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¹ Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.
² The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.
1. Final publishable summary report

This section must be of suitable quality to enable direct publication by the Commission and should preferably not exceed 40 pages. This report should address a wide audience, including the general public. The publishable summary has to include 5 distinct parts described below:

- An executive summary (not exceeding 1 page).
- A summary description of project context and objectives (not exceeding 4 pages).
- A description of the main S&T results/foregrounds (not exceeding 25 pages).
- The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results (not exceeding 10 pages).
- The address of the project public website, if applicable as well as relevant contact details.

Furthermore, project logo, diagrams or photographs illustrating and promoting the work of the project (including videos, etc…), as well as the list of all beneficiaries with the corresponding contact names can be submitted without any restriction.

1.1 Executive summary (Public)

Tremor is the most common movement disorder and it is strongly increasing in incidence and prevalence with ageing. More than 65% of the population with upper limb tremor presents serious difficulties in performing activities of daily living (ADL). Tremor is not life-threatening, but it can be responsible for functional disability and social inconvenience. It is typically managed by means of drugs, surgery (thalamotomy), and deep brain stimulation, but treatments are not effective in approximately 25% of patients.

The main objective of the project is to validate, technically, functionally and clinically, the concept of mechanically suppressing tremor through selective Functional Electrical Stimulation (FES) based on a (Brain-to-Computer Interaction) BCI-driven detection of involuntary (tremor) motor activity:

- The system will detect and monitor involuntary motor activity (tremor) through a multimodal BCI. The proposed BCI will combine CNS (Electroencephalography, EEG) and PNS (Electromyography, EMG) data with biomechanical data (Inertial Measurement Units, IMUs) in a sensor fusion approach. It will model and track tremor and voluntary motion.
- It will also include a multi-channel array FES system for selective stimulation of muscles for tremor suppression while reducing the influence on voluntary motion.
- For a potential commercial exploitation the embodiment must fit potential user expectations in terms of cosmetics, functionality and aesthetics.

Figure 1. The TREMOR concept: (1) a multimodal BCI system integrates information on brain activity, muscle activity and limb movement for a robust detection of tremor parameters (onset, amplitude and frequency), (2) an inverse dynamics muscle model provides information on required muscle activation parameters to attain (a) muscle impedance modulation and (b) muscle out-of-phase stimulation, (3) a multichannel FES system closes the human-in-the-loop system within fatigue and pain limits.

TREMOR proposes a multimodal BCI in which the main goal is identifying, characterizing and tracking involuntary motor bioelectrical and biomechanical activity as a command to trigger a biomechanical suppression of tremor. The concept of TREMOR is graphically depicted in figure 1.
1.2 Project context and objectives (Public)

In the TREMOR project concept, a multimodal BCI is proposed in which the main goal is identifying, characterizing and tracking involuntary motor bioelectrical activity as a command to trigger a biomechanical suppression of tremor. The BCI is as follows:

- It works both on CNS and PNS bioelectrical activity since TREMOR target both CNS and PNS generated tremors (typically essential, Parkinsonian and kinetic tremors). If only CNS activity is recorded, PNS generated tremors would be missed;
- It complements CNS and PNS data with motion data (IMUs) as the approach requires tremor information (frequencies, amplitudes) at a joint level;
- A local embodiment is proposed. In addition, the embodiment is preferable on a textile substrate that a patient can put on without taking care of electrode location.

The TREMOR system constitutes a novel, non-invasive and painless method for tremor suppression. In order to reach this objective the main scientific challenges have been:

1. To implement a self-learning, multimodal BCI system (EEG, EMG). The BCI should provide information on tremor onset and other related information, e.g. tremor frequency and affected joints.
2. To complement BCI related tremor information by means of IMUs sensors so that kinematic information, e.g. Real Time (RT) angular position and speed, on voluntary and tremor motion is obtained at each anatomical joint level.
3. To study neurophysiological mechanisms of tremor, with a special focus on single motor unit level as a means for improving tremor characterization.
4. To develop muscle activation models in order to determine optimum FES muscle stimulation patterns for predefined limb motion and biomechanical characteristics.
5. To develop a multi-channel addressable array FES system for selective muscle stimulation.
6. To explore biomechanical tremor suppression through feedback-controlled FES without affecting voluntary movement. This involves: (1) Detecting tremor onset; (2) Detecting and tracking tremor and voluntary motion; (3) Determining muscle activation patterns for active tremor reduction (out of phase muscle activation) and semi-active tremor reduction (muscle impedance modification); and (4) Optimizing FES patterns.
7. To implement the system in an aesthetically appealing wearable garment.
8. To clinically and functionally validate the TREMOR system in order to investigate long-term effects of chronic FES. Complement the clinical validation with a usability analysis.

In the specific area of BCI research as well as in the field of decomposition of EMG, we proposed strengthening the original TREMOR consortium and activities in the following crucial themes:

1. Increasing robustness in the TREMOR BCI concept by systematically testing different EEG artefact suppression techniques (as one of the main limiting factors for robust signal processing and feature extraction) with respect to: (a) effectiveness of artefact suppression; (b) tremor extraction; (c) negative and positive impacts of artefact removal to EEG classification and detection of tremor onset from EEG; and (d) computational insensitivity and suitability for online processing.
2. Implementation and validation of novel techniques for tremor onset/offset detection in EEG, e.g. in the field of dynamics dependency analysis of multiple data streams and in the time-series analyses. This activity should follow experimental testing of different feature extraction techniques from artefact-free EEG acquired in different experimental conditions.
3. Development and validation of techniques for decomposition of non-invasively acquired surface EMG compound signals, e.g. blind source separation methods, in particular those based on independent component analysis, sparse component analysis and on the novel convolution kernel compensation (CKC) technique. These techniques would be used to further illuminate the physiological mechanisms contributing to muscle tremor and to further outline the connection among brain waves and EMG tremor patterns.
4. Development and validation of advanced techniques for extraction of information from spatially and temporarily heterogeneous and multimodal data streams, including standard coherence/correlation...
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The TREMOR consortium set up a methodological approach and a work plan to attain project’s objectives. This work plan consisted of nine (9) work packages, which are briefly described in the following paragraphs:

WP1: Elicitation of User Needs & Neurophysiological study was coordinated by Université Libre de Bruxelles (ULB, Partner 4) and led by Prof. M. Manto. A summary of this WP objectives is as follows: (1) Selection of users representative of relevant tremor groups: essential (postural), Parkinsonian (rest) and intentional (kinetic); (2) Selection of a control group; (3) Neurological, electrophysiological (evoked potentials) and imaging study (Brain MRI, PET) of patients to be recruited for the user analysis and clinical trials; (3) Analysis of the state-of-the-art, in particular of the results of the previous DRIFTS project; (4) Definition of neurophysiologic aspects for the development of the TREMOR system: target anatomical joints, target muscle groups for the EMG part of the BCI, target muscle groups for the FES tremor suppression system; (5) Definition of testing protocol: double blind protocol, placebo effect, tasks (both clinical and functional), and request to the ethical committees for approval; and (6) Definition of metrics and evaluation criteria.

WP2: System’s conceptual design was coordinated by Instituto de Biomecánica de Valencia (IBV, Partner 2) and led by Dr. J.M. Belda. The objectives of this WP have been: (1) To develop a concept for the TREMOR system in terms of tremor groups to be addressed, anatomical joint to be covered and overall system architecture; (2) To incorporate user needs and user criteria in the design of the system; (3) To outline a concept for the multi-channel BCI and FES system, including number of recording and stimulation channels and a first proposal for the electronic and control structure; (4) To develop a conceptual design of processing algorithms: algorithms for tremor onset detection as well as frequency and amplitude estimation, concept control strategies for both the active and semi-active tremor suppression strategies, a first estimation of computational burden; and (5) To develop a conceptual design for the integration of the active system in an active garment, including a first selection of adequate flexible energy supplies.

WP3: Multichannel EEG, EMG and IMU recording and FES system design and development was coordinated by Aalborg University (AAU, Partner 5) and led by Prof. D. Popovic. The objectives of this WP have been: (1) To design and prototype the control and power electronics for a multi-channel recording and stimulation system according to the conceptual design. Each channel in the system should be independently addressable; (2) To test tremor identification algorithms from WP4 and control strategies from WP5-WP6 on the control electronics; (3) To integrate the system in a mock-up garment for functional tests with patients; and (4) Optimization according to the results of functional tests.

WP4: Multimodal BCI for tremor identification, characterization and tracking was coordinated by Consejo Superior de Investigaciones Científicas (CSIC) and led by Prof. J.L. Pons. The objectives of this WP were: (1) To develop a BCI system based on motor bioelectrical activity (CNS and PNS) of the subject. The system should deliver voluntary movement intention and tremor onset at each muscle group in all anatomical joints defined in WP1 and WP2; (2) To complement the BCI system with biomechanical information (from solid state accelerometers and gyroscopes) to fully characterize tremor at each joint; (3) To test BCI algorithms both with data obtained from DRIFTS databases (laboratory tests) and with users after programming the BCI on the control architecture of WP3; (4) To evaluate the dynamics of tremor, i.e. tremor migration and tremor fluctuation, under the application of load; and (5) to assess the performance and computational complexity of different sequential compound signal separation techniques suitable for real-time extraction or enhancement of component corresponding to tremor from reduced set of EEG channels; (6) to implement and validate self-adaptive tremor detection from EEG; and (7) to characterize and quantify tremor in neural drive to muscles.

WP5: Musculoskeletal inverse dynamic model was coordinated by Università degli studi Roma Tre (Partner 3) and led by Prof. T. D’Alessio. The objectives of this WP have been: (1) To develop a Real Time inverse dynamic model of the human upper limb musculoskeletal system suitable for implementing the control strategies of WP6; (2) To study and develop a model for the semi-active control strategy; (3) To study and develop a model for the active control strategy; (4) To test and optimize the models with a partially
integrated version of the TREMOR system before the integration phase; and (5) To quantify the computational burden associated to this model and the optimization of the implementation.

WP6: Control strategies for FES active & semi-active tremor suppression was coordinated by CSIC and led by Prof. J.L. Pons. The aims of this WP were: (1) To link the information provided by the BNCI on tremor characteristics (WP4) and the inverse dynamic musculoskeletal models (WP5) in semi-active and active tremor suppression strategies to be programmed on the control electronics (WP3); (2) To develop an impedance control approach for the semi-active tremor reduction strategy; and (3) To develop a model-based control approach for the semi-active tremor reduction strategy.

