Executive Functions Assessment Based on Wireless EEG and 3D Gait Analysis During Dual-Task

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Abstract

In this study, an EEG-based investigation of different levels of executive function activation (e.g., inhibition and working memory) during walking is performed in order to understand the executive funcions specifically involved during walking. Subjects were asked to perform the cognitive tasks by holding a wireless controller with their right hand. The wireless controller was chosen over the voice response to minimise muscle artefacts. The experimental protocol was composed by two part. In the first part, the subjects were required to execute the cognitive tasks by sitting on a chair; in the second part, the tasks were executed during walking. EEG data were collected with the wireless device ab medica Helmate composed by 10 dry electrodes positioned according to the international notation 10-20: AFz (ref), Fpz (ground), Fp1, Fp2, Fz, Cz, O1, O2, C5, and Cz. Quantitative gait assessment was performed with a 3D optoelectronic system consisting of eight Smart-D cameras at frequency of 100 Hz (BTS Bioengineering, Milan, Italy), for the calculation of spatial-temporal and kinematic parameters. 3D-stereophotogrammetric analysis was conducted using Helen Hayes M.M. markers set protocol, including 22 markers placed on the following body landmarks: spinous processes of C7 and S2, acromioclavicular joint, anterior superior iliac spine, greater trochanter, medial and lateral epicondylus femoris, fibular head, medial and lateral malleoli, I metatarsal heads and heel bilaterally.

Executive Functions Assessment Based on Wireless EEG and 3D Gait Analysis During Dual-Task

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***Abstract*—Different levels of cognitive inhibition activation during a dual task (cognitive and motor) execution were detected by means of electroencephalography (EEG). Lightweight wireless EEG device, with eight channels and dry electrodes, was used to minimized interference during spontaneous walking assessed by 3D gait analysis. Inhibition (Go-NoGo cognitive task) resulted more involved than working memory (N-Back cognitive task) during ambulation as revealed by the variation in stride length and foot progression. A significant relation was found between the increase of relative power in the delta band at Fz and inhibition activation levels in both sitting and walking conditions. No significant EEG-trends emerged for working memory during walking. This study reinforces the hypothesis of the prevalent involvement of inhibition with respect to working memory during walking, until now based only on prefrontal functional near infrared spectroscopy (fNIRS) evidences and gait speed. Moreover, the foundations are laid for EEG-based monitoring of cognitive processes involved in gait.**

***Index Terms*—Gait analysis, working memory, inhibition, EEG, dual task.**

I. Introduction

EXECUTIVE functions (EFs) are neurocognitive processes needed to organize, plan and regulate daily life actions [1]. According to Diamond et. al [2], the basic EFs are working memory, inhibition and cognitive flexibility. The working memory is the ability to keep in mind information while performing complex tasks [3]. The inhibition allows to control thoughts, behavior, and/or emotions by overcoming a strong internal predisposition or external pull [2]. The cognitive flexibility is the ability to adapt to rapidly varying circumstances [4].

EFs represent multifaceted cognitive phenomena and, consequently, are not related to specific area of the brain. Indeed, several brain regions have shown a non-random association with executive functions [5]. In particular, EFs are associated with parietal lobes, limbic areas, subcortical areas, frontal lobes, prefrontal lobe, prefrontal cortex, and cingulate cortex [6].

Many studies have shown the inability of elderly patients or with neurological disorders to manage daily activities due to the aging or damage of the above neuronal circuits [7], [8].

Therefore, the monitoring and the training of the impaired EF could be useful for early diagnosis and treatment of neurological diseases, respectively. Recently, approaches to discriminate the elemental components of FE are emerging in order to improve the effectiveness of rehabilitation. [9].

Several bio-markers are proposed in the literature for EF detection. Among them, electroencephalographic (EEG)-based methods are becoming increasingly important [10]–[12] thank to their high temporal resolution and good real-time performance [13]. The most discussed EEG features in the literature for the EFs analysis are the power spectral density (PSD), in the different bands, [14]–[16] in Fz, Cz, Pz [17]–[20], FP2 and FP1 [20]–[22], C4 and C3 [22], O1 and O2 [20], according to International System 10/20 .

The mental fatigue is a gradual and cumulative process associated with a decline in the mental efficiency due to excessive mental and/or physical activities, an impaired mental performance, or feelings of disinclination for any effort [23], [24]–[27].

EEG-based methods are widely used in the investigation of mental fatigue being sensitive to EFs [28]–[30]. In particular, EEG spectral bands variations have been extensively studied [31], [32] in Fz, Cz, Pz, Foz [13], [19], [33], [34], C3 [13].The ability to carry out cognitive tasks while simultaneously walking is one of the most essential skill for daily-life activities [35]. From last years, gait has been no longer considered as an automatic activity but as an activity influenced by EF influences. Indeed, many studies revealed an increase in cognitive–motor interference due to a greater complexity of the cognitive task [36]–[39].

