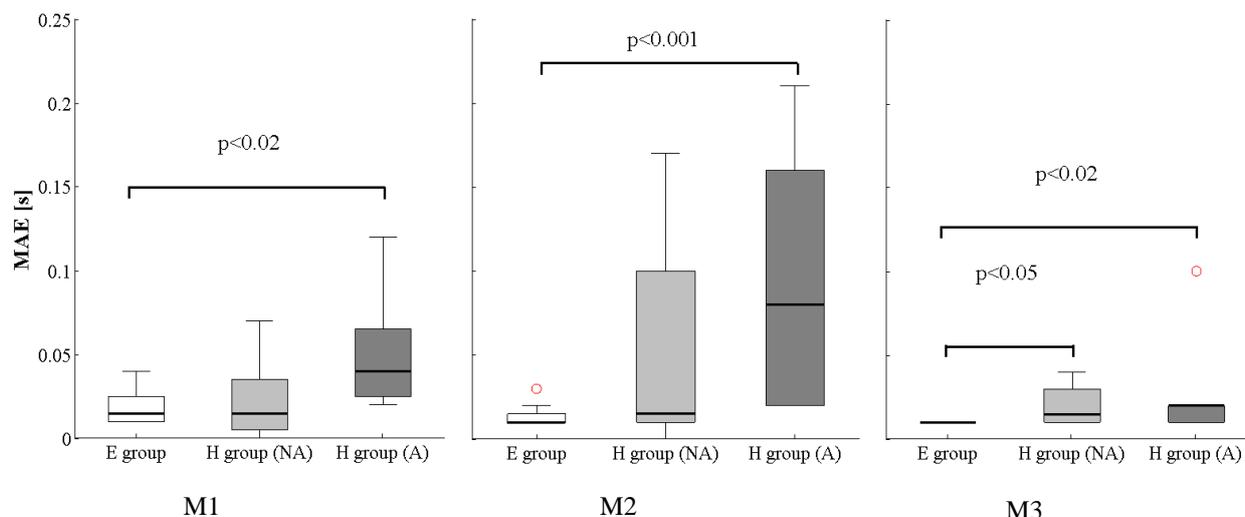|		mean (*sd*)	*MAE*	
FC	E	38 (*29*)	43	
	H	1 (*78*)	57	
		-12 (*85*)	70	
		[*ms*]		*MAE%*
stance time	E	-3 (*30*)	23	3%
	H	-76 (*96*)	91	9%
		-71 (*100*)	87	9%
swing time	E	5 (*28*)	21	5%
	H	75 (*91*)	91	21%
		72 (*100*)	86	18%

*Fig. 3. Minimum, first quartile (q1), median, third quartile (q3) and maximum values of **stride duration** estimate mean absolute errors (MAE) as obtained from M1, M2 and M3. Errors larger than q1+1.5(q3+q1) or smaller than q1–1.5(q3–q1) are considered outliers and are represented with circles. Subjects groups are listed in the x-axis and represented by the relevant initial. Affected (A) and non affected (NA) side estimate errors obtained for the H group are reported separately.*

Since M2 searches for an original repeatable event in each gait cycle in the vicinity of the IC occurrence, instead of searching for ICs, errors estimates were only compared between M1 and M3. Instead, stride duration estimate errors were compared between all tested methods. Moreover, since only M3 allows to estimate FC timings, and stance and swing durations, no statistical analysis for comparison between methods was conducted for these parameters.

In the healthy elderly group, no extra event were found for any of the tested methods while missed events were found only in M1, confirming the results obtained in our previous study [12]. The accuracy in estimating stride duration can be considered acceptable for all methods. No significant difference was found for IC timings estimate errors. Moreover, the maximum *MAE%* value found for the estimate of the stride duration was lower than 2%, confirming that all methods can effectively estimate stride duration of healthy gait. More critical is the determination of stance and swing durations provided by the M3 (*MAE%* values resulted much larger than those obtained for the stride duration).