WP7: System integration was coordinated by Technaid (partner 8) and led by Mr. J. Roa. The objectives of this WP were: (1) To integrate all the system components (BCI electronics and electrodes, stimulator, control system etc.) into an active garment for tremor suppression. The system will be ready for clinical trials in several prototypes (at least two for each testing location); (2) Final selection of the textile substrate amongst commercially available orthotic garments; (3) Final selection of flexible polymeric batteries to be integrated in the active garment; and (4) Functional tests in the laboratory.

WP8: Functional and clinical validation. Usability analysis was coordinated by ULB and led by Prof. M. Manto. The objective of this WP was to execute the testing protocol defined in WP1 for the validation of the prototype. A representative set of users will be selected to conduct the trials. Usability issues will be evaluated: success/failure rate in performing the defined tasks, time cost, adaptive difficulty, subjective evaluation, etc.

WP9: Exploitation and dissemination was coordinated by Technaid and led by Mr. J. Roa. The objectives of this WP have been: (1) To investigate the possibilities for commercialization of TREMOR outcomes; (2) To investigate commercialization of sub-outcomes of TREMOR; (3) Protection of exploitable results; and (4) Dissemination of scientific results.

1.3 Description of the main S&T results (Confidential)

1.3.1 User needs and neurophysiologic study (WP1)

In the framework of this task, we implemented the mediation between clinicians and users and the project research activities. In so doing, the following research activities have been performed. Results for this research activity have been collected in Deliverable D1.1 and Deliverable D1.2.

Updated analysis of the state-of-the-art

The international literature has been reviewed on a regular basis. In this context, a continuous review and analysis of the literature has been carried out to have a continuously updated state-of-the-art available. In particular, the analysis referred to the following topics:

- Functional Electrical Stimulation (FES) studies with special attention to the standardization of the stimulation parameters and to the application in a rehabilitation framework.
- EEG data processing to detect movement intent, targeting Human Machine Interface applications.
- sEMG processing for event detection with special focus on the activation patterns associated with tremorous movements.
- Musculo-skeletal modelling in a 3D environment for the simulation of upper limb movements under the relative degrees of freedom.
- Biologically inspired modelling for motor control in order to apply the theoretical work presented in literature into the applicative framework of smart control of neuro-prosthetic devices.

Three documents have been issued along the project lifecycle including annual updates of this literature review.

Selection of tremor groups and representative users & Definition of criteria for the selection of users to be involved in every phase of the project
In the framework of this task, criteria to select the patients were defined. Two tremor groups have been considered, Parkinson tremor and essential tremor. The table below includes a description of patient involves along the project.

User needs analysis

Patients have been questioned about their independence and ability in daily living activities by using the following questionnaires: Schwab and England Activities of Daily Living scale, Extended ADL score according to Nourie and Lincoln scale.

ULB team have generated a new scale called ADL-T24. The scale includes a core of key-activities, which cause functional problems, social problems or a combination of functional and social difficulties. These activities have been extracted on the basis of interviews about the main difficulties of our patients.

ULB started the validation of the ADL-T24, an ADL questionnaire specifically devised for tremor patients. The scale includes a core of key-activities, which cause functional problems, social problems or a combination of functional and social difficulties. These activities have been extracted on the basis of interviews about the main difficulties of our patients.

The correlation with functional tasks (such as the 9-hole peg test) has been investigated.

Definition of the protocol to evaluate the patients

The clinical protocol developed in the framework of TREMOR included extensive information about the medical history of the patients and took into account both types of tremor being considered within TREMOR. The protocol was detailed in early stages of the project (Deliverable D1.1) and then it was updated right before the start of proof of concept (Deliverable D8.1).

Definition of protocols for usability analysis

Similarly to the clinical protocol, protocols were defined for usability assessment. These protocols were based on the following topics: 1) Definition of ergonomic requirements by focusing on the control box to achieve an easy human-computer interaction, letting all kind of users operate the system, 2) To assess the ease of use by focusing on the dressing on and off the system (Ease-of-use Test), 3) To assess the ease of learning by focusing on the operation of the control box (Easy-of-learning Test) and the performance of the Activities of Daily Living (ADL Test), and 4) To assess the comfort by focusing on the analysis of pressures and temperatures in the interface between the user and the system for each component (Comfort Test). The defined protocols were applied to users for the assessment of the aspects of usability in order to define the conceptual design of TREMOR system.

Neurophysiological study of tremor fluctuation

The kinematic and electromyography features of tremor in upper limbs have been investigated, along with EEG recordings, in order to compute: inter-muscular coherence, cortico-muscular coherence, and cortico-
cortical coherence. Neurological evaluation has been completed by brain imaging studies (brain CT-scan, brain MRI, FDG-PET study).

1.3.2. System’s conceptual design (WP2)

In this research activity, the consortium translated the users’ requirements elicited in the previous activity into a concept for the TREMOR system.

Concept design for the active garment

IBV and Smartex have jointly approached the concept design for the active garment, basis of the TREMOR system. The activity of Smartex aimed at the design and the implementation of system mock-ups to evaluate different technical solutions in terms of functionality and wearability. The design was based on the requirements provided in after the analysis of users’ requirements. The following solutions have been addressed: (1) Sleeve made of elastic fabric, with hole on the elbow to allow an easy electrode location, with pocket for the electronics; (2) Sleeve made of elastic fabric, with hole on the elbow to ensure right placement, with pocket for the electronics, dimension adjustable through the use of straps. The strap also acts as tool to increase the contact of the electrodes on the skin; (3) Sleeve realized with elastic fabric, with hole on the elbow for the right placement, with pocket for the electronics, dimension adjustable through the use of straps. The strap also acts as tool to increase the contact of the electrodes on the skin, with 3 zones with different elasticity (to insulate the electrodes regions from mechanical solicitations); and (4) Open sleeve with straps to apply the hydrogel on the electrodes before the closure of the sleeve, with the same functions of previous solutions.

The design of the fabric follows a multilayer structure for functional purposes. The sleeve consists of at least two layers, (1) the internal one made of fabric where the textile electrodes are integrated; and (2) the external layer made of elastic fabric acts as insulation layer to avoid electrical artifacts, see figure 3.

![Shaped Design](image)

**Figure 3.** Different mock ups for the active garment concept.

Concept design of BCI multimodal system

Two TREMOR systems were envisaged. A first system was based on all available modalities (EEG, EMG, IMus) while the second one is only based on EMG and IMUs. Functional electrical stimulation (FES) was to be available for both systems. The former was devoted to physiological studies performed in various research activities along the project (mostly WP4 and WP7). The latter was envisaged as the basis for the proof of concept of tremor attenuation through FES techniques.

CSIC has been involved in the development of the concept design of the real-time software architecture to acquire the information of the multimodal BCI, fuse the information and generate the FES stimulation patterns by integrating all these equipment. The second system is the one was described in the Concept design of Deliverable D2.1 and it is a wearable embodiment of the former one.

Technaid, as responsible for the integration task (WP7), defined the concept design of the system control architecture. The RT software was defined to be based on programming the BNCI acquisition software in a commercial multi-threaded RT operating system (QNX Neutrino).

Concept design of tremor suppression control strategies and FES management
CSIC focused on the concept design of the control strategies for tremor suppression based on FES. Moreover, a protocol for the assessment of these basic algorithms has been defined.

Concept design of control electronics

Technaid, as responsible for the integration task (WP7), defined the concept design of the system control architecture. As indicated above, it was based on a multi-threaded real-time operating system (QNX Neutrino).

1.3.3. Multi-channel EEG, EMG and IMU recording and FES system design and development (WP3)

In this research activity, hardware aspects supporting all sensing modalities (EEG, EMG, IMUs) as well as functional electrical stimulation (FES) were designed and prototyped. Results in this WP were collected in three deliverables (Deliverables D3.1, D3.2, and D3.3). According to the TREMOR approach (based on an iterative optimized development of software and hardware systems) these prototypes were integrated into the TREMOR platform for their validation with users. The following paragraphs summarise these developments.

Definition of the EMG and FES array

A textile based FES and EMG electrode array was developed and tested. AAU tested the array of electrodes fixed in a wearable textile for acquiring EMG signals to evaluate the feasibility. Results showed that the impedance of electrodes was very good and that the signal-to-noise ratio was high. Activities of individual fingers could be recognized.

Figure 4. Top, Layout of the electrodes; Bottom, comparison between raw (blue) and noise cancelled EMG (red) as recorded from textile electrodes.

A more in-depth analysis of textile based electrodes for EMG was implemented by AAU. They concluded that the prototype of textile electrode grid detects signals with sufficient SNR even without gel or water. The recorded signals are usually affected by large 50-Hz interference (Figure 4), however processing the signals with adaptive filtering could efficiently solve this problem. A method for reducing the 50 Hz interference has been implemented and proved effective.

Moreover, as for other recording systems for surface EMG, the signals presented large motion artifacts. Also signal processing could effectively reduce this noise source. A wavelet filtering approach was implemented and refined in collaboration with other partners.

In conclusion, with advanced filtering, which can be implemented online, the multi-channel EMG signals recorded by this first prototype of textile grid were of sufficient quality for the applications within TREMOR, even without the use of gel or water. Sawn and welded electrodes did not show substantial differences in recording performance, therefore the choice could be grounded on the production costs.

The textile electrodes were also tested for functional electrical stimulation purposes by UNA Sistemi. Results showed that the selectivity was good when each pad was separately covered with a gel. The motor threshold (intensity that elicited movement) was about 7 mA (50Hz, 300 µs-pulse duration). Pain was found to be tolerable.

Development of the EMG and EEG acquisition Hardware and Software

Based on the information provided during the Concept Design (WP2), CSIC defined, developed and validated a portable hardware for the acquisition and process of EEG information. The system was developed in a
modular approach and is able to acquire and amplify the information from 8-channels. The electronic architecture of this hardware is open so it is compatible with other devices. The output of the device, i.e. data saved, was compatible with BCI2000 standard. This means that the data saved by this system can be easily read by any Matlab routine developed for BCI2000 standard. Validation of the hardware was performed with successful results.

This development was considered by the review team of marginal value to the project and the consortium was advised to concentrate on the core activity of the project. Further developments were abandoned.

AAU was responsible of the definition of the multi-channel electromyography (EMG) recording system. The task included the selection of the hardware suitable for the reliable detection of the tremor parameters with portable real-time equipment. Based on previous experience, AAU developed a new EMG amplifier that allowed the simultaneous recording of intramuscular and surface EMG signals.

As to the FES hardware, CSIC developed drivers (Linux and QNX Neutrino) to integrate the UNAFET8 stimulator (see next task) to the TREMOR platform. Moreover, a Simulink model was developed to integrate UNAFET8 stimulator to Matlab, this allowed a platform for rapid testing novel control approaches.

**Basic FES controller design**

The First FES system (the UNAFET8 stimulator) was designed following the concept of the TREMOR project defined according to User Requirements. Technical aspects of the first FES system design met the outcomes of Clinical, Functional and Usability aspects (Deliverable D1.1 and Deliverable D1.2).