According to the attentional capacity theory, people have limited cognitive capacity [40]. Consequently, the performance of two simultaneous tasks doing simultaneously two tasks requiring the same cognitive resources leads to a decrease in efficiency on one or both (dual task effect) [41], [42].

Moreover, the increase in the complexity of one or both tasks may led to a cognitive fatigue or exhaustion of cognitive resources [43], [44]. As a result, the increase in cognitive–motor interference may result in increased risk of falls and loss mobility, especially in elderly and people with neurological diseases [45]. For these reasons, rehabilitation of

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motor skills can benefit from EFs reinforcement. In particular, therapies can be more effective by focusing on the specific impaired EF.

Interaction between EFs and motor tasks is widely investigated [2], [46]–[49], especially by means of *dual task* [50]. Fingers motor tasks [36], driving simulated tasks [40], [42] and different levels of walking were explored [47], [48], [49], [51], [52], [53], [54]. The most analysed gait features are spatial-temporal parameters, such as velocity, step and stride length [47], [49], as well as EMG signal [51] for the identification of muscle time activation.

The EEG feature most investigated for the EFs detection during walking is the PSD in several bands (alpha, beta, gamma, delta and theta) [51], [52], [54]–[57].

Some limitations emerged from those studies. As far as the EEG detection is concerned, the EEG-cap was characterized by a high number of wet electrodes and wired transmission resulting in low wearabiliy. Regarding the gait analysis, studies were focused on forced and bound in place walking (e.g. on-beam gait). In this way, the spontaneous walking was not represented properly. Moreover, the analysis is limited to the spatial-temporal parameters by excluding the kinematic ones.

Recently, few studies aimed to understand EFs are specifically involved during walking. In [58], relationships between cognitive functions and walking were explored by means of fNIRS measurements and gait speed. Both neurophysiological and motion analysis highlighted a prevalent involvement of inhibition with respect to working memory during gait. However, only the prefrontal cortex was explored and gait analysis was limited to the gait speed assessment. Moreover, only the activation-no activation of executive functions were compared.

In this study, an EEG-based investigation of different levels of executive function activation during walking is performed. Healthy subjects are included in this exploratory study, based on previous evidence showing the invariance of neurophysiological features with ageing, with regard to the activation of cognitive functions in dual-tasks [58]. A spontaneous walking set up is achieved by means of a lightweight and wireless EEG device with few channels and dry electrodes. Despite the few electrodes, four different cortical areas are monitored (prefrontal, frontal, medial, occipital). Quantitative gait assessment is performed by a gold standard 3D motion analysis wich allowed to process both spatio-temporal and kinematic data. For the selective activation of inhibition and working memory, standardised cognitive tasks are employed. Moreover, the subject can implement the cognitive task by minimizing artefacts produced by vocal or gestural responses. The aim of the study is the foundation of EEG-based monitoring of cognitive processes involved in gait

The study is structured as follows: in Section II, the experimental protocol and data processing procedures are presented. Section III reports the results of the EEG, cognitive and gait analysis. Finally, the results are discussed in Sections IV.

II. Material and methods

In this section the EEG instrumentation, the experimental protocol, and the EEG and gait data processing are presented.

A. Experimental sample

Thirteen healthy subjects (5 females and 8 males, 24 ± 3 years) were involved in the study according to the following inclusion criteria: BMI $< 25\ kg/m^2$, lack of pain, right-handed, no muscle-skeletal injuries in the last 3 months, no surgical interventions in the last 6 months, no skeletal dysmorphism, and no cognitive impairment.

The volunteers were informed in detail about the goal of the experiment and signed the informed consent form for authorizing the inclusion in the study. All procedures were conducted in compliance with the Helsinki declaration. The Ethics Committee of Psychological Research of University of Naples Federico II approved the research.

B. Experimental protocol

The participants came into a silent room and sat in a comfortable chair. After the experimental protocol was described, the device for EEG acquisition was set up and the markers for gait analysis were placed (Fig 1.a). Subjects were asked to perform the cognitive tasks by holding a wireless controller with their right hand (Fig 1.c). The wireless controller was chosen over the voice response to minimise muscle artefacts. The experimental protocol was composed by two part. In the first part, the subjects were required to execute the cognitive tasks by sitting on a chair; in the second part, the tasks were executed during walking. Cognitive tasks employed for this study were:

- *Go-NoGo task*. The task mainly activates *inhibition*. Subjects had to respond (by pressing the button on the controller) or inhibit a response (by not pressing the button on the controller) depending on whether a 'go' or 'no-go' stimulus (i.e., trial) was heard. The decrease in the time between stimuli led to an increase of the task difficulty. The task was performed at two levels of difficulty: with 2-s and 1.3-s inter-trial distance in the *Go-NoGo_1* and *Go-NoGo_2*, respectively.
- *N-Back task*. The task mainly activates *working memory*. A sequence of stimuli (e.g. letters) was presented to subjects. For each stimulus (i.e., trial), they had to decide whether the current stimulus was identical to the one heard N trials before. The difficulty of the task varied according to the load factor N. The task was performed at two levels of difficulty: with $N = 1$ and $N = 2$ in the *NBack_1* and *NBack_2*, respectively.

