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Gait Parameters of Elderly Subjects in Single-task and Dual-task with three different MIMU set-ups

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***Abstract*— The increasing average age of the population emphasizes the strong correlation between cognitive decline and gait disorders of elderly people. Wearable technologies such as magnetic inertial measurement units (MIMUs) have been ascertained as a suitable solution for gait analysis. However, the relationship between human motion and cognitive impairments should still be investigated, considering outcomes of different MIMU set-ups. Accordingly, the aim of the present study was to compare single-task and dual-task walking of an elderly population by using three different MIMU set-ups and correlated algorithms (trunk, shanks, and ankles). Gait sessions of sixteen healthy elderly subjects were registered and spatio-temporal parameters were selected as outcomes of interest. The analysis focused both on the comparison of walking conditions and on the evaluation of differences among MIMU set-ups. Results pointed out the significant effect of cognition on walking speed ($p = 0.03$) and temporal parameters ($p \leq 0.05$), but not on the symmetry of gait. In addition, the comparison among MIMU configurations highlighted a significant difference in the detection of gait stance and swing phases (for shanks-ankles comparison $p < 0.001$ in both single and dual tasks, for trunk-ankles comparison $p < 0.001$ in single task and $p < 0.01$ in dual task). Overall, cognitive impact and MIMU set-ups revealed to be fundamental aspects in the analysis of gait spatio-temporal parameters in a healthy elderly population.**

Keywords*— *aging, cognition, gait analysis, dual task, MIMU system, gait spatio-temporal parameters

I. Introduction

Nowadays, human motion analysis, biomechanics and computational human modelling are widely performed in several fields, such as medicine, sports, ergonomics and industry [1]–[4]. Concerning the clinical framework, the analysis of gait patterns has found applications for numerous attempts, especially for the description of deviation from normal behavior and the correspondent link to the pathology. Gait abnormalities are commonly described in terms of variability, kinematics and asymmetry [5], [6]. Both in pathological and elderly subjects, gait analysis contributes to the prevention of fall-risk and loss of balance [7], and allows the identification of pattern alterations, possible causes and necessary interventions (treatment and/or rehabilitation) [8].

Aging is one of the most important and unavoidable causes of gait disorders and risks of incidents [9]. Cognitive decline is a common chronic disability in elderly people and it is recognized as an independent risk factor for falls and dementia [10]. Moreover, gait abnormalities might be strongly related to cognitive impairments and, for this reason, their relation must be investigated and understood [10]. Gait assessment under dual-task or multi-task conditions has been proposed in literature as a monitoring procedure of cognitive effects on human basic activities of daily living [11]. In 2014, Howcroft and colleagues [12] studied the effects of a cognitive load (a verbal fluency task requiring the participants to say words starting with A, F, or S) during walking on elderly individuals. Data collected with insole sensors and back accelerometer highlighted differences between walking conditions, with significant increasing of stride time, stance time and swing time in case of the dual-task. In 2018, Commandeur and colleagues [13] analyzed different daily activities (single- and dual-tasks) in older adults with the attempt to select the most sensitive scores and outcomes for the prediction and classification of fall-risk. Gait spatio-temporal parameters revealed to be suitable outcomes. More recently, Hillel et al. [14] used a lower-back accelerometer to evaluate the effect of environment and cognitive load on gait. The study pointed out a significant difference in gait spatio-temporal parameters both in the comparison between single- and dual-tasks, and in the comparison between laboratory and daily living.

Considering previous studies, both observational and instrumental analyses are proposed [15]. During last decades, researchers focused on the development and validation of suitable, easy to use, small, practical and accurate wearable devices as fundamental instruments for gait analysis [16]. Among the proposed tools, magnetic inertial measurement units (MIMUs) have been identified as a suitable solution [17]. Several tests have been proposed to evaluate and compare different MIMU positions and algorithms [18], even in presence of cognitive load [19].