The First FES system met characteristics of subsystems tested in AAU and ULB laboratory and clinical experiments. These subsystems were developed by CSIC, AAU and UNA and include the components of the multi-channel BCI system for identification of tremor movement via EEG, EMG and IMUs recording systems.

Following the initial concept of the first FES system, a conceptual active garment was defined by IBV and STEX in interaction with AAU and UNA.

Expertise coming from AAU and UNA in electrodes applications as well as in the development of methods for selective FES was shared with Tecnaiid and STEX. Equally, Tecnaiid and STEX shared their experience with conductive materials and provided samples for testing of the First FES system.

In collaboration with CSIC and Università degli studi Roma Tre, AAU and UNA decided to provide an open platform of the First FES system that was suitable for the development of the concept of tremor suppression control strategies.

**Study of the electrodes to be activated**

An experimental protocol for the definition of optimal stimulation patterns was developed. This protocol aimed at defining the shape and position of the surface electrode for selective control of wrist extension and flexion by means of electrical stimulation.

The multi-pad electrodes used in the experiments were developed by SMARTEX and comprised 24 pads (1cm diameter) distributed over an area (7cm -10 cm) positioned over dorsal and volar aspects of the forearm. The FES (four-channel) stimulation system comprised also an oval reference electrode over the carpal tunnel. The protocol aimed at measuring seven angles: proximal inter-phalangeal and metacarpal phalangeal index and ring finger joint rotations, wrist extension/flexion and ulnar/radial rotation, and pronation/supination of the forearm.

The optimal electrode was determined as the combination of pads that led to wrist and forearm rotations being similar to the trajectories of healthy individuals. Analysing the aggregate error defined as the sum of squares of differences between the angles measured when stimulating and the angles measured in healthy individuals assessed the similarity of trajectories.

**Advanced FES controller design and prototyping**

AAU and UNA Sistemi jointly proposed a new version of FES (the so-called Advanced FES controller). The advanced FES system was designed according to a flexible concept and the specified technical characteristics. It allowed flexible research on BCI, FES, musculoskeletal models and control strategies for tremor.
suppression. All parties agreed to proceed with this new version. In this regard, UNA Sistemi: (1) Issued a communication protocol between PC and advanced FES unit; (2) Produced 15 advanced FES units. Two units were handed to AAU and four units to CSIC. The rest of them were ready to be delivered to other partners as need arose; (3) Produced PC software for setting FES parameters and start/stop function; (4) Produced PC software for boot loading new software for FES units; and (5) Provided pilot tests in Parkinson Disease patients with tremor.

1.3.4. Multimodal BCI for tremor identification, characterization and tracking (WP4)

In this research activity, algorithms for extraction of users’ intention to move, tremor onset, tremor amplitude, frequency and phase as well as techniques for improving artifact rejection (for EEG) and algorithms to analyse the neural drive to muscles were proposed out of a fusion concept of EEG, EMG and IMU information.

Development of algorithms to identify voluntary motor commands

The physical requirements for the BCI — minimal risks, low cost, portability, high temporal resolution, and fast time response — were early considered during the project proposal preparation, when EEG was selected as the most appropriate technique to implement the BCI. In the current project stage, the following additional requirements were specified for the identification procedures according to our goal and application context:

- Robustness against tremorous movements.
- Voluntary movement detection must be predictive, in order to allow an anticipative control.

In agreement with this, we decided to base the identification procedure on the event related desynchronization and resynchronization (ERD / ERS) phenomena that underlies the motor activity. Both are observable on the EEG central mu rhythm, whose features were first described by Gastaut et al. in 1952. Since then, the behavior of this rhythm with regard to voluntary movements has been largely studied. Interestingly, mu rhythm changes from a synchronized into a desynchronized mode when a voluntary movement is initiated, and the ERD precedes about 2 seconds the movement onset. The other two phenomenon were discarded due to the following issues:

- Bereitschaftspotential. This potential was initially considered since it starts about two seconds before the movement onset. It was not used finally because of its large time-constant.
- Cortico-muscular coherence. Università degli studi Roma Tre carried out a preliminary evaluation of this approach. They concluded that its high computational requirements hinder its application in real time scenarios.

Intention detection is facilitated by the stated knowledge about brain topography, signal amplitude, and frequency response of the ERD in the generality of healthy people. Nevertheless, the feasibility to detect the patient’s motor intention heavily depends on the extent to which the EEG patterns associated to ERD can be reliably recognized automatically. The main obstacle to achieve this goal is that these patterns are contaminated by spontaneous EEG activity, and the resulting signal to noise ratio is very low. Other immanent problem to the technique is the variability among subjects. Being an additional obstacle, specific for our project, the brain damages and alterations suffered by tremor patients, and the lack of knowledge about how they could affect the ERD/ERS phenomenon.

CSIC proposed to adopt a standardization of the experimental and analytical procedures consisting of: defining a common set of experimental and recording options, creating a shared experimental database, testing on it any proposed algorithm, sharing partner experiences, selecting the most effective algorithms, and integrating the resulting ones.

The experimental protocols detailed very thoroughly: instructions to patients, tasks to be carried out by patients, number and frequency of the movements to perform, movement amplitude and speed, clues given to patients during the task performing, exact timing for each and every event, etc. The protocols were designed in such a way that facilitated the later investigations on the detection of the movement intention in patients affected by tremor.

The main role of the EEG-based detector developed in the TEMOR project was to provide information about the movement intention of the subjects measured. The system must be able to work continuously and be a
usable solution for activities of daily living. This requirements lead to two main consequences that have been addressed in our proposal:

- The reduced number of electrodes used allows the system to be thought of as a daily usable solution, as stated in the DoW.

- The system is specifically developed for running online, continuously checking whether the cortical electrical activity measured corresponds to a premovement state and avoiding the usage of external cues as timing references, which means that our EEG based detector works as an asynchronous-BCI.

As the detector is supposed at first to work at the same time as the inertial and EMG sensors, its contribution to the global system relies on the principal lack of these other two sensing devices: motor activity characterization by means of IMUs and EMG can only be achieved once the movement has been initiated, so the anticipative feature of the ERD phenomenon is the main criterion for developing and optimizing the EEG-based detector.

Moreover, as the detector system must be capable of working on different subjects, it has to be able to adapt its internal processing and classifying parameters to each specific person wearing the system, and this is also an essential aspect addressed in our detector design.

Three partners were involved in this task, CSIC, ULB and Università degli studi Roma Tre. Based on these requirements, different kind of machine learning algorithms were developed by each partner and compared, ending up in the selection of a Bayesian classifier, which fulfills, fulfilling the (figure 5).

![Figure 5. Schematic design for the detection of movement intention based on EEG signals.](image)

Considering the generality of the patients a universal identification algorithm has been proposed. The algorithm has a self-learning capability, as it uses the information provided by IMUs and EEG to update periodically the patient’s motor model employed for the prediction.

The algorithm proposed was validated with data of the experimental sessions with tremor patients (ULB and IBV) and at CSIC with control subjects. The detector produced a detection of an average of 66% of the movements and less than 5 false predictions per minute are obtained in the best case.

A run interval of one of the patients measured with 7 consecutive correctly classified movements and one wrong activation during 120 seconds is shown in Figure 6.
At ULB a different approach was taken to cope with algorithm efficacy. They studied the EEG recordings in order to extract useful parameters for the project and have focused on central area of the scalp. ULB data were collected with sterile subcutaneous electrodes in order to improve the quality of the signal.

At Università degli studi Roma Tre two approaches for the detection of voluntary motor activity were developed. Both approaches follow the guidelines developed during the concept study:

1. The first approach is based on the estimation of cortico-muscular coherence (CMC) between EEG and EMG signals. The proposed design is based on a bivariate auto-regressive (BAR) representation of the signals under analysis. Parameters of the BAR model are used to characterize a closed-loop representation for the generation of the two signals, and to represent the time-frequency map of the corticomuscular coherence. Occurrences of coherence contributions in the beta band (15-30 Hz), after a significance assessment provided by a thresholding procedure, have been used to detect voluntary movement. The threshold for zero coherence has been obtained by using a surrogate data approach. A time-frequency protocol has been developed in order to determine the beginning of voluntary activity during movement based on the occurrence of significant coherence values in the beta band. In the figure below, the upper panel shows EMG with muscular activation as reference (red); the middle panel represents EMG with the output of the CMC-based voluntary motor activity detection algorithm (black); the lower panel shows the corresponding CMC map.

2. The second approach is a real-time voluntary motor activity detection algorithm based on identifying the Event Related Desynchronization and Resynchronization (ERD/ERS) phenomena. Since desynchronization and resynchronization of EEG rhythms in the alpha (ERD) and beta (ERS) band is particularly visible in selected sub-bands (depending on the subject), the algorithm segments the EEG signal in the frequency domain (sub-band filtering) and processes the single sub-band segments, making a real-time envelope estimation of the power of the de-referenced EEG signal in the selected sub-band. A dynamic threshold method has been studied and implemented in order to detect both ERD and ERS in their selected sub-bands. Information on voluntary movement onset is then gained when ERD is detected, while offset information can be obtained both from ERS detection or by voluntary EMG offset. Results of this kind of analysis are exemplified in figure 8.
Both approaches (CMC and ERD/ERS) have been tested on data recorded during consortium experimental session on tremor-affected patients. The cortico-muscular algorithm highlights clear contributions in the beta band before short wrist movements and some events in lower bands (which have been associated in literature to involuntary activity) during sustained tremor events. The algorithm based on ERD detection revealed desynchronization events in the sub-bands of the alpha band during the execution of voluntary movement with a high rate of precision. However, the approach suffers from a low specificity (high number of false positives), and the phenomenon is not clearly visible in all the subjects. In the figure below, the upper panel shows a sample of the rectified EMG along with muscular activation as reference (red), while the lower panel reports the same rectified EMG both with the output signal from the ERD-ERS-based detection algorithm (red).

![Figure 8. Sample of ERD-ERS detection results.](image)

After comparison, the Bayesian classifier was selected as final solution of TREMOR project due to its self-learning characteristic, which allow the system to adapt to the different users. Results of this classifier indicated that the amount of time anticipated is, for most of the trials detected, over the minimum time needed in order for this information to be used by the posterior tremor cancellation strategies, and the recall rate achieved shows that for most of the people measured more than 68% of the movements are anticipated. On the other hand, it is also important to note that the mean length of the AU for the pre-movement detection cases is lower than 1.5 seconds, which means that the time precision of the movement onsets estimations is very high.

