Combined EEG/EMG Evaluation during a Novel Dual Task Paradigm for Gait Analysis

M. de Tommaso, E. Vecchio, K. Ricci, A. Montemurno
Basic Medical, Neuroscience and Sensory Systems Department, Bari "Aldo Moro" University
Bari, Italy

D. De Venuto, V.F. Annese

Politecnico di Bari
Dept. of Electrical and Information Engineering
Via Orabona 4, 70125 – Bari, Italy

Abstract — Little knowledge is available about neural dynamics during natural motor behavior and its perturbation in aging and neurological diseases. In the present study, we aim to evaluate electroencephalography-electromyography (EEG-EMG) co-registration features of rest and walking in basal condition and under cognitive tasks in normal subjects to characterize a "normal gait" and to define the possible paradigm to detect abnormal behavior. We realized EEG-EMG co-registration in 17 healthy subjects in different conditions: 1) sitting, 2) standing 3) walking. A P300 oddball paradigm was performed during 4) standing condition and 5) during walking. We found that the P300 component amplitude increases during physical activity. The negative correlation between age and P300 component vanishes during gait. The spectral width of the total alpha rhythm appears reduced in the course of P300 in a static situation, with likely phenomena of desynchronization related to cognitive task. During gait, the activity is canceled, suggesting a state of "idling" of cortical areas previously involved in the process of recognition of the target stimulus. Additionally, EMG co-contraction and µ-rhythm desynchronization (µ-ERDs) are also analyzed using wireless equipment. It is demonstrated the EMG co-contraction validity, showing the possibility to discern a normal gait (tot. steps: 60; max co-contraction time: 100ms; average: 20ms) from a perturbed one (tot. steps: 60; max co-contraction time: 260ms; mean: 70ms). µ-ERDs were detected in about 60% of the analyzed steps, showing medium variations in µ - power of about -2.4.

Keywords—*EEG, EMG, dual task, P300, gait analysis, ERD, EMG co-contraction.*

I. Introduction

Gait disorders are a common and significant cause of reduced quality of life and independence. Falls are one of the most important consequences of gait disorders, but slow and insecure gait and 'fear of falling' also have great clinical significance. Gait disorders can be classified according to the system responsible for the abnormal locomotion, according to the underlying disease associated with the abnormal gait or by its phenomenology. Increased attention has recently been given to the cognitive aspects of gait. These also are assessed as part of the routine evaluation of gait disturbances. Fall risk assessment is an essential part of the evaluation of a patient with gait disturbance including internal and external risk factors.

The process of normal walking is complex, consisting of voluntary and automated sequences of motor patterns. In fact, little knowledge is actually available about neural dynamics during natural motor behavior and its perturbation in aging and neurological diseases. The electroencephalogram (EEG) allows non-invasive measurement of synchronous rhythmic activity in populations of cortical neurons in humans. By simultaneously recording the peripheral muscle activity by electromyography (EMG) during movements, it is possible to look for cortical rhythmic activity that is correlated (coherent) with the peripheral muscle activity and thus plays a role in cortical control of movements. This cortico-muscular coherence analysis is widely applied in studies of the human cortical motor system [4]; the movement and muscle artifacts in EEG recordings by a wired system during walking make difficult their use during gait analysis. Previous studies have shown that EEG spectral power in the µ and β band decreases over sensorimotor areas during isolated foot movements in motor preparation and different walking [5]. The contribution of voluntary and automatic motor control mechanisms in determining normal gait and postural control during walking is still under study. In movement disorders as Parkinson's disease, a reduced motor starting is indicated by an altered modulation of the cortical potential preceding voluntary movement. The relationship between cognitive function and gait has emerged recently. Gait disorders and falls are more prevalent in demented patients compared with non demented subjects, and there is a direct relationship between cognitive impairment severity and increased gait abnormalities [6,

7]. One method that has been used to determine the attentional demands of a particular task is called the dual-task paradigm [8, 9]. In recent years, the dual task paradigm has been widely used as an experimental method to explore the interplay between gait and cognition [6]. The dual-task methodology requires an individual to perform a task that is being evaluated in terms of its attentional demand (primary task), while simultaneously performing an alternative task (commonly termed a "secondary probe task).