Previous studies on MIMUs usage for gait analysis have been conducted. The first one [20] concentrated on the validation of two different MIMU set-ups (trunk and ankles) and the corresponding algorithm for the detection of gait events. Gait trials were performed by three healthy young subjects at three different speeds (slow, normal and fast) and spatio-temporal parameters were estimated as outcomes. The comparison with a gold standard stereophotogrammetric system confirmed the suitability of both MIMU configurations, but the trunk-MIMU revealed the best accuracy. In the second study focusing on the trunk-MIMU usage [21], the experiment was extended to an elderly population. Tests were conducted by eleven healthy elderly subjects walking in four different conditions (slow speed, normal speed, fast speed and dual-task). Spatio-temporal parameters estimated with MIMUs were compared with ones obtained from stereophotogrammetric system adopted as the gold standard. The suitability, the accuracy and the robustness of the trunk-MIMU in gait evaluation were confirmed in all the tested conditions. Additional investigations might enhance the measure of the cognitive impact on gait parameters in healthy elderly subjects by means of different MIMU configurations.

According to this purpose, the aim of the present study was the comparison of single-task and dual-task walking in

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elderly participants by using three different MIMU set-ups (trunk, shanks, ankles) and algorithms [20], [22]–[25]. In detail, gait sessions of sixteen healthy elderly subjects were acquired and spatio-temporal parameters were considered as objective outcomes of interest. The analysis focused both on the comparison between single-task and dual-task walking conditions, and on the comparison of MIMU set-ups (trunk, shanks, and ankles).

II. MATERIALS & METHODS

A. Participants

A power analysis was performed prior to the experiment to define the number of participants. A normal distribution on preliminary data was assumed. The Walking Speed (m/s) was selected as the main outcome to calculate the sample size (level of significance $\alpha = 0.05$, standard deviation $\sigma = 0.12$ m/s, minimum relevant difference $\Delta = 0.10$ m/s, power level P = 80%). Consequently, sixteen healthy elderly subjects (8 males and 8 females) were recruited to participate in the experiment according to four inclusion criteria:

- age equal to or greater than 65 years old at the time of the experiment;
- no declared neurological disorders during the test;
- no musculoskeletal diseases in the last five years before the experiment;
- no external or internal prostheses.

Mean and standard deviation values of participants' anthropometric data were calculated and reported in Table I:

TABLE I. SUBJECTS' DATA (MEAN ± STANDARD DEVIATION)

Age (years)	*Height (m)*	*Weight (kg)*	*BMI (kg/m²)*
68.1 ± 4.2	1.7 ± 0.1	69.6 ± 12.8	25.1 ± 2.8

The study was approved by the Local Institutional Review Board. Procedures were conformed to the Helsinki Declaration. All participants gave their written informed consent before the beginning of the test.

B. Instruments

Five MTx MIMUs (Xsens, The Netherlands) were adopted as instruments for the experimental test. Each of them contained a tri-axial accelerometer (range ± 5 G), a tri-axial gyroscope (range ± 1200 dps) and a tri-axial magnetometer (range ± 75 μT). One MIMU was fixed through an elastic band on the trunk of participants (TRN) at the level of L1 vertebra. Other two elastic bands were used to position two MIMUs on subjects' right and left shanks (SHA) in correspondence of the proximal extremity of the tibia. Finally, two MIMUs were fixed posteriorly on participants' right and left ankles (ANK) by using a well-stretched self-adhesive gauze (Fig. 1).

MIMUs on trunk and ankles were oriented with the x-axis (x_{TRN}, x_{ANK}) pointing downward, the medio-lateral y-axis (y_{TRN}, y_{ANK}) directed toward the participant's right side and the anterior-posterior z-axis (z_{TRN}, z_{ANK}) pointing in the direction opposite to gait. MIMUs on the shanks were oriented with the x-axis (x_{SHA}) pointing downward, the medio-lateral y-axis (y_{SHA}) directed toward the participant's left side and the anterior-posterior z-axis (z_{SHA}) pointing in the same direction of gait (Fig. 1). MIMUs were connected forming a chain through cables. In addition, TRN MIMU was also connected to the control unit called Xbus Master and sending data to PC via Bluetooth. The Xsens proprietary software MT Manager was used for data acquisition at a sampling frequency of 50 Hz.

C. Protocol

The experimental test was conducted indoor in a laboratory at Politecnico di Torino. A linear walking path of 6 meters was marked on the floor as guidance for subjects. Participants were asked to walk barefoot, back-and-forth and at a self-selected comfortable speed along the path marked on the floor. The test was repeated in two different conditions: single-task and dual-task. In single-task walking condition, subjects concentrated only on walking without conducting any other activity. In dual-task condition, while walking, subjects answered questions about their habits and lives asked by researchers. For both walking conditions, all participants performed 26 back-and-forth trials along the path. Accordingly, for each subject and each walking condition, a total number of gait cycles between 150 and 300 was collected. The order of the two gait sessions was randomized for all participants. Data were acquired at the same time with the three MIMU set-ups.