The task stimuli were acoustically provided to guarantee a natural walking during the execution of the cognitive tasks. Each subject was asked to perform the following steps (i) while sitting and (ii) by barefoot waking on a 6 m at a self-selected normal speed:

- without concurrent tasks;
- executing the *Go-NoGo_1*;
- executing the *Go-NoGo_2*;
- executing the *N-Back_1*;
- executing the *N-Back_2*;

The gait analysis was performed in condition (ii).

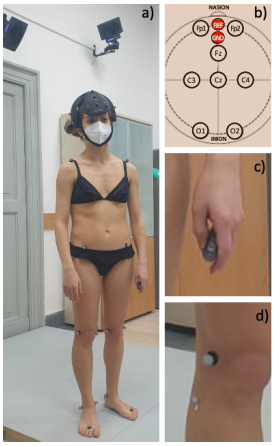

Fig. 1. Experimental set-up. Participant is wearing the EEG cap in the Gait-Analysis Lab (a). EEG channel disposition according to the International System (b). Controller used by the user to answer the cognitive task (c). One of the 22 markers placed on the participant to acquire kinematic data (d).Participant agreed to the use of the image in the publication by signing the photo release form.

C. Hardware and Software

EEG data were collected with the wireless device *ab medica Helmate* [59] and certified for clinical applications. The device is an ultralight foam helmet composed by 10 dry electrodes positioned according to the international notation 10-20: AFz (ref), Fpz (ground), Fp1, Fp2, Fz, Cz, O1, O2, C5, and C6 (Fig. 1.b).

Customised software was developed to provide the cognitive tasks, acquire and monitor the EEG signal [60]. Quantitative gait assessment was performed with a 3D optoelectronic system consisting of eight Smart-D cameras at frequency of 100 Hz (BTS Bioengineering, Milan, Italy), for the calculation of spatial-temporal and kinematic parameters. 3D-stereophotogrammetric analysis was conducted using Helen Hayes M.M. markers set protocol [61], including 22 markers placed on the following body landmarks: spinous processes of C7 and S2, acromioclavicular joint, anterior superior iliac spine, greater trochanter, medial and lateral epicondylus femoris (Fig. 1.d), fibular head, medial and lateral malleoli, I metatarsal heads and heel bilaterally.

D. EEG data processing

In the pre-processing phase, the fourth-order Butterworth bandpass filter [0.5 - 45] Hz was applied to the EEG data. Then, the removal of transient artefacts were performed by means of the *Artifact Subspace Reconstruction* (ASR) [62] with a cutoff of 15. Firstly, this method decomposes a signal into parts. Subsequently it automatically defines a threshold according to the variance distribution of the signal. Then, it discards noisy components above the threshold. Finally, it uses the remaining components to reconstruct the signal. After ASR application, the EEG traces were divided into epochs. The length of each epochs depend on the duration of the trial: in the N-Back task, each trial lasts 1.5 s at both levels of complexity, while, in the Go-No Go task, trials last 2 s or 1.3 s, for the first and second level of difficulty, respectively.

The features extracted from the signal were the PSDs computed in the alpha ([8-13] Hz), theta ([4-8] Hz), beta ([13-30] Hz), low beta ([13-20] Hz), high beta ([20-30] Hz), gamma ([30-45] Hz) and delta ([1-4] Hz) bands. In addition, the Theta-Beta Ratio (TBR) was computed. Then, for each parameter, the mean values over all the epochs were computed for the steps described in Section II-B.

Statistical analysis were performed on all the extracted features in order to find a relationship with level of executive function activation. Four analysis contexts were identified by combining the condition (sitting or walking) with the cognitive task (N-Back or Go-NoGo). For each analysis context, three levels of activation were considered by distinguishing (i) no cognitive task execution, (ii) first and (iii) second level of the cognitive task difficulty. The inter-subject Spearman rank correlation coefficients were computed to find a monotone relationship between EEG features and level of executive function activation in the four analysis contexts. Finally, the EEG features revealing the Spearman rank correlation coefficient equal to 1 or -1 (increasing or decreasing monotonic trend) were subjected to a Friedman test to determine whether the difference between the features for the various conditions was statistically significant. All statistical analysis were performed using R [63].