The consortium carried out a detailed study of the possible relationships between the different pathologies related to tremor and some ERD features. This study is detailed in deliverable D8.2. An analysis of variance (ANOVA) has been performed on the data of all the experimental sessions carried out along TREMOR project involving EEG measurements while subjects performed self-paced movements with the dominant hand. The total dataset and the three factors considered are listed in Table A.

<table>
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<th>Diagnosis</th>
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<tr>
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<tr>
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<table>
<thead>
<tr>
<th>Condition</th>
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The dependent variables extracted for each subject measured were:
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The ERD anticipation (the length of the interval from the time at which the average ERD shows a significant decrease to the movement onset).

- The power decrease (ratio between the movement state spectrum and the basal state spectrum at the frequency where the highest difference is found).

- The frequency of the alpha rhythm.

No statistically significant difference was found between the control and patient groups as well as within the different tremor groups (different pathologies). In spite of the existence of evidences of the peculiarities of the ERD features in patients with Parkinson disease, the data collected did not show any such differences, but this might be due to the lack of a sample dataset representative enough.

Despite the low number of samples for each group, only a significant difference between the power decrease of the patient groups above and below 65 years old was found (F=8.686, p=0.016, α = 0.05) (Table B).

Nonetheless, these results were expected a priori since the influence of the age on the sensorimotor rhythms is well documented in the literature.

Development of algorithms to identify tremor onset

This task was coordinated by AAU. In this context, first, a model of the surface EMG during tremor was developed. This model constituted an attempt to combine neuromuscular models with biomechanical models and models of surface EMG generation, and served as a tool for investigation on tremor characterization algorithms based on EMG activity.

Based on literature review, experimental data obtained recording sessions, and simulated EMG from the above presented model, it was concluded that a feature of tremor EMG is a relatively clear spectral peak at the oscillation frequency. On this basis, the proposed algorithm to detect tremor onset relies on the power spectrum of the surface EMG.

As pathological tremor exhibits frequencies in the range of 3-12 Hz, only this part of the power spectrum is used for the analysis. First, the total power in this range is computed. Tremor detection is then based on fitting a Gaussian distribution around the spectral peak to estimate its width. This width is narrower in the case of tremor, Figure 9 (right), compared to conditions with no tremor, Figure 9 (left); i.e. in case there is tremor, most of the power in the 3-12 Hz range will be located within a little frequency range of the peak frequency.

<table>
<thead>
<tr>
<th>(I) Age Range</th>
<th>(J) Age Range</th>
<th>Means Differences (I-J)</th>
<th>Typical error</th>
<th>Sig.</th>
<th>Confidence Interval 95% LowerLimit</th>
<th>Upper Limit</th>
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<td>5,43331</td>
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<td>-31,1420</td>
<td>-8,024</td>
</tr>
</tbody>
</table>

Table B. Multiple Comparisons for the ERD power decrease factor. Mean quadratic error = 81,750. * α = 0.05.

- The ERD anticipation (the length of the interval from the time at which the average ERD shows a significant decrease to the movement onset).

- The power decrease (ratio between the movement state spectrum and the basal state spectrum at the frequency where the highest difference is found).

- The frequency of the alpha rhythm.

Figure 9. The principle of the tremor detection algorithm using simulated surface EMG data. The dotted line indicates the frequency with the highest power, and the arrow indicates the width of the spectral peak around this frequency.
In order to increase the robustness of the algorithm, and to avoid influence of recorded channels with poor signal-to-noise ratio, the 6 outliers (three lowest and highest values) of the detection parameter (width of spectral peak) for all 16 channels per muscle are discarded, and the detection is based on the mean value of the remaining channels, exploiting the possibilities of multichannel EMG recording. The algorithm proves to be efficient, i.e. detect tremor onset without false positives in its absence, using length of data down to 1 s, Figure 10.

This algorithm was implemented in the TREMOR platform, and was validated during the recording experimental sessions (held at Brussels during March 2010) where it served to monitor tremor onset.

Following to this validation, AAU worked on a novel method for EMG-based tremor detection. This method is based on the Iterated Hilbert Transform. The description of the algorithm and its validation on the simulated and experimental data are described in the deliverable D4.1. The IHT was used to construct a multi-component AM-FM representation of the rectified EMG signal. By using our surface EMG model, we conducted a number of preliminary simulations in which we analyzed the spectral characteristics of the obtained AM components. Specifically, we were looking into the spectral energy around the frequency of the imposed cortical oscillations. We discovered that the energy of the first component in this band was several magnitudes higher than the energy of the other extracted components, consistently in all simulated conditions, and this indicated that the first component could be used to extract the underlying tremor signal.

Therefore, to get an estimate of the tremor, the first component extracted by the IHT is band-pass filtered within the tremor-frequency range (3-15 Hz). We also discovered that the low-passed (< 3 Hz) version of the first component gives the mean value of the rectified EMG. Therefore, to get an estimate for the level of voluntary activity, the standard deviation is calculated for the estimated tremor signal and subtracted from the mean of the rectified EMG. In this way, both the tremor component and the degree of voluntary activation can be determined from the first IHT component. This is thanks to the joint action of the heterodyning capturing effect of the Hilbert Transform and the component separation obtained by the Bedrosian Theorem.

Furthermore, the algorithm output may be applied in the other aspects of the tremor-suppression system: For example, the extracted tremor-component captures information about tremor-frequency and phase, which may be used as a supplement to the parameters extracted by using inertial sensors. Furthermore, the estimation of the degree of voluntary activity may be used to assess whether the voluntary movement is occurring. This is relevant if the "stimulate-when-needed" strategy is used, i.e., the stimulation is applied only when the voluntary movement is being performed.

Since IHT was able to detect tremor onset based on EMG signals, the consortium decided to evaluate other AM-FM demodulation algorithms for tremor detection. Therefore, after evaluating the IHT approach itself, the next step was to compare our method with the state-of-the-art AM-FM demodulation techniques. We
selected two approaches: Multiband Energy Separation Algorithm (MESA) and Periodic Algebraic Separation and Energy Demodulation (PASED). MESA is a technique based on a multiband approach to separate the AM-FM components, which are subsequently demodulated by the energy separation algorithm to extract the instantaneous amplitudes and frequencies of each component. PASED can be methodologically divided into two procedures: 1) the separation of the multicomponent AM-FM signal into mono-components using periodicity-based signal modeling and algebraic separation techniques, and 2) the AM-FM demodulation of each mono-component using the energy separation algorithm.

The three methods were tested by using simulation-generated data. Our model of surface EMG during tremor was used to generate 995 surface EMG signals encompassing 80 different simulation settings, i.e., five tremor frequencies (4, 6, 8, 10 and 12 Hz) x four tremor intensities (from low to high) x four levels of voluntary activations (5, 10, 15, and 20% MVC). We decided to use the simulations to generate the data, because the parameters are set to known values, and the methods can be therefore evaluated and compared objectively. Two measures were adopted to evaluate the performance: 1) root mean square error (RMSE) in the estimation of tremor frequency, defined as the RMS of the difference between the estimated tremor frequency and the known (preset) frequency of the induced tremor, and 2) signal-to-noise ratio (SNR) of the tremor-component estimated relative to the tremor-component from the similar simulation settings but without tremor. Figure 11 shows the average RMSE and SNR for the three algorithms as a function of the frequency of the induced tremor.

![Figure 11. RMSE of estimation of the FM parameters and SNR in estimation of the AM parameters of tremor with IHT-, MESA-, and PASED-based demodulations. SNR is expressed in decibels.](image)

**Definition of inertial sensor subsystem**

In the context of this task, CSIC and Technaid led the definition of the Inertial Sensor Subsystem to be used in TREMOR. The inertial system is a new generation of IMUs based on off-the-shelf Technaid IMUs, developed by taking into account the results of the preliminary recording sessions (held at Brussels). IMUs were be used within TREMOR to: (1) work out limb posture (as a source of information for musculo-skeletal models, see below), and (2) extract tremor parameters at joint level. In particular, for the first objective of the IMU system a definition of a body to sensor calibration protocol in order to translate the recorded motion with IMU into joint rotations has been developed. This procedure permits fast sensor placement and robustness when there is uncertainty in sensor placement, as it might appear when the user is wearing the final garment.

Technaid customized its IMU product for TREMOR project. The sensor eventually developed is able to provide information about joint acceleration, velocity and position. Moreover, a biomechanical model for the extraction of this information based on IMUs sensors was developed. Technaid also developed a QNX Neutrino driver for the integration of IMU sensors in the TREMOR platform.

**Development of algorithms for tracking and extraction of tremor characteristics**

This task aimed at extracting instantaneous tremor amplitude and frequency from kinematic (IMU) information at joint level, and was coordinated by CSIC. The first step consists in characterizing joint rotations with IMUs. Differential measurement of a sensor placed distally with respect to the joint, and another one placed proximally is implemented. Both sensors have one of their axes aligned with the user’s joint. Targeted anatomical movements are: wrist flexion/extension, wrist adduction/abduction, forearm pronation/supination and elbow flexion/extension.
The proposed algorithm for extraction of tremor parameters first separates tremor patterns from raw angular data, and afterwards estimates its instantaneous amplitude and frequency. Real-time separation of voluntary and concomitant tremor motion relies on their different frequency contents, whereas tremor modeling is based on an adaptive LMS algorithm and a Kalman filter, Figure XX.

1. Estimation of voluntary movement is based on the fact that tremor alters voluntary motion in an additive manner, and that volitional movement during the activities of daily living (ADL) occurs in a frequency band lower than tremors. In fact, tremor is generally assumed to happen in the 3-12 Hz band whereas ADL are performed at a frequency below 2 Hz, (as ascertained in deliverable D1.1). The approach consists in modeling volitional motion as a first order process which is tracked with a Critically Dampened Filter, an optimal type of g-h tracker, Figure 12 (A). Based on the additive nature of tremor, removing the voluntary component from the recorded joint rotation immediately yields the tremor component of motion, Figure 12 (B).

2. Estimation of instantaneous tremor parameters is implemented by means of two algorithms. First a Weighted Frequency Fourier Linear Combiner (WFLC) tracks instantaneous tremor frequency, Fig 12 (D). This algorithm implements an adaptive Fourier model of the signal, which is fitted to the input signal based on the Least Mean Square (LMS) recursion, a gradient-like approach. Next a Kalman Filter that incorporates a harmonic model of tremor, estimates instantaneous amplitude taking into account WFLC frequency, Fig 12 (C). The Kalman filter outperforms existing tremor modeling algorithms based on its intrinsic optimal nature.

Evaluation with data from experimental sessions (held at Brussels in January 2009) yielded an average tremor amplitude estimation error of 0.001±0.002 rad/s (typical amplitude of tremor patients ranges between 1 and 2 rad/s), with frequency estimation in agreement with spectrograms.