D. Signal processing and data analysis

Customized Matlab routines were defined to post-process signals and analyze data acquired from both single-task and dual-task sessions of gait and from all the MIMU set-ups.

First, the average walking speed was estimated for each subject dividing the total gait path by the travel time. In detail, the total gait path was obtained only from the straight parts, without considering the gait during turn. Then, inter-subjects mean and standard deviation values of Walking Speed (m/s) were calculated for both gait conditions. The parametric paired t-test (2 tails, significance level: $\alpha = 0.05$) was conducted to investigate the statistical difference between single-task and dual-task sessions of gait.

Subsequently, registered walking trials were analyzed to identify gait events from each MIMU set-up by using three algorithms inspired by previous literature works [20], [22]–[25]. According to the first algorithm, gait events were detected from the anterior-posterior acceleration signal of trunk-MIMU. More in detail, heel-strikes (HSs) and toe-off (TOs) were selected as maximum and minimum peaks of this signal, respectively [20], [22]. Considering the second algorithm, gait events were identified from the medio-lateral angular velocities of the two shank-MIMUs [23]. HSs and TOs were chosen as the peaks following and preceding the upward concaves, respectively. Finally, the third algorithm was used to select gait events from the medio-lateral angular velocities of the two ankle-MIMUs [24], [25]. HS and TO events were detected as peaks following and preceding the upward concaves, respectively.

Once gait events were identified from each MIMU set-up through the corresponding algorithm, the following spatio-temporal parameters were calculated: Stride Time (s), Step Time (s), Stance Time (s), Swing Time (s) and Limp Index (estimated as the ratio between right and left values of Stance Time). Intra and inter-subjects mean and standard deviation values of these parameters were estimated for each MIMU set-up and for both walking conditions. According to the gait symmetry of involved subjects, parameters assessed separately for right and left sides were averaged.

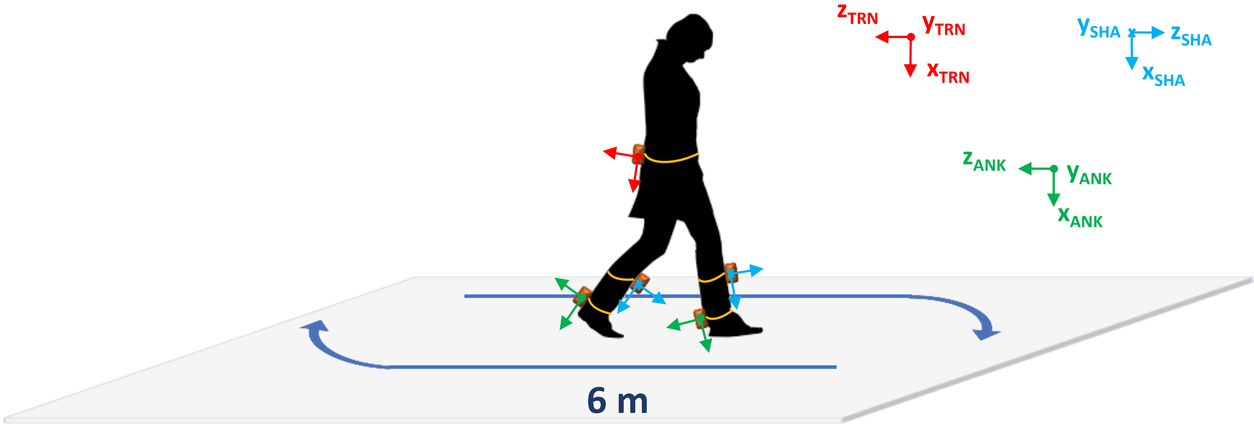

Fig. 1. Graphical representation of the walking path and the orientation of MIMU reference systems. Colors are used to distinguish among MIMU set-ups: red color for the trunk (TRN), blue color for the shanks (SHA) and green color for the ankles (ANK).