E. 3D Gait data processing

The raw data were processed by the Smart Analyzer (BTS-Bioengineering, Milano, Italy). Seven spatial–temporal parameters were calculated: cadence, gait speed, stance, swing and double support phases percentage, stride length, step width. Moreover, nine kinematic parameters were computed, refer to Gait Variable Scores (GVS) for lower limbs range of movement: pelvic tilt, rotation and obliquity, hip flexion–extension, adduction–abduction and rotation, knee flexion–extension, ankle dorsiflexion and foot progression). Finally, the Gait Profile Score (GPS) was obtained by the sum of the root mean square (RMS) of differences between a patient's data and a reference value related to a population of healthy individuals [64]. Higher GVS and GPS scores indicate larger deviations from a physiological gait.

Statistical differences between left and right sides for all spatial–temporal and kinematic parameters were tested via non-parametric Wilcoxon signed-rank tests. Mean values and Standard Deviations (SDs), across all trials of each session, were calculated for the spatial–temporal and k parameters. Inter-subject significant differences for all features were tested using Wilcoxon-Mann-Whitney test for six different comparisons (Walking vs N-Back_1, Walking vs N-Back_2, Walking vs Go-NoGo_1, Walking vs Go-NoGo_2, N-Back_1 vs N-Back_2 and Go-NoGo_1 vs Go-NoGo_2). All statistical analysis were performed using R [63].

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III. Results

A. EEG results

According to the Friedman test ($\alpha = 0.05$), twenty-seven features for inhibition and sixteen for working memory exhibited a statistically significant monotonic relationship with

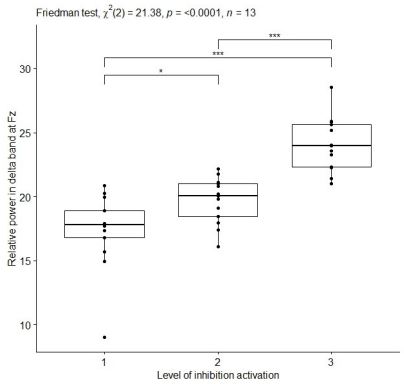

Fig. 2. Box plot of relative power in delta band at Fz (averaged on each subject) at varying levels of inhibition activation in the sitting condition. Single, double and triple asterisks denote significant difference at (p <.05), (p <.01), and (p <.001), respectively.

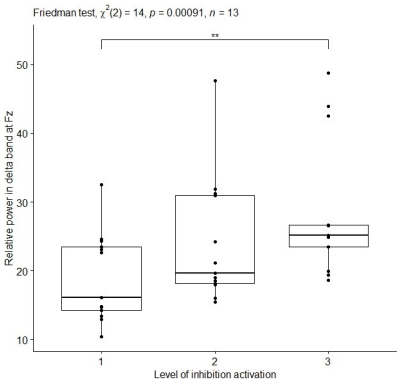

Fig. 3. Box plot of relative power in delta band at Fz (averaged on each subject) at varying levels of inhibition activation in the walking condition. Single, double and triple asterisks denote significant difference at (p <.05), (p <.01), and (p <.001), respectively.

executive function activation levels in the sitting condition. In Tab. III-A, the ten EEG features with the lower p-values are reported for each executive functions. EEG features with high effect size values (i.e., >0.8, based on benchmarks suggested by Cohen [65]) were: (i) relative power in delta band at Fz during Go-NoGo execution by sitting ($\chi^2(2) = 21.40$, $p = 0.0002$, effect size= 0.82), (ii) relative power in delta band at C3 during Go-NoGo execution by sitting ($\chi^2(2) = 24.20$, $p = 0.0001$, effect size= 0.93), and (iii) absolute power in high beta band at Fz during N-Back execution by sitting ($\chi^2(2) = 20.20$, $p = 0.0004$, effect size= 0.92). In the last case, two subjects were excluded from the statistical analysis due to technical problems. Box plots of the values of the three aforementioned EEG features are reported in Figs. 2, 4, and 5 for Relative delta power at Fz, C3 and Absolute delta power at Fz, respectively.

The results of the Friedman test were confirmed by a further Spearman rank correlation analysis conducted at the level of single subjects. This analysis was restricted to the EEG features with high effect size for both executive functions. In particular, the absolute power in high beta band at Fz for the working memory and the relative power in delta band at C3 and Fz for the inhibition. In Tabs. II and III, Spearman's rank correlation coefficient is shown for the selected EEG features in the selected channel compared with EEG features in the same band in the other channels. This analysis showed that the monotonicity at the EEG features and levels of activation of the executive functions was also confirmed at the individual subject level, for at least 10/13 subjects.

The high effect size of sitting condition was not confirmed for the same EEG features during walking. Moreover, the results of the Friedman test revealed a p-value greater than 0.05, in the case of N Back for absolute high beta at Fz. Only for the Relative power in delta band at Fz, a medium (i.e., > 0.5) effect size emerged during walking ($\chi^2(2) = 14.00$, $p = 0.00091$, effect size= 0.54). For this feature, the bloxplot is reported in Fig. 3.