The algorithm was implemented in the TREMOR control architecture. Moreover, it has been validated in two recording sessions following the stepwise validation of partially integrated components. During the session held at Brussels in January 2010 the algorithm was employed to analyse tremor characteristics in real-time, while during the session held during March 2010 the algorithm was employed to trigger compensation strategies based on the detection of tremor onset.

Algorithms for modality fusion
Research activities in this area were coordinated by CSIC with contributions from AAU and Università degli studi Roma Tre. First, integration of the different modalities included in the tremor BNCI were implemented. Modality integration responds to a hierarchical architecture, see figure 13. First, BCI information indicates the user’s intention to move, which implies that if tremor appears the system must compensate for it. Next, EMG information monitors tremor onset, pointing out that the system has to suppress it when it appears. FES based tremor suppression will be driven by instantaneous tremor parameters provided by the IMUs.

This hierarchical approach presents a number of advantages: (1) the patient will not be stimulated if tremor does not pose a functional issue, i.e. when there is no intention to perform a task, and (2) the patient is not stimulated in the absence of tremor, as tremor may not appear during the execution of certain movements.

![Figure 13. Hierarchical integration of sensor modalities to drive FES based tremor suppression.](image)

**Algorithms for advanced suppression of EEG artefacts and tremor extraction.**

The objectives were to implement and assess compound signal separation techniques suitable for real-time extraction and enhancement of the component corresponding to tremor from reduced set of EEG channels.

In summary, 51 different Independent Component Analysis (ICA), Empirical mode decomposition (EMD) and Principal Component Analysis (PCA) algorithms have been tested and mutually compared for efficiency in suppression of 14 different types of EEG artefacts, enhancement of tremor-related EEG component and computational complexity. The best compromise between the stability of convergence, artefact rejection and computational complexity was demonstrated by the SOBI and AMUSE algorithms. RUNICA algorithm produces the highest artefact rejection ratios, but at the costs of processing time, whereas fastICA demonstrated excellent average performance but suffered from unstable convergence (regardless of the number of EEG channels employed) and relatively large computational costs in the case of 10 or more EEG channels.

![Figure 14. Spatial maps of three independent EEG components: a) as identified by the SOBI algorithm applied to different repetitions of the Rest task (RE1 and RE2), and b) as identified by the SOBI and RUNICA algorithms when applied to the same set of EEG signals of Arms Outstretched (AO) task. Blue color corresponds to negative values, red to positive values. Due to the amplitude ambiguity of ICA algorithms, the polarity of spatial maps may be switched during the different runs (e.g. central and right plot in a). Images were created by sLORETA tool [Pascual-Marqui 2002]. Values of missing EEG electrodes have been interpolated.](image)
A selected subset of ICA algorithms (SOBI, AMUSE, RUNICA, fastICA and JADE) were mutually compared on EEG from 8 additional tremor-affected patients (experimental protocol in Valencia, December 2010). All together, 13-channels of EEG (FC3, FCz, FC4, C5, C3, C1, CZ, C2, C4, C6, CP3, CPZ and CP4 electrodes) were recorded during three repetitions of different daily activities (arms resting on the lap, arms outstretched, finger-to-nose and finger-to-finger tasks). The convergence stability of ICA algorithms was tested by mutually comparing: a) the mixing matrices identified by the same ICA algorithm on pairs of consecutive repetitions of the same task, and b) the mixing process identified by two different ICA algorithms from the same set of EEG signals. In both cases, the Amari index was used to measure performance.

When applied to EEG signals from consecutive repetitions of the same task (e.g. RE01 and RE02), the SOBI algorithm identified 8 ± 2 common components in both tasks (Figure 14). In the same setup, RUNICA identified only 4 ± 1 common components. On average, when SOBI and RUNICA were applied to consecutive repetitions of a task, they both managed to identify 4 ± 2 common components, which confirms the stability of independent component extraction process.

Algorithms for advanced extraction of tremor onset from EEG.

This task was coordinated by UM. The main objective was to propose and validate adaptive tremor detection and classification techniques to be combined with preprocessing techniques developed in the previous research activity. The potential breakthrough was achieved by adapting the previously developed Convolution Kernel Compensation algorithm to the EEG signals and by using information about characteristics of individual motor units discharge patterns during tremor (see next research activity).

The CKC decomposition of EEG was further tested on 24 additional tremor patients recorded in Valencia (June 2010, Dec. 2010, June 2011). Out of the last 16 patients, tremor-related EEG component was consistently extracted from 12 patients, whereas in 4 patients the tremor-related EEG component was extracted in approximately half of recorded tasks only.

Time delay between extracted tremor-related EEG component and tremor component from rectified EMG has also been assessed by using cross-correlation of tremor components extracted from EEG and rectified EMG. Results from 22 tremor-affected patients show that the EEG-based tremor component anticipates the EMG-based component for around 19.7 ± 13.1 ms (Figure 15), in agreement with previously observed cortico-muscular time-lags.

![Figure 15. Time delays between extracted tremor-related EEG component and rectified surface EMG for different EMG channels (left subplot) and time delays between rectified EMG from different channels and extracted tremor-related component (right subplot). EMG was recorded with a grid of 64 surface electrodes during the Arms Outstretched (AO) task of a tremor affected patient. Mean value of EEG-EMG delay (18 ms) is well within the physiological limits reported by other independent studies [Raethjen et al. 2007, Rothwell et al. 1991], whereas the observed mean value of EMG-EEG delay (36 ms) is not.

Characterization and quantification of tremor in neural drive to muscles

A novel Kernel Compensation (CKC) algorithm for decomposition of high-density surface EMG during tremor has been developed and validated on signals from 6 tremor-affected patients (experimental session in Valencia, June 2010).
During the last months of the project, this algorithm has been thoroughly tested on additional sets of synthetic and experimental signals from 16 tremor-affected patients. Synthetic signals were generated with advanced EMG simulator developed by AAU partner (see description above). Three tremor frequencies were simulated (5 Hz, 8 Hz and 11 Hz) and each tremor frequency was combined with four different excitation levels (0%, 5%, 10% and 20% of maximum voluntary contraction - MVC). Experimental signals were recorded in Valencia (December 2010 and June 2011).

The results on synthetic signals demonstrate high performance of surface EMG decomposition. In the case of simulated tremor with central frequency at 5 Hz and 20 dB SNR, the newly proposed method identified ~10 motor units with sensitivity of motor unit discharge identification ≥ 95% and false alarm and miss rates ≤ 5% (average over all excitation levels, except 0% MVC). This number decreased with increasing noise power and reached ~8 motor units for 10 dB SNR and ~4 motor units for SNR of 0 dB. At higher tremor frequencies (8 Hz and 11 Hz), the number of identified motor units decreased in most of the cases, although this decrease was not significant (Wilcoxon rank sum test, P=0.05). Moreover, in a few cases the number of identified motor units increased with the tremor frequency. For example, the highest average number of identified motor units was observed at the tremor frequency of 8 Hz, excitation level of 20% MVC and 20 dB SNR.

In experimental high-density surface EMG signals, recorded from 22 tremor-affected patients (experimental sessions in Valencia, June and December 2010, June 2011), the modified CKC technique identified 2490 motor units (6 ± 4 motor units per contraction). The number of identified motor units varied significantly over different contractions (range from 0 to 22), with the lowest average number of identified motor units during the rest condition.

In conclusion, the performance of the proposed CKC decomposition method was sufficiently high in all tested conditions, although it is not completely independent of the tremor frequency. The method demonstrates potential for physiological studies of motor unit behaviour in pathological tremor, optimization of tremor treatment and tremor diagnosis. Detailed results of these studies have been reported in Deliverable 4.3.

The possibility of assessing the neural drive to muscles from motor unit spike trains, and not from the crude EMG signal, motivated our study on the physiological mechanisms that underlie tremors from a motor unit perspective. Therefore, we employed the multi-scale model of tremor developed in TREMOR to investigate against the hypothesis that tremor constitutes a common synaptic input to the whole motor unit pool. Our simulation analysis indicates that in such condition, the major features reported in intramuscular analysis of tremors, namely enhanced motor unit synchronization (Figure 16) and paired and tripled discharges appear, which validates the assumptions of the model to a certain extent. Moreover, the model suggests that the correlation/coherence amongst groups of motor units (the so-called cumulative spike trains) increases as more motor units are considered together, until a plateau is reached. Such plateau indicates a saturation of the motor unit pool when transmitting the tremor, and is a consequence of linear transmission of the synaptic input. Our experimental analysis is in agreement with these findings.

![Figure 16](image-url)

**Figure 16.** Analysis of the characteristics and neurophysiological implications of motor unit spike trains in tremor: (a) estimation of motor unit synchronization with the Strength of Common Input (CIS) [Nordstrom1992], which is 8.225 for this case (in the absence of tremor, the CIS is 0.203), and (b) boxplot showing the correlation between 80 random CSTs comprising from 1 to 10 MNs and the tremor oscillator (800 in total).
1.3.5. Musculo-skeletal inverse dynamic model (WP5)

In this research activity, the TREMOR consortium led by URT developed direct and inverse musculo-skeletal models. These models were foreseen to provide feed-forward FES parameters to be used in the control scheme. It was soon apparent that customisation of these models was going to be a difficult task and then the consortium proposed the use of these models to support a benchmarking platform were the effect of FES parameters could be assess prior to actual tremor suppression.

Development of dynamic modeling algorithms for each joint under relative degrees of freedom.

A musculo-skeletal model of the human upper limb has been developed. Modelling and technical choices have been based on adaptability and modularity of the chosen environment with respect to the model to be developed. Simulation environments are based on the MSMS and Virtual Muscle open source code by USC with Simulink porting for the dynamic analysis. This software, customizable at various levels, enables the user to develop accurate models of human and prosthetic limbs and simulate them to predict their movements in response to different control strategies and external perturbations. Muscles are modelled as a combination of elastic and contractile elements including also the properties of the tendons. Contractile elements produce force as a function of recruitment, frequency modulation, length and velocity, including viscoelastic elements for passive muscle force. Passive elastic elements represent series compliance of tendons and aponeuroses. The inputs to the model are the activation functions, that incrementally recruit the motor units modulating their firing rate, and the muscle lengths.

The skeletal model takes into account 3D movements obtained as a combination of the following degrees of freedom: elbow flexion-extension and forearm pronation-supination, wrist flexion-extension and adduction-abduction. The muscular model is constituted by 14 muscles of the upper limb (Bicep Long Head, Bicep Short Head, Tricep Lateral Head, Triceps Long Head, Tricep Medial Head, Brachial, Brachialis, Pronator Quadratus, Pronator Teres, Supinator, Flexor Carpi Radialis, Flexor Carpi Ulnaris, Extensor Carpi Radialis, Extensor Carpi Ulnaris). Physiological properties of muscles have been obtained from data provided by the literature.