The Bereitschaftspotential (BP), reflecting activity in the primary and supplementary motor areas of the cortex (M1 and PMA) and nearby somatosensory cortex that leads to voluntary muscle movement; in addition the suppression [event-related desynchronization(ERD)] of the μ and β rhythm in sensorimotor areas has been demonstrated during active walking [5]. A tool to evaluate cognitive processes is the P300: it is an Event-Related brain Potential (ERP), which reflects neuro-electric activity, related to attention allocation and activation of immediate memory [10]. More specifically, the P300 is considered able to represent processes involved in stimulus evaluation or categorization. It is usually elicited using the oddball paradigm, in which low-probability target items are mixed with high-probability non-target (or "standard") items.

All these neurophysiological aspects may be useful in detecting the initiation and probably maintenance of sequential movement during normal walking. The integrated study of agonist-antagonist limb muscle contraction, with the EEG patterns of μ and β band as well as premotor slow potential and the influence of a dual task condition will enable to extract a paradigm of normal walking and patterns of gait perturbations and fall risk. In addition, the paradigm of dual task with the evaluation of P300 allows a measurement of the cognitive commitment of the performed tasks.

The aim of the present study is twofold: i) it shows preliminary findings regarding main EEG-EMG features during rest and walking in basal condition and under oddball P300 cognitive task in normal subjects and ii) it presents the approach and the experimental results for EMG co-contraction and μ-rhythm desynchronization (μ-ERDs) calculation during the gait.

In addition to try to shed light on the cortical implication during the complex event of gait, our contribution finds wide applications in the field of Ambient Assisted Living (AAL), since, if supported by a proper wireless sensor network, offers a non-invasive tool for prevent falls in subjects with neuro-degenerative diseases. The present work is organized as follows. In Section II the methods for P300 analysis, EMG co-contraction and μ-ERDs are presented. Section III deals with the experimental obtained results. Finally, Section IV aims to clarify and discuss the presented results.

II. METHODS

A. Dataset and Experimental Approach for P300 Analysis

Subjects & Equipment. Seventeen volunteers were examined. Central and peripheral nervous system diseases were excluded after a careful interview and objective general and neurological examination. They were 5 males and 12 females, aged 18-65 years. The EEG–EMG recording was obtained by standard MICROMED (EEG apparatus Micromed Brain Quick, Mogliano Veneto, Italy). The EEG was recorded by 21 surface electrodes, with a further electrode above the right eyebrow for electro-oculogram (EOG) recording, referring to the nasion. Further bipolar derivations were used to record EMG signals from the right and left anterior tibialis and right and left lateral gastrocnemius muscle. The ground electrode was positioned over the cervical zone. All subjects were recorded by an EEG cup, with superficial EMG electrodes fixed by collodion. The amplifier box was introduced in a backpack and electrodes cables were carefully fixed at the legs.

Experimental procedure. Subjects were recorded while 1) sitting on a chair for 5 min., 2) standing for 5 min and 3) walking for 5 min along a 10m long route. The P300 oddball paradigm was performed during 4) standing condition and 5) during walking. The stimulation paradigm was carried out by the Brain Quick Micromed program, delivering 2 acoustic stimuli (1500 Hz target tone and 1000 Hz frequent tone, both with an intensity of 70 dB SPL and duration of 75 millisecond - rise and fall time 10 milliseconds).