In order to implement a statistical analysis of results, the Shapiro-Wilk test was implemented to verify the normal distribution of data ($p > 0.05$). Then, the parametric paired t-test (2 tails, significance level: $\alpha = 0.05$) was conducted to compare the two walking conditions for each spatio-temporal parameter and each MIMU set-up. Moreover, the same test was repeated comparing each couple of MIMU set-ups for all gait parameters and for both walking conditions. Finally, outcomes were graphically represented through bar diagrams, stressing the comparison of walking conditions and MIMU set-ups.

III. Results

Inter-subject mean and standard deviation (std) values of Walking Speed were 0.92 ± 0.04 m/s for the single-task, and 0.87 ± 0.05 m/s for the dual-task. The parametric paired t-test (2 tails, significance level: $\alpha = 0.05$) revealed a statistically significant difference for Walking Speed between single-task and dual-task sessions of gait (p-value = 0.03).

Table II shows inter-subjects mean and standard deviation values of the spatio-temporal parameters (Stride Time, Step Time, Stance Time, Swing Time, Limp Index), estimated from each MIMU set-up (trunk, shanks, ankles) and for both single-task and dual-task conditions.

The Shapiro-Wilk test attested a normal distribution of spatio-temporal parameters among subjects ($p > 0.05$), justifying a parametric statistical analysis.

Fig. 2 shows a graphical summary of the outcomes. Bar diagrams of spatio-temporal parameters for the two walking conditions and the three MIMU set-ups are compared. In addition, statistically significant differences found with t-tests are shown above bars.

Table III contains results of the parametric paired t-test (2 tails, significance level: $\alpha = 0.05$) comparing single-task and dual-task for all gait parameters and all MIMU set-ups.

Table IV depicts results of the parametric paired t-test (2 tails, significance level: $\alpha = 0.05$) conducted to compare two different MIMUs set-ups for all gait parameters and both walking conditions.

IV. Discussions

Among different aspects of aging, cognitive decline represents a chronic disability strongly correlated with gait disorders of elderly people. Wearable devices such as inertial sensors have been proposed as a suitable solution for gait analysis. However, their usefulness in investigating the relation between human motion and cognitive impairments could be deeper analyzed, especially with the attempt to select the best sensor position.

The aim of the present study was to compare two different walking conditions (single-task and dual-task) in an elderly population through three MIMU set-ups (trunk, shanks, and ankles) and related algorithms [20], [22]–[25]. To this purpose, sixteen healthy elderly subjects were involved in the experiment and their spatio-temporal parameters were considered as objective outcomes. A statistical analysis was conducted for the comparison of both walking conditions and MIMU set-ups.

TABLE II. Gait spatio-temporal parameters estimated from each MIMUs setup and for both walking conditions

	Gait spatio-temporal parameters Mean (std)					
	Trunk		***Shanks***		***Ankles***	
	Single	***Dual***	***Single***	***Dual***	***Single***	***Dual***
Stride Time (s)	1.17 (0.02)	1.24 (0.03)	1.18 (0.02)	1.24 (0.03)	1.17 (0.02)	1.24 (0.03)
Step Time (s)	0.58 (0.01)	0.62 (0.02)	0.59 (0.01)	0.62 (0.02)	0.59 (0.02)	0.62 (0.02)
Stance Time (s)	0.72 (0.02)	0.77 (0.02)	0.73 (0.02)	0.78 (0.03)	0.69 (0.01)	0.74 (0.02)
Swing Time (s)	0.45 (0.01)	0.47 (0.01)	0.45 (0.01)	0.46 (0.01)	0.48 (0.01)	0.50 (0.01)
Limp Index	1.01 (0.01)	1.01 (0.01)	1.00 (0.01)	1.01 (0.01)	1.00 (0.01)	1.00 (0.01)