Given the need for specific customization of model parameters, a decision was taken to use this musculo-skeletal model to develop a benchmark platform. The design and development of a software benchmark platform on which the musculo-skeletal direct and inverse models could run off-line was then the objective of further research activities. This is fed by IMU data collected patient by patient. In this way, insights on the best stimulation parameters to be used during FES treatment can be obtained.

Development of the Adaptive Inverse Internal Model of the arm

This research activity aimed at the design of an Inverse Model-Controller (IM-C), that is an Inverse Model of the arm to be used for the Control of the FES. IM-C can be tailored to the patient’s characteristics and to the implementation of the control strategies. Two different models for two different control strategies (namely the Active Control Strategy, ACS, and the Semi Active Control Strategy, SACS) have been studied thus giving rise to the delivery of two different models called as IM-ACS and IM-SACS.

The work has been divided into two parts: i) the first part studied, designed and implemented an inverse model of the upper limb to be used for the active control strategy, IM-ACS. The technical choices and the technical characteristics were provided in the first activity report and are only summarised in the following lines for the sake of completeness; ii) the second part developed an inverse model of the upper limb to be used in the semi-active control strategy, IM-SACS. This model aims at mapping the desired kinematic properties of a given joint (i.e. stiffness, inertia) to the co-contraction level for the muscles acting on that joint.

The IM-ACS is fed by the desired motion (or force) of a given anatomical joint (at least the wrist flexion-extension and adduction-abduction, the elbow flexion-extension and the forearm pronation-supination) and gives as output the muscle activation patterns (MAPs) to be used to stimulate muscles out-of-phase for tremor reduction. The model was implemented by Artificial Neural Networks (ANNs) in order to be used in a biologically inspired tremor controller that combines feed-forward and feedback mechanisms. An ANN for every muscle was implemented and was trained to provide, in correspondence to the kinematic data (i.e. torque) of a tremor sequence, the MAPs that generated it. These MAPs are used to set the stimulation...
parameters for an active (out-of-phase) FES control strategy. Technical details about implementation and preliminary results were reported in the deliverable D5.2. The effectiveness of the stimulation strategy was assessed in terms of the power of the residual tremor after the stimulation, that is interpreted as an indicator of the correctness of the state predicted by the model and, consequently, as a measure of the effectiveness in tremor reduction.

The IM-SACS aims at reducing tremor by modulating the biomechanical impedance characteristics of the human arm. The input to the model is the desired mechanical impedance at a given anatomical joint, and the output is a MAP able to provide the requested input impedance. The wrist flexion-extension and the elbow flexion-extension are considered as the relevant anatomical DoFs as suggested by the results obtained in WP1. The output MAP will be used to stimulate the tremulous muscles with a defined co-contraction level, in order to reach the desired stiffness at the joint and reduce tremor.

The IM-SACS is composed by two three-layer ANNs corresponding to the DoFs taken into account (elbow flexion-extension and wrist flexion-extension). Input to the ANNs is the desired apparent impedance at one joint, together with the actual tremor frequency and the maximum angular velocity recorded in the last tremor sequence; the output of each ANN is provided by one neuron returning the co-contraction level (i.e. a real number in the range 0÷1) that is used to dimension (amplitude modulation) the MAP needed to obtain the tremor reduction.

![SACS scheme](image)

**Figure 17.** SACS scheme. Each ANN is fed with a desired stiffness level at one joint and provides the MAP corresponding to the co-contraction level needed to reach that biomechanical state, by stimulating the muscles that control that particular DoF (Radio-Carpal RC, Humero-Ulnar HU).

The desired impedance is represented by the stiffness (chosen as the representative parameter for the impedance characteristics) that is estimated by the Biomechanical Arm Model (BAM), developed in the previous research activity. In this framework the BAM receives an external tremor torque to one DoF and allows to measure the corresponding angular displacement of the simulated tremor movement. The apparent stiffness at the joint is calculated as the ratio between the torque and the angular displacement.

The tremor frequency, as provided by the EMG algorithms described in the previous heading, is used as input in order to take into account the dependency on frequency of both muscular activation and limb impedance and the maximum angular velocity contains information related to the actual tremor amplitude.

![ANN structure](image)

**Figure 18.** Structure of the ANNs implementing the inverse model for the semi-active control strategy. Output co-contraction level is determined as a function of the 3 input variables.

The training set is constructed by simulating tremor movements under different conditions. Tremor is modelled by applying to the BAM a pseudo-sinusoidal external torque acting on the joint. Different tremor-induced movements with frequency in the range (3-12) Hz and co-contraction levels between 0 and 1 are
simulated; the corresponding values of stiffness, as measured after the simulation, are used as the training set for the ANNs implementing the IM-SACS.

Implementation of the algorithms under real time environment

A C++ Neural Network package suitable for the integration of the inverse model in the TREMOR platform has been designed and delivered to the consortium integration team. The ANNs for ACS and SACS have been trained under Matlab environment using the BAM as described before. Biases and weights of the trained ANNs can then be exported in a C++ Neural Network environment that has been specifically developed. Once the object net has been created and initialized with the weights and biases, it is possible to use it for the simulations.

The nets implemented for the active control strategy have 30 inputs, 150 hidden neurons and 30 outputs, with transfer functions “tansig” for the hidden layer and “sigmoid” for the output layer. Since the ANN package implementing the active control strategy works on a 30 samples window, it has been set to work in a sample by sample way, updating the network output at each new sample of the incoming data stream of angular velocity. In this way, the on/off muscle activation pattern can be provided at each time step by taking into account the forthcoming sample of angular velocity. Such a strategy makes it possible to drive the stimulator on/off timing in real time, by applying the resulting activation pattern for one muscle to the antagonist one.

The ANNs implemented for the IM-SACS have 3 inputs, 15 hidden neurons and 1 output, with transfer functions “tansig” for the hidden layer and “sigmoid” for the output layer.

In vitro testing

The musculo-skeletal direct and inverse dynamic models were tested in vitro after the development of software dedicated to simulation purposes. This software represents the core of a test platform to be used to simulate the effect of the delivery of the FES patterns on a patient-by-patient basis under varying conditions such as planar and three-dimensional movements.

The platform contains: (1) ANNs implementing IM-ACS to link FES patterns to joint torque or force; (2) ANNs implementing IM-SACS link FES patterns to limb impedance; and (3) BAM model for the simulation of arm movements before and after the FES patterns delivery for tremor reduction.

IM-ACS and IM-SACS can be run sequentially in order to assess the best strategy on the basis of several elements such as patient, tremor and movement characteristics. Patient characteristics can be considered in a calibration phase where BAM model is tuned on anthropometric data and ANNs implementing IM-ACS and IM-SACS are trained by using data set specifically obtained on the patient.

The BAM’s tuning is carried on by modifying a number of patient-specific parameters such as:

- Length and masses of the segments constituting the skeletal model
- Muscle lengths
- Muscle attachment points
- Muscle Specific MVC
- Distribution and number of motor units driving each muscle contraction

The training sets for ANNs can be constructed by using either experimental data (to be extracted from IMU recordings acquired during sessions with the patient) or simulated data extracted from BAM. Even if the experimental sessions with patients could appear uncomfortable and time consuming, they can be considered indeed as: 1) an useful step in terms of promoting the familiarization of the patients with the experimental set-up; 2) an initial cost to be paid for increasing the effectiveness of the treatment thanks to the knowledge about the best strategy to apply which can be obtained after the simulation.

1.3.6. Development of a model for selective FES muscle stimulation (WP6)

Work has been focused on the refinement of our methodology for calibration of FES parameters, and development and evaluation of two closed loop tremor suppression strategies: the so-called semiactive strategy which is the implementation of a co-contraction of antagonist muscles and the so-called active strategy which is the implementation of opposing forces by FES of antagonist muscles.
Development of a model for selective FES muscle stimulation.

Three main activities have been developed in the framework of this research activity. The first one, coordinated by Università degli studi Roma Tre, is the development of a two-step model that simulates nerve recruitment when FES is applied via surface electrodes. The model is employed to understand the mechanisms—and benefits—underlying stimulation with matrix electrodes, and to justify hypotheses raised by experimental findings. In parallel, IBV has developed a single joint model which parameters can be easily estimated in a single step. This model was implemented in the TREMOR platform for the experiments with patients, and exploited by tremor suppression strategies. Finally, work on these models was complemented with a selectivity protocol coordinated by CSIC. This closed loop selectivity protocol is fundamental to identify the optimal stimulation sites and parameters when the user wears the system.

**Two-step model to simulate nerve recruitment under FES**

The two-step arm model comprises a finite element model (FEM) of the passive tissue response to FES, and an active model describing nerve fibers behavior. The FEM model of the upper limb involves a simplified cylindrical multilayered structure, which comprises skin, fat, bone and muscle, Fig. 19 (a). Integration of the FEM model yields the electrical field produced into the tissues by the current injected through the surface electrodes, Fig. 19 (b), which constitutes the input to the model. The active model, on the other hand, represents the dynamic properties of the nervous system, and has been developed after the axon structure described in deliverable D6.1. Axons are grouped in nerve bundles of 100 axons located at different depths, which typology and diameter as distributed following Fig. 19 (c). The two-step model takes as inputs (to the passive tissue model) the electrode configuration and stimulation parameters, and yields nerve recruitment and the strength duration curve (SDC).

![Figure 19. Passive cylindrical model of the arm: (a) model with bipolar electrodes, (b) example of distribution of current density, and (c) diameter distribution of 1000 axons.](image)

**Single joint FES model**

This model considers FES parameters as inputs, and provides joint angle as output. Joint impedance is also characterized. Moreover, it presents the advantage with respect to existing approaches that parameters are estimated in a single step, eluding the need of a complex experimental protocol. The proposed model includes both a physiologic representation of muscle behavior and a biomechanical characterization of a joint. Validation of the model with four users demonstrates that the proposed approach constitutes a reliable model of FES stimulation of the wrist, with adjusted R^2 over 0.97. As the model fully captures the frequency response of the system, it constitutes the basis for the implementation of the semi-active control strategy, see next research activity.

A simplification of the model by considering the stimulation amplitude as only input was implemented. The advantage of the model is that it can be adjusted for each muscle with only 5 stimulation bursts (of 1 s each), which renders it interesting for implementation into a stand-alone device. The model was evaluated in a group comprising 8 individuals (one of them an essential tremor patient), with very good results in terms of R^2 for most of the movements (R^2>0.7 for 12 out of 14 movements). Figure 20 (a) shows the overall estimation of stiffness, while figure 20 (b) represents the viscosity versus torque; no clear trend in the data is observed. Both results are in agreement with the literature.
Figure 20. Estimation of joint stiffness and viscosity for all the trials: (a) means stiffness estimated from the whole dataset, (b) scatter plot illustrating the relationship between viscosity and torque.