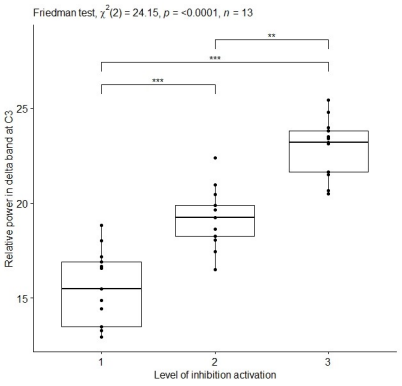

Fig. 4. Box plot of relative power in delta band at C3 (averaged on each subject) at varying levels of inhibition activation in the sitting condition. Single, double and triple asterisks denote significant difference at (p <.05), (p <.01), and (p <.001), respectively.

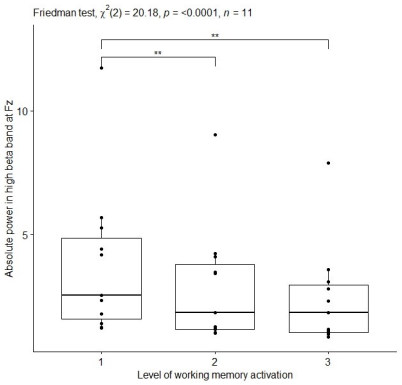

Fig. 5. Box plot of relative power in high beta band at Fz (averaged on each subject) at varying levels of inhibition activation in the sitting condition. Single, double and triple asterisks denote significant difference at (p <.05), (p <.01), and (p <.001), respectively.

TABLE I
FRIEDMAN TEST RESULTS IN TERMS OF P-VALUE, EFFECT SIZE AND χ^2 FOR EEG FEATURES RELATED MONOTONICALLY WITH EXECUTIVE FUNCTION LEVEL OF STIMULATION. RESULTS WITH HIGH EFFECT SIZE (>0.8) ARE HIGHLIGHTED IN RED. REL. = "RELATIVE", ABS. = "ABSOLUTE", N.M. = "NO MONOTONICITY".

Task	Band	Channel	Sitting			Dual task walking		
			p-value	eff. size	χ^2	p-value	eff. size	χ^2
N Back	Abs. high beta	fz	0.00004	0.92	20.20	0.36800	0.08	2.00
	Abs. high beta	cz	0.00043	0.65	15.50		n.m	
	Abs. high beta	c4	0.00646	0.42	10.10	0.52900	0.06	1.27
	Rel. low beta	o1	0.00786	0.37	9.69	0.00230	0.47	12.20
	Rel. delta	cz	0.00786	0.37	9.69		n.m	
	Rel. delta	c3	0.00917	0.36	9.38		n.m	
	Abs. beta	fz	0.01160	0.41	8.91		n.m	
	Rel. beta	o2	0.01250	0.34	8.77	0.02490	0.28	7.38
	Rel. delta	o2	0.01250	0.34	8.77		n.m	
	Abs. beta	c4	0.01690	0.34	8.17	0.69500	0.03	0.73
Go NoGo	Rel. delta	c3	0.00001	0.93	24.20	0.00917	0.36	9.38
	Rel. delta	fz	0.00002	0.82	21.40	0.00091	0.54	14.00
	Rel. delta	cz	0.00004	0.79	20.50	0.00156	0.20	12.90
	Rel. delta	c4	0.00004	0.79	20.50	0.00091	0.54	14.00
	Rel. delta	o1	0.00007	0.73	19.10	0.00289	0.45	11.70
	Rel. delta	o2	0.00009	0.72	18.60	0.00197	0.48	12.50
	Rel. delta	fp1	0.00018	0.66	17.20	0.01830	0.31	8.00
	Rel. low beta	c3	0.00046	0.59	15.40	0.03230	0.26	6.86
	Rel. low beta	fz	0.00091	0.54	14.00	0.06270	0.21	5.54
	Rel. high beta	fp2	0.00273	0.45	11.80	0.00156	0.50	12.90

Subject	Channels							
	o1	*c3*	*fp1*	*cz*	*fz*	*fp2*	*c4*	*o2*
1	-1	-1	1	-1	-1	0.5	-1	-1
2	-1	-0.5	1	-1	-1	0.5	-1	-0.5
3	-1	-1	0.5	-1	-1	-1	-1	-1
4	-1	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
5	-1	1	1	0.5	-1	0.5	0.5	-0.5
6	-0.5	-0.5	-1	-1	-0.5	-0.5	-0.5	1
7	-0.5	0.5	0.5	-0.5	-1	0.5	-0.5	1
8	1	-0.5	-1	-1	-1	-0.5	-0.5	0.5
9	1	-1	-1	-1	-1	-1	-1	1
10	-1	-0.5	-1	-1	-1	-0.5	-0.5	-0.5
11	0.5	-1	1	-0.5	-1	-1	-1	1
12	-0.5	-1	-0.5	-1	-1	0.5	-1	-1
13	1	0.5	1	0.5	0.5	0.5	-0.5	0.5