Performed analysis. Artifact detection was realized after a visual inspection, and electrodes oscillation features were characterized in each patient, taking into consideration both frequency and amplitude. In addition, eye movement features were checked considering the EOG channel. An automatic artifact rejection paradigm was implemented in each case by means of ASA software (ANT software). Both EEG and EMG signals were sampled at 256 Hz and filtered in a range of 7-12 Hz and 13-30 Hz (corresponding to alpha-mu and beta rhythms bands). The EMG signals were in addition filtered in the 10-60 Hz and 60-90 Hz frequency ranges. Coherence analysis between single EMG and EEG channels in the 7-12 Hz and 13-30 Hz

frequency bands was performed, according to ASA 4.7.1 software. For the cognitive task, at least 30 artifact-free EEG tracks corresponding to the rare stimulus were averaged in each case to extract the main waveforms, the N2 in the time range 175-280ms and the P3 component in the 290-500ms time interval. Time off-line analysis was from 100ms pre-stimulus to 900ms post-stimulus with 100-0ms baseline-correction. An automatic rejection of artifacts was employed taking into consideration electrodes oscillations and electro-oculogram, by means of ICA (Independent Component Analysis). We performed a semiautomatic Peak Detection with the maximum area for the different components of ERP's wave, which considered at least 50% amplitude prevalence of the positive wave in the time range 290-500ms obtained by the rare stimulus in comparison to the frequent one. The semiautomatic analysis was further validated by visual inspection.
The N2-P3 wave's amplitude and latencies and EEG and EMG spectral values were evaluated by multivariate ANOVA analysis with EEG and EMG channels as variables and conditions standing1) vs walking 2) vs standing during P3 3) vs walking during P3 4) as main factors. A post-hoc Bonferroni test was run out by means of IBM SPSS statistic software vers 21. Correlation analysis between age and main ERP and EEG spectral features was performed by Pearson correlation test.

B. Dataset and Experimental Approach for EMG Co-Contraction and μ-ERDs Computation

Subjects & Equipment. This dataset is based on recordings on 10 healthy subjects (aged between 24 – 28 years) acquired with a wireless EEG and EMG recording system. The EEG was recorded by 32 channels wireless headset (reference: nasion, ground: ear lobe) exploiting active electrodes (conditioning integrated circuit are embedded in the electrode performing amplification filtering and digitalization). The EEG sampling rate was 500 Hz with 24-bit resolution. Eight single collecting bipolar and active wireless electrodes (Tibialis, Gastrocnemius, Abductor and Rectus Femoralis of both legs) recorded the EMG. Each collecting point wirelessly transmit data to the same processing gateway. EMG data have been sampled at 500Hz and digitalized with a 16-bit resolution.

Experimental Procedure. Subjects were asked to perform some different types of deambulation: normal gait, gait with obstacle and gait performing a cognitive second task (dual task – DT). We asked subjects to relax the face and jaw muscles and to minimize eye blinks and swallowing during data capture periods, in order to reduce related artifacts.

Performed analysis. The EEG and EMG synchronization, as well as all the proposed results about EMG co-contraction and μ-ERDs computation, have been carried out using "Matlab" by "Mathworks". Three tools for gait analysis have been developed: (i) EMG trigger generation with dynamic threshold, (ii) EMG co-contraction, (iii) μ-rhythm event related desynchronizations (μ -ERDs). The automatic EMG trigger generation is exploited in order to obtain an univocal muscle activation flag, enormously reducing data, without losing the target information.

A single fixed threshold comparator cannot return good results due to EMG nature: a dynamic threshold is on-line calculated on the instantaneous power of the rectified EMG. Agonist-antagonist EMG trigger signals are multiplied and normalized to compute the co-contraction time: long co-contraction times (> 500-600ms) are index of unbalance or instability during the gait. Alongside, EEG signals are filtered (1-40 Hz) amplified (5000 V/V) and opportunely subtracted (motor-cortex and occipital one) for reducing common artifacts. A 2Hz resolution Short time Fourier Transform (STFT) is performed on these data to calculate the time-frequency behavior of the motor-cortex brain activity, leading to the Power Density Spectrum computation. When an EMG trigger rising edge arrives, the μ - band power is also calculated in a 500ms time slot before and after the EMG activation. Defining Δμ as difference from the spectrum power of the μ-rhythm before and after the muscle activation:

$$\Delta\mu = \mu Power_{1\ (\text{before activation})} - \mu Power_{2\ (\text{after activation})} \quad (1)$$

it is possible to record μ-rhythm variations. A negative value of Δμ is desirable: this indeed would symbolize a synchronization of μ-rhythm (μ-ERS) immediately after the step or, equivalently, a μ-rhythm desynchronization (μ-ERD) just before it.