Automatic calibration of the array of electrodes

The protocol for selectivity assessment aims at extracting the optimal geometry, i.e. combination of matrix electrodes, to elicit a certain movement minimizing discomfort and pain. The first version of the protocol consisted in sequentially stimulating all the electrodes on a muscle and evaluating the movement generated. A figure of merit evaluated the quality of the movement by computing the difference between the desired and undesired motions, which serves to evaluate the performance of stimulation of each electrode.

In a second step, this protocol has been updated by developing a smart closed loop algorithm that minimizes calibration time. The algorithm starts stimulating in the central position of the array and displaces toward the preferred direction, understood as that defined by the neighboring electrode that provides the highest value of the figure of merit. The algorithm also evaluates the minimum number of electrodes amongst the identified ones that achieve best muscle response. Figure 21 shows a flowchart illustrating the smart calibration algorithm, and an electrode geometry for two forearm poses to elicit wrist flexion and forearm pronation.

Figure 21. Smart closed loop algorithm for calibration of FES: (a) flowchart, (b) geometries defined for wrist flexion and pronation in two arm poses.

Development of a control approach for semi-active tremor suppression

The so-called semi-active tremor suppression approach relies on concurrent stimulation of a pair of antagonist muscles (i.e. co-contraction) to increase limb impedance (stiffness and/or damping), which in turn, permits filtering out the tremor while leaving the concomitant voluntary motion unaltered. The underlying principle is that an increase of joint impedance decreases the natural cut-off frequency of the joint (which transfer function resembles that of a low-pass filter), and attenuates the tremor (which frequency is in the range of 3-12 Hz) minimally affecting the volitional movement (that is in approximately 1 Hz).

We have iteratively developed and validated two closed-loop versions of this strategy. The first closed-loop version controlled simultaneously the stimulation to be delivered to both antagonists based on the
instantaneous amplitude of the tremor. The controller was updated in every tremor period taking into account the parameters derived in the current one (with the algorithms developed in WP4), which gives the approach a certain predictive nature. A look up table (LUT) that was identified previously during a calibration phase served to choose the stimulation level, figure 22 (a); an example of control output is shown in figure 22 (b). The controller here implemented was a simple proportional (P) feedback loop. This strategy was evaluated during the functional session held in Valencia in March 2011.

![Figure 22](image)

**Figure 22.** First closed-loop version of the semi-active strategy: (a) Block diagram showing the controller implemented for one joint, and (b) Example of the output of the controller during a rest task performed by an essential tremor patient; top: wrist rotation (black), tremor estimated online (red) and zero crosses (blue circles); bottom: rectified wrist motion (black) and controller output (red dashed line).

The second closed-loop version introduced a couple of modifications: i) the contraction level of each muscle was modulated independently, and ii) a (rule-based) proportional-integral (PI) controller was introduced, figure 23 (a). The first modification was motivated by the non-stationary physiologic response of the muscle, which deviates the limb form the neutral position at the end of the session, due to the fact that the LUT does not account, for example, for muscle fatigue. The latter modification was introduced to account for the accommodation to stimulation and the errors during the identification of the LUT; in this version we included a simple saturation to limit the stimulation and control the current to be delivered to each muscle. Definition of such saturation (for each muscle) constitutes the only calibration that needs to be done on the user when he/she wears the system. The remainder of the control algorithm is implemented like in the previous version; an example of the control output is shown in figure 23 (b). This implementation was employed during the final functional and usability tests, held at Valencia in May, June and July 2011.

![Figure 23](image)

**Figure 23.** Second closed-loop version of the semi-active strategy: (a) Block diagram showing the controller implemented for each muscle of the joint, (b) Example of a patient with Parkinson’s disease performing a finger-to-finger test: online estimation of tremor (black) and the proportional (red) and integral (blue) components of the control action. The control actions (discrete values) are represented when they are first applied, i.e. at the beginning of a tremor period. A positive action corresponds to wrist extensors, a negative to flexors; both tremor amplitude and the integral action are scaled [x 20] for visualization sake.
Development of a control approach for active tremor suppression

The active tremor suppression strategy aims at generating an out-of-phase activation pattern of the tremulous limb in order to compensate for the on-going tremor. This approach hence resembles the noise cancelling problems often found in control literature, and implies: i) obtaining a good estimation of tremor frequency, ii) estimating adequately the severity of the tremor, and iii) identifying the required activation levels to elicit a muscle contraction that effectively matches that of the tremor. The ultimate goal is to implement a repetitive controller that uses the estimation of tremor intensity in the current period to generate a command that will be applied to the muscles in the next one.

As for the semi-active approach, we have developed two closed-loop versions of the active strategy. In the first implementation we also relied on a LUT to convert the control action to be applied to a pair of antagonists into stimulation commands, figure 24 (a). Computation of the control action for the next period follows the same scheme that for the first version of the semi-active strategy presented above. The only difference is that, in this case, selection of the muscle to stimulate is done based on the zero crossings of the angular velocity, which indicate a switch in the direction of rotation of the limb. An example of the controller output is shown in figure 24 (b).

The second closed-loop version of the active strategy implements the same modifications mentioned in the previous epigraph for the semi-active approach, namely: i) independent control of each muscle to compensate for the non-stationary nature of muscle response to FES, and ii) introduction of a rule-based proportional-integral regulator, figure 25 (a). Selection of the muscle to stimulate was again done by zero crossings, which corrected the prediction derived from the estimation of tremor frequency. An example of the final outcome of the controller is shown in figure 25 (b); it illustrates how the proportional-integral increases the control action until saturation to compensate for the tremor. This implementation was also employed during the functional tests carried out in Valencia in May and July 2011.
Figure 25. Second closed-loop version of the active strategy: (a) Block diagram showing the controller implemented for each muscle of the joint, (b) Example of an essential tremor patient performing a postural test: tremor estimated online (black) and amplitude of the stimulation pattern applied to wrist extensors (red) and flexors (blue). A positive value in angular velocity corresponds to wrist extension; tremor amplitude is scaled [x 20] for visualization sake.

Definition of figures of merit

Regarding this task, after detailed analysis of the functional experiments, we observed that the metric initially proposed to estimate the outcome of the TREMOR system, equation (1), is not the most adequate one since it does not account for the inherent non-stationarity of both the tremor and the FES-based strategies. Therefore, we decided to perform a windowed analysis of the data, and take the median of the peak at tremor frequency in both situations, equation (2).

\[ R = \frac{A_{sm}}{A_{mm}} \]  
\[ R = \frac{\bar{A}_{sm}}{\bar{A}_{mm}} \]

where \( A_{sm} \) and \( A_{mm} \) represent tremor amplitude in suppression and monitor modes respectively, and \( \bar{A}_{sm} \) and \( \bar{A}_{mm} \) their medians after splitting the data in 1 s non-overlapping windows.

Figure 26 highlights the need to account for signal non-stationarity: it compares the spectrum of the whole signal with a series of spectra calculated in 1 s non-overlapping windows; the attenuation estimated with the original method is \( R = 0.487 \) (equation (1)), while for the novel one is \( R = 0.736 \) (equation (2)). Apart from this figure of merit, we have also employed the severity as defined in previous reports.

![Figure 26](image)

1.3.7. System integration (WP7)

This research activity was aimed at bringing together system components into the TREMOR FES-based tremor suppression devices.

Selection of textiles substrate and batteries.

This task aimed at: (1) developing the active garment that will interface with the user through acquisition and stimulation electrodes and IMUs, and (2) identifying the type and power of the batteries that could be incorporated in the final product. The former was done by taking into consideration the concept design for the active garment previously described. The selection of textile substrates accounted for requirements identified in WP1. Regarding the latter, an estimation of energy consumption and use indicates that Li-ion batteries, such as the ones employed in mobile phones, constitute a viable solution.

Development of the active garment comprised two key steps: 1) selection of the optimal textile substrate, and 2) development of sewn electrodes suitable for both transcutaneous neural stimulation and recording. Regarding the selection of the optimal textile substrate, results of a focus group on “upper limb orthosis for tremor suppression” indicated that the preferred shape was a sleeve-like design. Functional and usability requirements motivated the development of an active garment with three areas with different elasticity: both
endpoints, a perspiration region in between muscle groups with a landmark on the olecranon process, and the electrode area, figure 27. Fabrics chosen were Meryl Skinlife for both the sensing and non-sensing areas, and Formentera textile for the perspiration region. Interlaced Bekiflex cables connect the electrodes with the electronics.

Figure 27. Inner and outer view of the active garment, depicting areas with different elasticity and matrix electrodes.

Component integration for stepwise integration

Technaid, in collaboration with CSIC, AAU, UNA, and STEX coordinated the integration of the different system components, namely IMU, EMG and EEG sensors and FES units, into the TREMOR platform. This integration comprised both software and hardware integration. This was done iteratively with feedback provided by users who participated in the assessment of partially integrated components.

Development of an analysis software application

CSIC coordinated this task that aimed at developing a user interface to control and monitor the TREMOR system. This interface allows the user to: 1) monitor and validate tremor suppression strategies, 2) analyse the data recorded, 3) store user information, such as clinical data, 4) compare different tremor suppression strategies, and 5) extract both voluntary movement and tremor characteristics.

Control architecture and modules

CSIC, in collaboration with Technaid, UNA, and AAU, coordinated this task that aimed at implementing the interface between the integrated TREMOR platform and the software application that drives the system.

First in this task, we identified from preliminary trials, a series of criteria to select the most adequate programming environment in which the TREMOR architecture should be built. These criteria were: 1) hard real-time features, to allow for synchronous acquisition of sensor modalities at different sampling frequencies, and to execute a robust fixed-frequency controller, 2) modularity, so that we can perform the stepwise integration, 3) possibility of programming in standard languages, to allow for an easier implementation of algorithms, and 4) ability to generate multiplatform code, foreseeing implementation in a portable device. On the basis of these criteria, the Consortium chose QNX Neutrino (QNX Software Systems, Ontario, Canada), a commercial microkernel real-time operating system (RTOS). The microkernel architecture of Neutrino implies that a very tiny kernel (a few KB), which only incorporates basic scheduling algorithms and tools for interprocess communication constitutes its core. Moreover, in Neutrino each device driver runs as a separate process that communicates with other processes, immediately allowing for a modular design. Hence, a device driver is equivalent to a user application for the operating system.

The project team was suggested by the review team to develop two prototypes in parallel. The first one would be the EEG-EMG-IMU based tremor compensation, as originally planned in the Description of Work, while the second one should be based on EMG and IMU data only. The control architecture could be adapted to meet this recommendation.