TABLE II
SPEARMAN'S RANK CORRELATION COEFFICIENT BETWEEN *absolute power in high beta band* AND THE WORKING MEMORY LEVEL OF STIMULATION IN A SITTING CONDITION. THE MOST SIGNIFICANT COEFFICIENTS (I.E., EQUAL TO -1) FOR THE EEG FEATURES WITH HIGH EFFECT SIZE FROM TAB. III-A ARE HIGHLIGHTED IN RED.

Subject	Channels							
	o1	*c3*	*fp1*	*cz*	*fz*	*fp2*	*c4*	*o2*
1	1	1	-0.5	0.5	0.5	0.5	1	1
2	1	1	0.5	1	1	0.5	1	1
3	1	1	1	1	1	0.5	1	1
4	1	1	1	1	1	0.5	1	1
5	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	0.5	0.5
7	0.5	0.5	1	0.5	0.5	1	0.5	0.5
8	0.5	1	1	1	1	0.5	1	1
9	1	1	1	1	1	0.5	1	0.5
10	1	1	0.5	1	1	0.5	1	1
11	1	1	1	1	1	0.5	1	1
12	0.5	1	0.5	0.5	0.5	0.5	1	1
13	1	1	1	1	1	1	1	1

TABLE III
SPEARMAN'S RANK CORRELATION COEFFICIENT BETWEEN *relative power in delta band* AND INHIBITION WORKLOAD IN SITTING CONDITION. THE MOST SIGNIFICANT COEFFICIENTS (I.E., EQUAL TO 1) FOR THE EEG FEATURES WITH HIGH EFFECT SIZE FROM TAB. III-A ARE HIGHLIGHTED IN GREEN.

B. Gait Analysis results

Inter-side analysis showed no significant differences between left and right, therefore, only left gait cycles were considered for subsequent statistical analyses. Inter-subject significant differences (p-value<0.05) for spatial- temporal and k parameters (GPS and GVS) between walking and different conditions of dual task were reported respectively in Table IV and V. Table IV shows a significant lower stride length during dual task, in particular during the execution of Go-NoGo_1 (p-value = 0.049) and Go-NoGo_2 (p-value = 0.046), with respect to walking; this finding was graphically reported via boxplots in Figure 6. Moreover, Table V showed a significant lower GVS of Foot Progression during dual task with Go-NoGo_1 (p-value = 0.045) and Go-NoGo_2 (p-value = 0.048) with respect to walking (as showed in Figure 7), and during dual task with N-Back_2 with respect to walking (p-value = 0.036). In particular, graphical representation of foot progression parameter during gait cycle was reported in Figure 7 and highlighted a trend of foot extra-rotation during cognitive-motor with Go-NoGo.

Experimental Conditions	Cycle Duration [s]	Cadence [step/min]	Gait Speed [m/s]	Stance Phase [%]	Swing Phase [%]	Double Support Phase [%]	Stride Length [m]	Step Width [m]
Walking vs. Go-NoGo_1	0.398	0.408	0.174	0.331	0.198	0.146	**0.049**	0.368
Walking vs. Go-NoGo_2	0.479	0.439	0.193	0.500	0.092	0.255	**0.046**	0.258
Walking vs. N-Back_1	0.418	0.439	0.224	0.500	0.244	0.164	0.145	0.183
Walking vs. N-Back_2	0.439	0.428	0.232	0.269	0.260	0.079	0.078	0.219
Go-NoGo_1 vs. Go-NoGo_2	0.428	0.400	0.489	0.306	0.132	0.324	0.459	0.408
N-Back_1 vs. N-Back_2	0.489	0.500	0.462	0.306	0.500	0.286	0.369	0.489

TABLE IV
WILCOXON MANN WHITNEY TEST RESULTS FOR SPATIAL-TEMPORAL PARAMETERS VARIATION AMONG DIFFERENT EXPERIMENTAL CONDITIONS. SIGNIFICANT DIFFERENCES (P-VALUE < 0.05) ARE HIGHLIGHTED IN BOLD.