III. RESULTS

A. Results for P300 Analysis

The 10-60 and 60-90 Hz Frequency range EMG analysis of the four muscles examined (left and right tibial, left and right gastrocnemius) in the 17 subjects confirmed a significant increase EMG activity in the four muscles in walking condition compared with standing and sitting conditions (Bonferroni: walking vs seated and standing $p<0.0001$). This EMG activity was not modified in the performance of the

cognitive task of P300 paradigm during walking (Bonferroni: walking+P3 vs walking: n.s.). The P300 amplitude increased during walking compared to standing condition (ANOVA F 7.52 P 0.008; Fig. 1), while there were no significant changes in latency (Fig. 1).

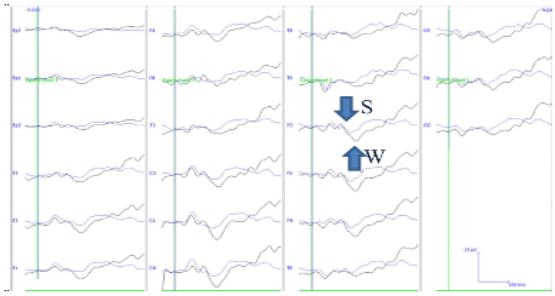


Fig. 1. P300 wave evaluated in standing (S, blue line) and walking (W, black line).

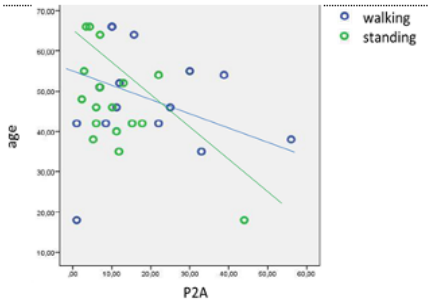
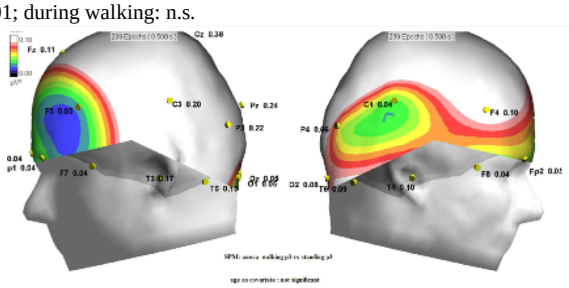


Fig. 2. P300 amplitude/age correlation: Pearson test in standing condition p<0.01; during walking: n.s.



Fig, 3. Statistical probability maps of alpha rhythm showing the p values of the comparison between the standing vs walking condition during P300 task.

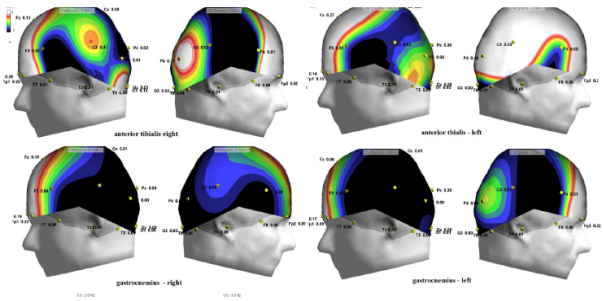


Fig. 4. Cross correlation maps for 7-12 Hz rhythm across muscles and EEG derivations. Dark color express high levels of coherence.

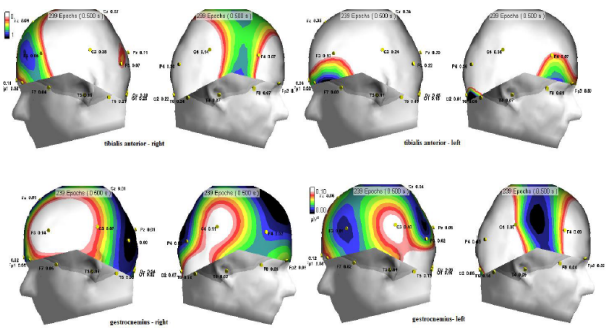


Fig. 5. Cross correlation maps for 7-12 Hz rhythm across muscles and EEG derivations during walking performing P300 cognitive task. Light colors express low levels of coherence.