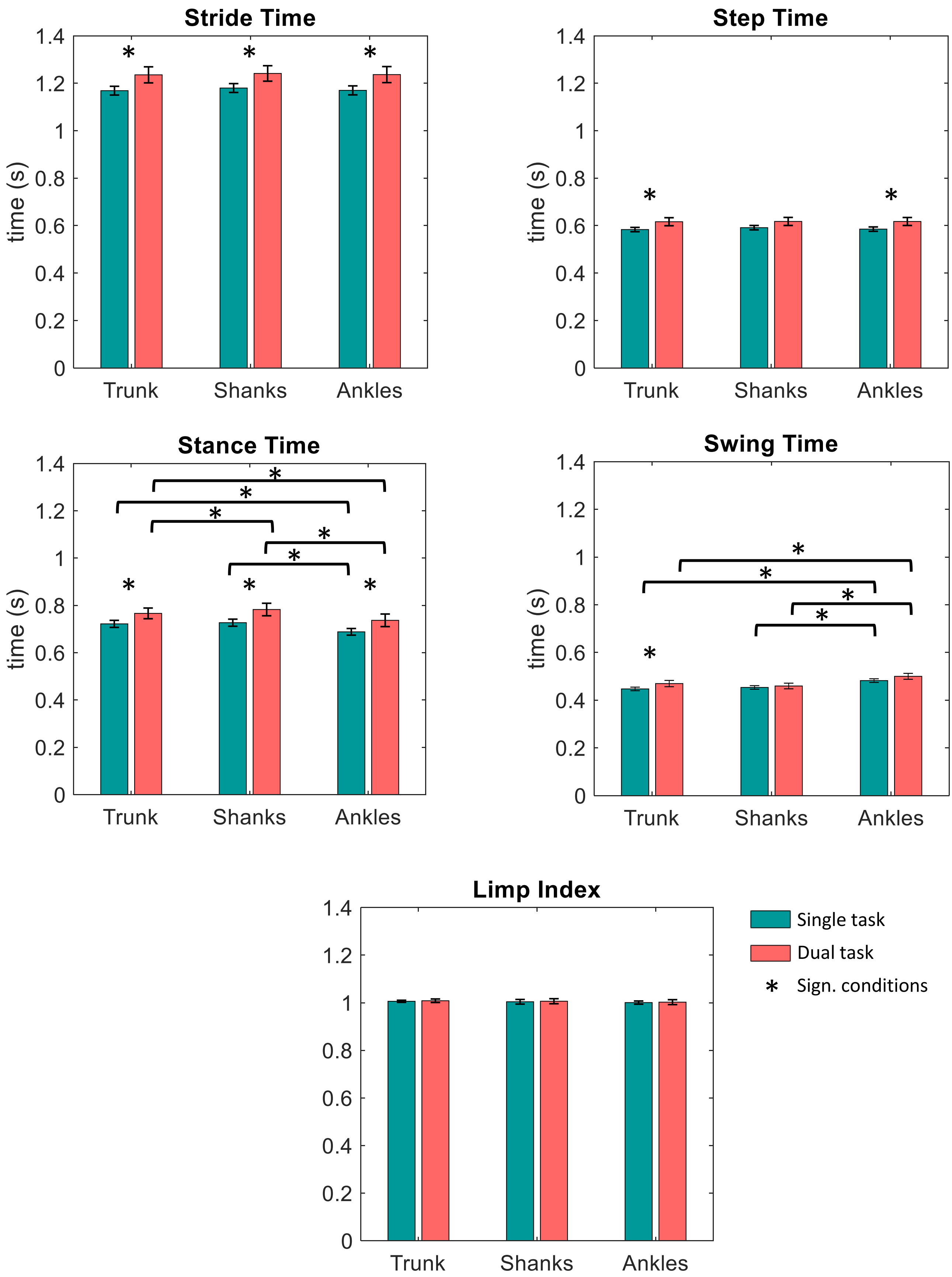

Fig. 2. Bar diagrams comparing walking conditions (single-task in dark green, dual-task in light red) and MIMU set-ups (trunk, shanks, ankles) for all gait spatio-temporal parameters (Stride Time, Step Time, Stance Time, Swing Time, Limp Index). Significant differences between walking conditions are marked by single asteriks, while significant differences among MIMU set-ups are reported by black lines below the asterisks.

TABLE III. RESULTS OF T-TEST COMPARING GAIT CONDITIONS

Comparison single - dual task gait			
	p_Value		
	Trunk	**Shanks**	**Ankles**
Stride Time (s)	**0.02**	**0.04**	**0.02**
Step Time (s)	**0.02**	0.08	**0.02**
Stance Time (s)	**0.02**	**0.02**	**0.03**
Swing Time (s)	**0.05**	0.59	0.09
Limp Index	0.73	0.83	0.75