Experimental Conditions	GPS	GVS								
		Pelvic Obliquity	Pelvic Tilt	Pelvic Rotation	Hip Abb-Abduction	Hip Felx-Extension	Hip Rotation	Knee Flex-Extension	Ankle Dorsi-Plantiflexion	Foot Progression
Walking vs. Go-NoGo_1	0.286	0.259	0.500	0.479	0.331	0.388	0.510	0.269	0.220	**0.045**
Walking vs. Go-NoGo_2	0.177	0.349	0.459	0.295	0.286	0.295	0.418	0.295	0.164	**0.048**
Walking vs. N-Back_1	0.205	0.428	0.469	0.429	0.459	0.359	0.331	0.438	0.177	0.119
Walking vs. N-Back_2	0.369	0.408	0.469	0.489	0.408	0.340	0.379	0.500	0.252	**0.036**
Go-NoGo_1 vs. Go-NoGo_2	0.359	0.397	0.510	0.379	0.408	0.398	0.449	0.124	0.340	0.152
N-Back_1 vs. N-Back_2	0.349	0.489	0.448	0.479	0.459	0.379	0.510	0.388	0.379	0.236

TABLE V
WILCOXON MANN WHITNEY TEST RESULTS FOR KINEMATIC PARAMETERS VARIATION AMONG DIFFERENT EXPERIMENTAL CONDITIONS. GPS = "GAIT PROFILE SCORE", GVS = "GAIT VARIABLE SCORES". SIGNIFICANT DIFFERENCES (P-VALUE < 0.05) ARE HIGHLIGHTED IN BOLD.

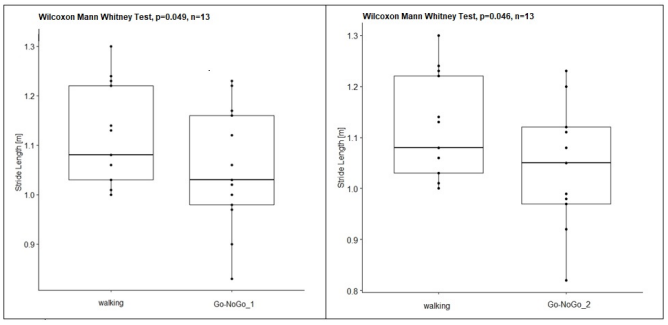

Fig. 6. Box plots of Stride Lenght inter-subjects distribution between walking and Go-NoGo_1 (left) and walking and Go-NoGo_2 (right).

C. Scores of cognitive tasks

In Table VI cognitive performance results are reported. The results are expressed in terms of percentage of correct answers. In particular, the N-Back tasks consist of 44 trials while the Go-NoGo tasks of 150, therefore the percentage values are computed on 44 and 150, respectively.

IV. DISCUSSION

The scores of the cognitive tasks exhibited high values between the various conditions for all subjects. This confirmed the subjects' adherence to the experimental protocol.

Monotonic relationships were identified between some EEG features and levels of activation of working memory and inhibition, while the subject is sitting and during walking. When the subject is seated, executive functions are stimulated only by the cognitive tasks. In this way, electroencephalographic interferences due to subject activities, other than the use of executive function, are minimized.

During walking, there is a worsening of the signal-to-noise ratio (typically of 10 dB) due to artefacts related to electrode movement. Therefore, the identification of EEG features becomes more difficult compared to sitting conditions. Namely, the relationships between EEG features and executive functions that emerged during the sitting condition may not be confirmed. However, under particular experimental conditions, the executive function might be overstimulated and the noise due to walking might be balanced by an increase in signal power.

Statistical results of gait analysis showed significant lower stride lenght during cognitive-motor task with Go-NoGo exercise in both level of difficulty with respect to mere walking (Table IV and Fig. 6). Significant lower stride length during dual task suggested a lower balance control and more instability in subjects during walking because of execution of Go-NoGo. Subjects reduced lenght of their stride and, consequently, their gait speed in order to better control their gait during dual task.