A correlation analysis showed a P300 amplitude reduction with age in the standing condition, but this negative correlation was not found during walking (Pearson test standing p<0.01; during walking: n.s. Fig. 2).

7-12 Hz Alpha-mu rhythm analysis. The EEG analysis showed a reduction in the μ-rhythm during execution of the cognitive task in static condition and a significant increase in temporal-frontal derivations under dynamic conditions. These variations were not age related. Statistical probability maps showing the p values of the comparison between the standing vs walking condition during P300 task underline an alpha de-synchronization performing P300 task in static condition; this activity is not present during walking (Fig. 3).

A coherence analysis between EEG and EMG rhythms showed a cross-correlation between 7-12 Hz EEG rhythm and the frequency spectrum of the agonist and antagonist muscles during walking (Fig. 4), which was reduced while performing cognitive task of P300 paradigm (Fig. 5).

B. Results for EMG co-contraction and μ-ERDs computation during the gait

The wireless equipment for the EMG co-contraction μ-ERDs computation during the gait. We exploited wireless recording systems for both EEG and EMG data collection in order to record data during natural gait minimizing artifacts due to wires oscillation and to the decreased mobility of the subject.

Regarding EEG recording equipment, a wearable and wireless system has been used. It consists of the following components: an electrode cap with 32 electrodes; a small transmitter at the back of the electrode cap; a base station that can connect to a laptop or other processing device via USB; a contactless charging pad, with cabling that can connect to a USB port or power outlet; supporting software and documentation. The entire system is specialized for

real-time processing in field environments, with top performance in noisy settings. The system samples at 500 Hz with 24 Bit resolution and extensive oversampling to improve the signal-to-noise ratio (SNR).
The system is equipped with active electrodes: microchips inside each electrode amplify, filter, and digitize the signal at the point of recording. This facilitates wireless transmission (eliminating the risk of noise from cables), improves signal quality. The electrodes are pre-positioned on a flexible cap according to the Extended International 10-20 System.
On the other hand, EMG recording has been carried out using an innovative multi-channel and multi-sensor wireless surface EMG system. The system is made of a base unit, with both digital and analog outputs, and up to 16 probe transmitter. The EMG system is made up by wireless and low-power electrodes for a quick patient set-up and for movements performed in total freedom; the receiver device is equipped with analog and digital (USB port) data output for all channels. It has been developed with high integration "SMD" technology and it is Certified as a Class IIa device according to EU directive 93/42. The recording electrodes are pre-gelled and disposable and have to be applied to the subject. The EMG acquisition module is applied on the surface electrodes using a snap connector. The EMG samples at 2kHz with a 16-bit resolution.
For both the systems, the absence of cables between the transmitters on the patient and the data receiver/recording unit allows data acquisition while patient is free to move performing low invasivity: this feature is very useful for clinical and scientific applications, for example in pathologic gait analysis or in rehabilitation. EEG and EMG data are synchronized on a laptop using multi-rate algorithms for down sampling EMG without losing information.

Automatic trigger generation. In order to evaluate the co-contraction we need to detect the instant when the muscles are activated. The wireless system used for this purpose, described above, can be programmed to automatically make this evaluation by defining a personalized threshold and then, from this a trigger.
The automatic EMG trigger generation showed good results also varying the amplitude and the type of the EMG signal. Generated trigger from Gastrocnemius showed, on 410 steps, 26 undesired de-activation (6.34%), 2 undesired activation (0.48%), with a medium activation delay of about 97ms. Generated trigger from Tibialis showed (on 410 steps) 43 undesired de-activation (10.49%), 5 undesired activation (1.22%), with a medium activation delay of about 97ms. The Tibialis generated trigger showed slight worse results due to its different EMG pattern during walk, experimenting a double contraction. It could be suitable to perform a fine-tuning depending on the subject and on the recorded muscle. Automatic EMG trigger generation allows to easily calculate gait parameters i.e. speed, step cycle, etc. For instance, it has been recorded that the subject performing a DT actually slows down the walk: the mean temporal distance between two activations of the same muscles raised from 1.5s (normal gait) to 2s (+ 33%) during the DT. Further tests have shown that if the cognitive task is more complicated, the walking speed slows down further.
Figure 6 is a demonstrative picture of the results achieved: the derived trigger (in red) totally preserve the EMG information (in blue) during a normal gait.