TABLE IV. RESULTS OF T-TEST COMPARING MIMU SET-UPS

Comparison MIMU set-up						
	p_Value					
	Trunk – Shanks		**Shanks – Ankles**		**Trunk – Ankles**	
	Single	**Dual**	**Single**	**Dual**	**Single**	**Dual**
Stride Time (s)	0.22	0.18	0.27	0.24	0.41	0.32
Step Time (s)	0.13	0.26	0.21	0.89	0.21	0.14
Stance Time (s)	0.61	**0.04**	**<0.001**	**<0.001**	**<0.001**	**0.01**
Swing Time (s)	0.31	0.23	**<0.001**	**<0.001**	**<0.001**	**0.01**
Limp Index	0.86	0.88	0.74	0.79	0.51	0.62

The first analyzed outcome was the Walking Speed. A significant decrease by around 5% was registered from gait sessions with single-task to the ones with dual-task. This result is consistent with previous literature studies [12] and it confirms the impact of cognitive load on walking speed of healthy elderly subjects.

Due to the current significant difference, a comparison of spatio-temporal parameters between the two walking conditions might be important for all MIMU configurations (Table II). All set-ups confirmed that gait of involved subjects was symmetric in both walking conditions, estimating a value of Limp Index around 1.00. On the contrary, as expected [12], [14], all MIMU configurations revealed an overall increase of temporal parameters with the dual-task. Moreover, considering all MIMU set-ups, this increase stressed a significant difference in some outcomes (Table III). In particular, the trunk-MIMU depicted a significant difference between walking conditions for all temporal parameters. For this reason, the trunk-MIMU revealed to be the most accurate and sensitive set-up not only in the estimation of spatio-temporal parameters of healthy young and elderly subjects [20], [21], but also in the detection of cognitive load effects.

In addition to the comparison between walking conditions, it is important to highlight possible differences of gait parameters among different MIMU configurations (Table IV). Considering the Limp Index, as expected, all MIMU set-ups and algorithms reported the gait symmetry of tested participants both in single- and dual-task. Moreover, the location of inertial sensors did not significantly influence the estimation of Stride Time and Step Time. Nevertheless, the differentiation of gait phases showed significant differences. In detail, ankles-MIMUs arrangement outlined a significant underestimation of Stance Time (0.69 ± 0.01 s for single-task, 0.74 ± 0.02 s for dual-task) and a significant overestimation of Swing Time (0.48 ± 0.01 s for single-task, 0.50 ± 0.01 s for dual-task) with respect to the other two set-ups. This aspect might be crucial for the gait analysis of an elderly population. Indeed, in order to identify possible abnormalities of gait pattern and balance, an accurate and reliable estimation of gait phases is required. Elderly subjects carry out a cognitive strategy to compensate possible instability and fall-risk provoked by age. In particular, they increase the percentage duration of stance phase at the expense of the percentage duration of swing phase [21].

Finally, a graphical comparison of all spatio-temporal parameters, walking conditions and MIMU set-ups was represented in Fig. 2 to sum up obtained results and stress the highlighted differences.

V. CONCLUSIONS

Overall, the results obtained in this study demonstrated that the cognitive impact and MIMU set-ups are fundamental aspects in the estimation of gait spatio-temporal parameters in a healthy elderly population. More in detail, outcomes revealed the significant impact of cognition on Walking Speed and temporal parameters, but not on the gait symmetry. Moreover, comparing the MIMU set-ups, variables highlighted no significant difference in the evaluation of Stride Time, Step Time and Limp Index. On the contrary, a significant difference was found in the detection of gait phases (Stance Time and Swing Time). This could be a fundamental aspect in the analysis of gait parameters in an elderly population.

Despite interesting results obtained in this study, some limitations could be pointed out. As already reported in previous literature works, the implementation of an experimental test in a laboratory setting might influence the gait performance. Due to the portability, wearability and ease-to-use characteristics of inertial sensors, future experiments might be conducted outdoor and during living activities. A second limit deals with the introduction of one cognitive load to the gesture of walking. More complex situations with multi-tasks conditions might influence the gait performance in a different way.

Future plans are first to include the estimation of single support and double support gait phases. Indeed, these parameters can be configured as important indices of stability. Moreover, additional cognitive loads to the human gait movements could be considered to test the effects of multi-tasks activities. Due to promising outcomes, the analysis might be extended to a pathological population to evaluate the reliability and effectiveness of inertial sensors solutions in these subjects. Finally, with a larger population, a comparison between male and female subjects could be hypothesized.

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