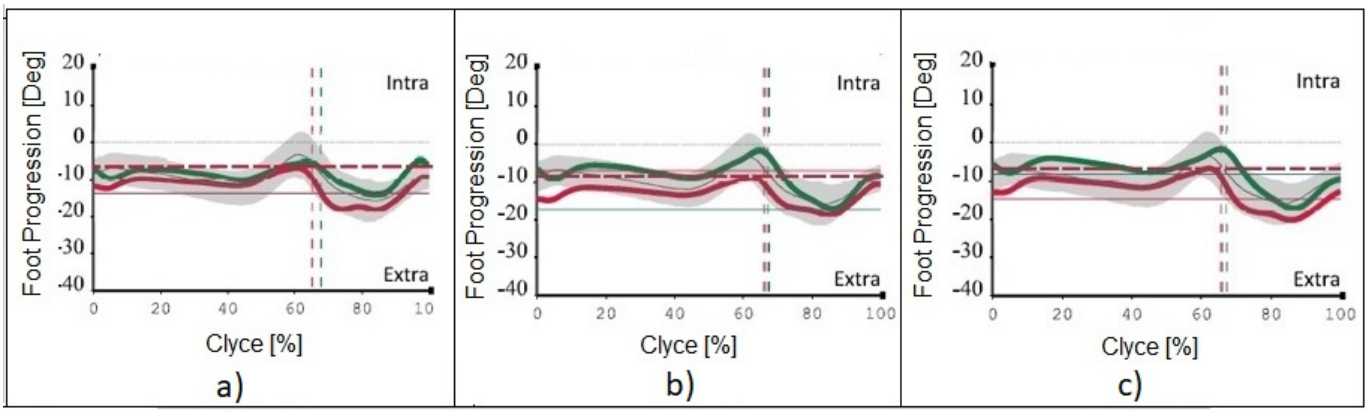

Fig. 7. Kinematic curves representation of Foot Progression parameter during gait cycle, related to mere walking (a), dual task walking with Go-NoGo_1 (b), and with Go-NoGo_2 (c). The right side and left side of the body are reported in green and red, respectively; horizontal dashed red line indicates peak of left foot progression trend; horizontal grey line is the threshold for Foot Progression parameter; horizontal red lines indicate mean values of Foot Progression for left sides; vertical dashed green and red lines delimited stance and swing phases, respectively, for left and right trends of foot progression. Deg= "Degree", Intra= "Intra-rotation" , Extra = "Extra-rotation".

Task	Condition	Level	Subject												
			1	2	3	4	5	6	7	8	9	10	11	12	13
Go NoGo	sitting	easy	100	100	99	100	100	98	99	98	98	99	99	97	100
		difficult	100	97	99	96	94	89	93	92	96	95	93	99	94
	walking	easy	99	100	99	100	98	100	81	94	97	98	81	100	97
		difficult	96	92	98	97	95	89	95	87	95	89	76	99	91
N Back	sitting	easy	98	100	100	95	100	100	95	98	100	98	95	100	95
		difficult	95	89	91	95	80	80	82	64	84	95	82	95	80
	walking	easy	93	93	100	100	91	95	98	100	98	95	98	98	100
		difficult	91	89	95	93	93	93	61	80	91	93	61	98	77

TABLE VI
SCORES (I.E., PERCENTAGE OF CORRECT ANSWERS) OF COGNITIVE TASKS FOR EACH SUBJECT AT VARYING OF CONDITION AND DIFFICULTY LEVEL.

Moreover, inter-subject statistical analysis for kinematic parameters underlining a significant greater GVS for Foot progression. This result was found during cognitive-motor task with Go-NoGo exercise in both level of difficulty with respect to walking (Table V), highlighting a different trend of this parameter with respect to its normal trend. In particular, an extra-rotation of feet was found in gait cycle during dual task with respect to walking as shown in Fig. 7 and modification of this parameter could be related to stride length significant decrease, as previously reported in literature [66]. In these conditions, an overdemand of cognitive inhibition can be supposed. Namely, both walking and Go-NoGo task are requiring the same cognitive resource. Eventually, a significant greater GVS for foot progression was found even during cognitive-motor task with N-Back exercise with grater level of difficult (Table V). This may indicate an involvement of working memory EF during motor task execution, but only in correspondence with high difficult of cognitive exercise. These results reveal a greater involvement of inhibition during gait with respect to working memory in agreement with previous studies ([67], [68], [69]).

EEG features, identified in sitting condition, did not maintained a statistically significant relationships with the levels of executive functions activation during walking. Indeed, the noise due to electrode movement on the skin during walking worsen the signal-to-noise ratio. The only exception was the relative power in delta band at Fz, for inhibition. This result represents an electroencephalographic grounding of the increased involvement of inhibition during walking. Indeed, the increased activation of inhibition, revealed by gait analysis, lead to an EEG signal strength balancing out the noise due to walking.

Moreover, the identification of a monotone relationship between EEG features values and the inhibition levels of activation is a first step toward the EEG-based monitoring of EFs fatigue during walking.

A. Limitations

The experimental sample was composed by only 13 healthy and young participants. In future study, a greater experimental sample will be enrolled by including also elderly and people affected by neurodegenerative disorders. Moreover, EEG signal was acquired by means of an eight-channel device. Therefore, the low spatial resolution may have penalised the identification of additional EEG features.

V. CONCLUSION

In this study, different levels of cognitive inhibition activaction were electroencephalographically identified during a dual task (cognitive and motor) execution.

A natural walking set up was achieved by means of a light and wireless EEG device with few channels and dry electrodes. Despite the few electrodes, four different cortical areas were monitored (prefrontal, frontal, medial, occipital).

Quantitative gait assessment was performed by 3D motion analysis system focusing on both spatio-temporal and kinematic data processing. For the selective activation of inhibition and working memory, standardised cognitive tasks were employed. Moreover, proper strategies were implemented for minimizing artefacts produced by vocal or gestural responses. The study poses the basis for EEG-based monitoring of cognitive processes involved in gait, and could be useful for fall prevention, and personalised rehabilitation in neurodegenerative conditions and elderly.

Future works will involve a larger experimental sample by including elderly and people affected by neurodegenerative diseases.

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