EMG Co-contraction time. Exploiting generated triggers, it is evident to verify the alternate agonist-antagonist limb muscle activation during the gait (see figure 7). In figure 8 and 9, it is possible to compare EMG co-contractions calculated on right Gastrocnemius and right Tibialis , respectively during a normal gait (60 steps) and a perturbed gait (60 steps) with obstacles performed by the same healthy subject. The y-axis reports the co-contraction time, while on the x-axis the samples. During the normal gait, the maximum EMG co-contraction time recorded was about 100ms. On the contrary, during the perturbed gait, the EMG co-contraction time is almost duplicated.
The maximum EMG co-contraction time recorded during the climb over obstacles was about 260ms. In addition to the peaks, the EMG co-contractions are higher and more frequent during the entire walk: the medium EMG co-contraction time during a normal walk was 20ms, while it was 70ms during the perturbed walk.

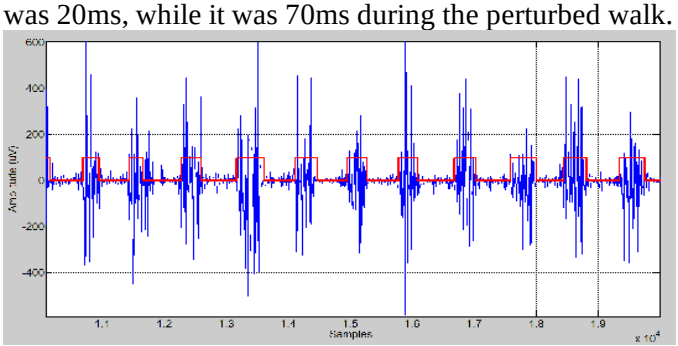


Fig. 6. Demonstrative picture of trigger derivation (in red) from EMG right Tibialis (in blue).

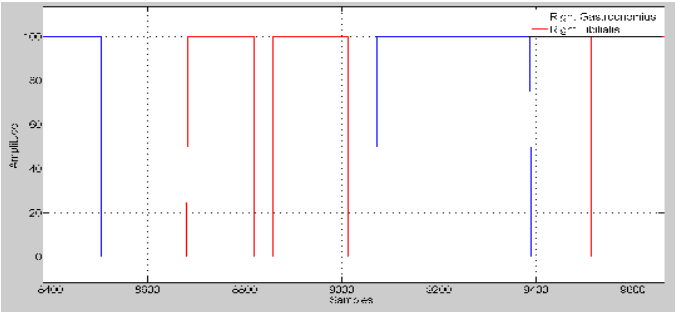


Fig. 7. Close up of one step described using generated triggers. Right Tibialis (in red) and right Gastrocnemius (in blue) activations are alternate.

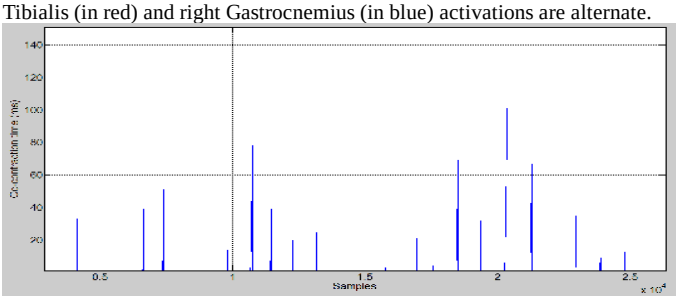


Fig. 8. Co-contraction time calculated on right Gastrocnemius vs. right Tibialis during a normal gait of 60 steps performed by a healthy subject.