Conversely, when applied to hemiparetic gait, the performance of all methods worsened notably. In particular, all methods missed a remarkable number of ICs (between 13% and 28% of the actual ICs) and M3 missed fewer FCs (8% of the actual FCs). On the contrary, extra events were more numerous in detecting FCs than ICs, in fact almost 20% of FCs detected by M3 were extra FCs (22% of detected FCs), while only M2 detected extra ICs (15% of detected ICs). Two hemiparetic subjects had to be excluded from the accuracy and statistical analysis, due to the higher number of missed events reported for all methods. In particular, for one subject characterized by a very low gait speed (0.44 m/s), all methods failed in detecting IC timings of the affected side. The presence of such a high number of missed and extra events is due to the great difference in the trunk acceleration signal patterns of hemiparetic with respect to normal gait.

The statistical analysis revealed that none of the tested methods outperformed the others in detecting IC timings. In hemiparetic subjects, the accuracy in estimating IC timings and stride duration highly decreased for all methods. Greater errors were found in the gait temporal parameters estimates for the affected side.

As hypothesized, in the hemiparetic group, the *MAE%* values obtained for all gait parameters were larger than those found for the elderly group. This was particularly evident for the stance and swing durations.

Significantly larger errors were found in the hemiparetic group with respect to the elderly group for both IC timing (Fig. 2) and stride duration (Fig. 3) estimates. Errors in detecting FC timings, as estimated by M3, were found not to be statistically different between the elderly and hemiparetic groups (Fig. 4). This could be explained by the fact that the estimates of FC timings were not particularly accurate also for the elderly group. As hypothesized, also stance and swing duration errors found in the hemiparetic group were larger than those found in the elderly group.

V.   CONCLUSION

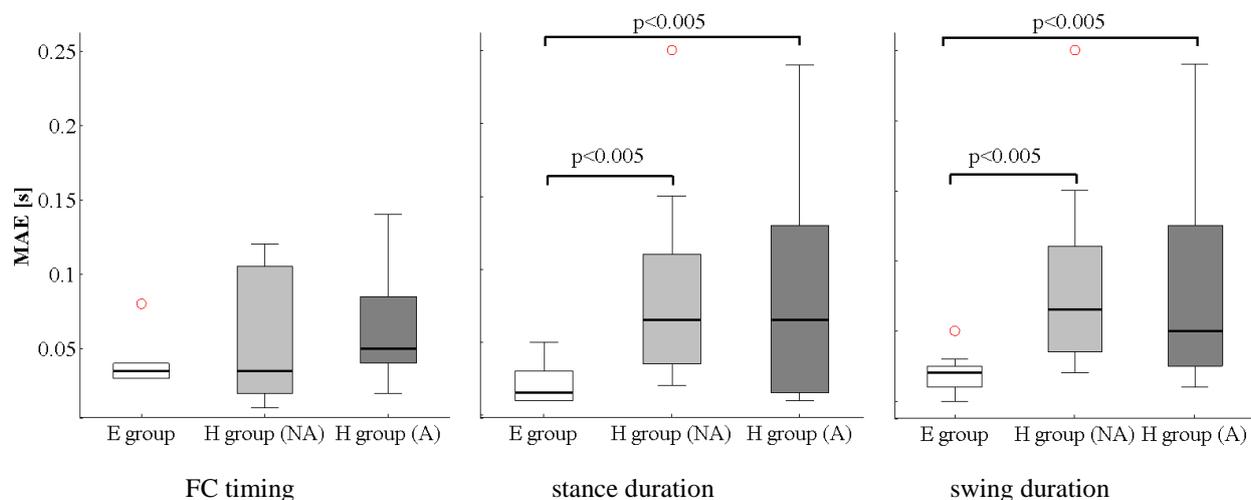The results obtained in the present study confirm our hypothesis that all tested methods dramatically reduced

*Fig. 4. Minimum, first quartile (q1), median, third quartile (q3) and maximum values of FC timings, stance and swing duration estimate mean absolute errors (MAE) as obtained from **M3**. Errors larger than q1+1.5(q3+q1) or smaller than q1–1.5(q3–q1) are considered outliers and represented with circles. Subjects groups are listed in the x-axis of the plots and are represented by the relevant initial. Affected (A) and non affected (NA) side estimate errors for the H group are reported separately.*

their performance when applied to hemiparetic gait. The higher number of missed and extra events resulting when any of the methods is applied to the gait of hemiparetic subjects, in addition to the lower accuracy of the estimates of the temporal parameters prevents from effectively using any of the tested methods.

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