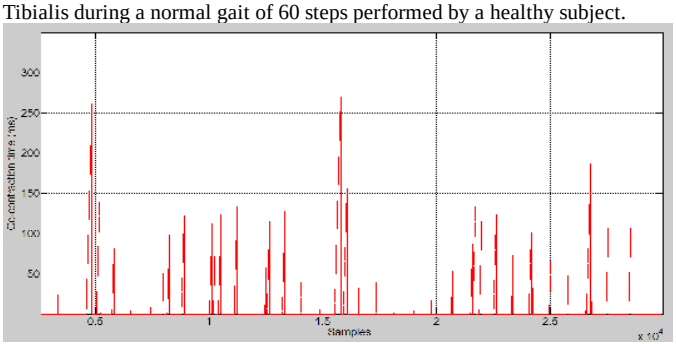


Fig. 9. Co-contraction time calculated on right Gastrocnemius vs. right Tibialis during a perturbed gait of 60 steps performed by a healthy subject.

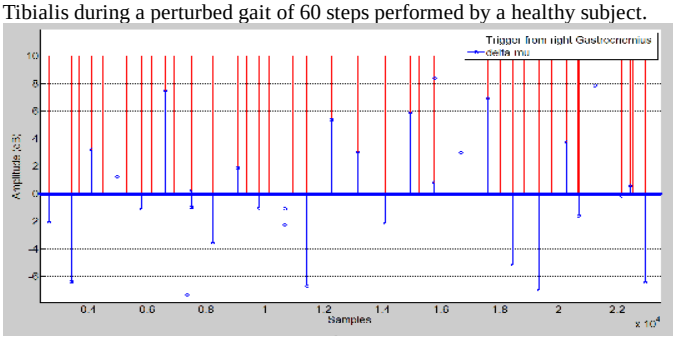


Fig. 10. Δμ (in blue) vs. right gastrocnemius trigger (red) during natural gait.

Table I Carachterization of μ-ERDs

	Left Gastrocnemius and C4 – O2	Right Gastrocnemius and C3 – O2
Steps	42	42
Mean Δμ (dB)	-1.17 (-2.33%)	-1.3 (-2.6%)
# of ERDs detected (Δμ <0)	28	23
Incidence of ERD	66.7 %	55.5%
Mean Power in μ-band before the movement(dB)	51.4	51.5
Mean Power in μ-band after the movement (dB)		

μ-ERDs during gait. The study on μ-rhythm de-synchronization (μ-ERDs) detection has been performed during
the normal gait, considering that ERDs have to be detected in the contra-lateral hemisphere involved in the movement:
thus, for right Gastrocnemius activations, C3 (left motor-cortex channel) is exploited, while for right Gastrocnemius contractions C4 (right motor-cortex) has been considered. As soon a new step is detected, EEG power in the μ-band is calculated on 500ms (250 samples) before and after the EMG activation and a Δμ (from formula (1)) is calculated. Considering the analysis performed on right Gastrocnemius and C3 – O2, we detected a negative Δμ (that means de-synchronization just before the step) during 23 steps out of 42 (left ERDs incidence: 55.5%).
The mean Δμ measured was -1.3dB (-2.6%), while the mean μ-power level before and after the activation in the left motor-cortex were respectively 51.5dB and 52.8dB. Regarding the analysis performed on left Gastrocnemius and C3 – O2 were slightly better: negative Δμ was detected during 28 steps out of 42 (right ERDs incidence: 66.7%). The Δμ mean value was -1.17 (-2.33%) and the mean μ-power level before and after the activation in the right motor-cortex were respectively 51.4 dB and 52.6dB. Figure 10 reports a close up of the Δμ behavior during a normal gait. Table I summarize the results concerning μ-ERDs

IV. DISCUSSION

A. Discussion for P300 Analysis

The muscle recruitment during walking does not seem to change during the execution of the cognitive task. The P300 component amplitude increases during physical activity. The negative correlation between age and P300 component vanishes during gait. The spectral width of the total alpha rhythm appears reduced in the course of P300 in a static situation, this is likely a phenomena of desynchronization related to cognitive task. During gait, the activity is canceled, suggesting a state of "idling" of cortical areas previously involved in the target stimulus recognition process. There is a cross correlation between alpha rhythm and spectral frequency of the agonist and antagonist muscles, which tends to shrink in the course of performing the cognitive task. The correlation is age-related, and it is lost along the gait in the elderly. The movement encourages cognitive activity, offsetting the age-related deficits. Although apparently the cognitive task does not alter the muscle recruitment, it produces a strong cortical activation and reduces the

coherence between cortex and effector, in a more evident way in older subjects.

B. Discussion for EMG Co-Contraction and μ-ERDs Computation during gait

The EMG co-contraction, together with the calculation of the EMG limb trigger generation, is a very effective tool to estimate the balance and the stability of the subject during the walk. It has been shown, indeed, the evident diversity between co-contraction pattern for normal and perturbed gait. It should be notice that those data are referred to an healthy people: even more evident results could be outlined performing the same analysis on a subject with impaired mobility (elderly, neuro-diseased subjects, etc.). The EMG trigger generation additionally allows easily evaluating gait parameters, such as speed or gaiting cycle, outlining critical gait patterns.
Usually in literature [5], ERDs are analyzed in single and controlled movement in laboratory situations. But the gait involves a multitude of muscles and it is largely automatic and natural. Therefore, it is inconceivable to find the same results proposed in the literature also for gait. From these analyses is therefore clear that μ-rhythm desynchronization during a normal walking has a statistical incidence rather than deterministic.

V. Conclusion

Gait disorders are a common and significant cause of reduced quality of life and independence. At the current state of the art, little knowledge is available about cortical implication during natural motor behavior and its perturbation in aging and neurological diseases. In this paper, we exploited EEG/EMG combination to analyze i) EEG-EMG features during rest and walking in basal condition and under oddball P300 cognitive task in normal subjects and ii) EMG co-contraction and μ-rhythm de-synchronization (μ-ERDs) calculation during the gait. The proposed studies can have a huge impact if used for applications in the frame of Ambient Assisted Living (AAL) technology for fall prevention. In this context, a complete cyber-physical system architecture performing early detection of falling risk and cognitive impairment can be set, including automatic gait analysis. Synchronous EEG and EMG collection nodes make up the proposed Wireless Body Area Network (WBAN), communicating wirelessly with a gateway through Bluetooth Low Energy (BLE) protocol. EEG data are collected using an EEG wireless headset with 32 electrodes (international 10-20 system); EEG sampling rate of 500 Hz with 24-bit resolution are suitable for this application. Regarding EMG, 8 collecting points (Tibialis, Gastrocnemius, Abductor and Rectus Femoralis of both legs) collect data and transmit wirelessly to the same processing gateway with 500Hz data rate and 16-bit resolution. Thus, the processing unit has available in real time EEG and EMG: data are synchronized and fast algorithms process and analyze them [11]. For comfortable use, a battery life of – at least – 10 hours, is needed, with a working range of 10 meters (between nodes and gateway). A huge amount of retrieved data is expected: a data rate of 250 kbps (~31 kBps) is needed. Above all, the requirement of wearability should never be neglected, achievable exploiting printed wireless and flexible active electrodes: EEG electrodes can be mounted on "bandana like" structure or on a cap, performing wearability while EMG electrodes can be attached directly to the muscles to be monitored through an adhesive or incorporated in a strip of soft cloth. The collecting unit is a μPC (IPad, laptop, smartwatch, etc.) with proper wireless communication interfaces for the BAN and an efficient wide-area communication interface (i.e. LTE). Strict real-time constraints call for maximum parallelism; high reliability and low power consumption require management/self-diagnostic functions [12, 13]. The proposed WBAN can provide action and reaction procedure: once predictive signs of falling risk or cognitive impairments are detected, such as abnormal co-contraction or critical motor-cortex involvement during gait are detected, the system could deliver both external (alarm, warning, etc.) and local (electrical stimulation) to correct the movement, heavily decreasing the risk of fall.

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