System integration and technical support to evaluation

The objective of this task was twofold: on the one hand, it should bring all the subsystems together both from a hardware and software perspective and, on the other, it should describe all the functions and protocols, during clinical, functional and usability evaluation.
As for the system integration, we have developed two platforms following previous recommendations from the review team. The first one comprises three sensor modalities (EEG, surface EMG and inertial sensors) and has been employed for physiological and BNCI aimed protocols, while the second comprises inertial sensors or inertial sensors plus EMG, and has been employed during the FES related experiments. Notably, the stimulation subsystem is integrated in both cases.

Integration of tremor detection from EEG with other components of the TREMOR device and technical support to evaluation.

This task was focused on integration of two novel Convolution Kernel Compensation (CKC) algorithms (first for extraction of central tremor-related component from multichannel EEG, second for decomposition of high-density surface EMG) into the existing tremor suppression platform of the TREMOR project. Both CKC decomposition algorithms have been ported from a Matlab prototyping environment into the C++ programming language, optimized for speed and implemented as dynamic libraries which are fully portable to both Windows and Unix-based operating systems. New C++ CKC implementations have been thoroughly validated on EEG and EMG signals from 22 tremor-affected patients (experimental sessions in Valencia, June and December 2010, June 2011) and their decomposition results compared with Matlab implementations. The results matched very well, as reported in the Deliverable D7.2.

After demonstrating that both implementations converge to the same solution, their processing time and memory consumption have been measured on the experimental EEG signals from fourteen tremor-affected patients. On a personal computer with the Intel Core i7 2.8 GHz CPU and 6 GB of memory, the C++ implementation of EEG decomposition was approximately two-times faster than its Matlab implementation (0.28 ± 0.1 s of processing time per one second of EEG recordings) and used approximately three-times less memory. The amount of required memory is still relatively high (1.7 MB for processing of 0.5 second of 28 channels of EEG) but can be controlled by the number of samples of EEG signals that are concurrently stored in the memory.

1.3.8. Functional and clinical validation. Usability analysis (WP8)

In this research activity, we aimed at reaching a proof of concept for the TREMOR system. This involved the update of testing protocols, the partial validation of system components and the final proof of concept and the analysis of clinical case studies.

Procedures for system validation.

In the framework of this task the testing protocol defined in WP1 was updated. Several experiments with patients were performed during the first 18 months of the project. These experiments induced updates in the original protocol defined in WP1. Moreover, the validation of partially integrated components of the system (see next research activity) required the elaboration of specific protocols. Specific testing protocols were created to: (1) Evaluate the sensibility to FES of people with pathological tremor; (2) Evaluate the selectivity provided by the matrix of electrodes in evoking hands and forearms movement; (3) Evaluate the semi-active FES-based tremor suppression strategy developed; and (4) Evaluate the active FES-based tremor suppression strategy.

Functional validation of partially integrated system components

This task ensured that the development of the system’s components follows an iterative approach in which components are assembled and tested, both in the laboratory and with the users, for an optimized final solution. This task involved functional trials with several representative users per tremor group (Rest, Postural) and per iteration.

In the framework of this task a number of experiments were carried out in line with the EC’s recommendations following the first review meeting. In particular, these experiments addressed Recommendation 2, “A milestone should be added to WP3 to assess the usability of the tissue electrode array before the development and integration work is started” and Recommendation 3, “It is important to verify as soon as possible whether FES is a practical solution for tremor suppression, which comfortably can be tolerated by users over practically useful lengths of time”.

- Evaluation of the performance of multimodal BCI interface in real-time. The algorithms were evaluated with tremor patients. The results were presented in deliverable D4.1. In summary, the single
trial EEG classifier was able to detect in real-time the intention of voluntary movement both in healthy and tremor users. Algorithms that process IMUs information are able to extract tremor characteristics: tremor amplitude and frequency.

- Usability evaluation of the smart textile developed by SMARTEX. This implied a test involving six volunteers. They wore the TREMOR system during three hours and an analysis of the microclimate between the sleeve and the arm of the user was performed. This test has been conducted at IBV from June to September 2010 even though the analysis phase of the data has been extended up to the end of the project. In this task also the textile electrodes have been assessed in terms of usability as part of an array of electrodes for selective FES in Belgrade (UNA) from February until March 2011.

- Functional evaluation of the smart textile developed by SMARTEX. These experiments should evaluate the performance of the textile matrix under FES stimulation and EMG acquisition. Aalborg University is performing these experiments and the result should be delivered at end of March and will be included in this activity report.

- Selectivity of the matrix of electrodes. As described in WP6.1, a protocol was defined to define the stimulation pattern of the matrix electrode to evoke hands and forearms functions. The developed algorithm has been tested in the framework of task WP8.2, and promises an easy and effective stimulation pattern definition. Results indicated the feasibility of textile based electrodes in generating selective movements.

- Pain assessment with tremor patients. In order to be able to suppress pathological tremor with FES, the level of sensation produced by the system should be acceptable for the patients. This work aimed at analyzing the sensibility to FES of different candidates pathologies for tremor suppression. 16 people took part in the analysis. 4 people of 3 pathologies corresponding to different types of tremor (Parkinson disease for rest tremor, Essential Tremor for postural tremor, ataxia for kinetic tremor) plus 4 control people without any kind of pathology. Two experiments were made simultaneously. In the first experiment, a set of low levels of intensity was applied to each person. In the second experiment, the intensity was increased to the maximum without a feel of discomfort from the user perspective. The other controlled variables were: the size of the electrode, the frequency and the muscle stimulated (flexor carpi radialis and extensor carpi radialis longus).

Final Proof of Concept

The objective of this task is to execute the validation protocol defined in the previous tasks in order to carry out the proof of concept of the TREMOR prototype. It has been coordinated and executed by IBV (Dr. J.M. Belda) with cooperation from UM, AAU, CSIC and URT. This task was planned to help define the robustness and reliability of the system. It was planned to involve trials with 5-7 representative users per tremor group (see Annex I to the contract). Tremor groups being considered are rest tremors (PD) and postural tremors (essential tremor), as it was concluded after the pain tests conducted in WP2.

Experimental sessions for this task have been implemented in IBV, Valencia, Spain. Several experimental session have been planned and conducted:

- 1. Experimental session to assess the clinical efficacy of the TREMOR system, held in Valencia (IBV) from the 22nd to the 25th of March 2011. Attendees: J.M. Belda-Lois, S. Mena and I. Busquets (IBV), A.D. Koutsou and J.A. Gallego (CSIC). This session was scheduled to evaluate the efficacy of both tremor suppression strategies while patients were performing the typical tasks employed in the clinic to trigger the different types of tremor, therefore it gave support to both work packages WP6 and WP8. Eight (8) patients suffering from Parkinson’s disease (n = 2), essential tremor (n = 5), or mixed tremor of unknown origin (n = 1) participated in the experiments; one of them had skin injuries in the forearm, and therefore no data was recorded for this subject. The data gathered served to further refine the tremor suppression strategies (WP6, reported in the updated version of Deliverable D6.1), apart from further demonstrating the feasibility of tremor suppression with FES based on both approaches.

- 2. Experimental session to assess the clinical efficacy of the TREMOR system, held at Valencia (IBV) from the 30th of May to the 2nd of June 2011. Attendees: J.M. Belda-Lois, S. Mena, I. Busquets and J.M. Laparra (IBV), and J.A. Gallego (CSIC). This session was scheduled to evaluate
tremor suppression with an updated version of both tremor suppression strategies. The performance of the system was also assessed during clinical tasks, and thus the experiments served as input to both work packages WP6 and WP8. Eleven (11) patients suffering from either Parkinson’s disease (n = 2 eventually recorded) or essential tremor (n = 7 eventually recorded) were recruited. Two patients (no clinical data available) did not realize the session: one because he refused to sign the informed consent, the other abandoned after setting up the system. Moreover, one of the nine (9) recorded did not exhibit tremor and hence did not perform the whole protocol. The outcome of these experiments served to validate the tremor suppression strategies, and to decide that during the usability trials we will only use the semi-active tremor suppression strategy, since it provided better performance according to the metrics defined, and was in general better perceived by the users.

- 3. Experimental session to acquire electrophysiological data in order to finalize the studies included in work packages WP4.6 to WP4.8, held at Valencia (IBV) from the 15th to the 17th of June 2011. Attendees: J.M Belda-Lois, S. Mena and I. Busquets (IBV), J. Ibáñez and J.A. Gallego (CSIC). This session aimed at acquiring high-density recordings of surface electromyography, electroencephalography together with kinematic data to finalize the studies on the pathophysiology of tremors (more in detail, on cortical-muscular connectivity and motor unit pool behaviour) that have been performed in the framework of TREMOR-EEU extension. Eight (8) patients suffering from Parkinson’s disease (n=3) or essential tremor (n = 5) participated in the experiments.

- 4. Experimental session on a assessment of the usability of the TREMOR system, held at Valencia on the week of the 27th of June. Attendees: J.M Belda-Lois, S. Mena, I. Busquets and J.M. Laparra (IBV), and J. Ibáñez and J.A. Gallego (CSIC). This session aimed both at evaluating the usability of the active garment form the standpoints of ease of use, comfort and cosmetics (we discarded the use of the active garment in tremor patients after the lab tests performed within the consortium, see deliverable D7.2), and at assessing the efficacy of tremor suppression strategies during activities of daily living. For this purpose a living lab that permitted the simulation of different activities, such as eating, drinking, using a key, buttoning a shirt or filling a poll was carried out. Eight (8) patients suffering from Parkinson’s disease (n = 5) or essential tremor (n = 3) were recruited and performed the evaluation. The outcome of this session was the evaluation of the usability of the TREMOR system, which is included in deliverable D8.2.

- 5. Experimental session to validate the biomechanical models developed in the framework of work package WP5, held at Valencia (IBV) on July the 18th, 2011. Attendees: J.M. Belda-Lois, S. Mena and I. Busquets (IBV), and E. Rocon and J.A. Gallego (CSIC). This session aimed at acquiring data for the validation of the inverse dynamic models developed in work package WP5. To this aim we concurrently acquired surface EMG and inertial sensor data during both FES-based tremor suppression and without it. Three (3) patients suffering from essential tremor (n = 2) and Parkinson’s disease (n = 1) participated in the study.

Revision of particular case studies

This task has been devoted to the study of particular cases in which the TREMOR system achieved unexpected results, either low or high attenuation of tremor. Two patients have been selected for the case studies. One as an example in which the performance of the tremor suppression strategies was better than expected and a second one in which the strategies failed. These two patients, selected from the earlier trials of tremor suppression have been follow-up in the physiological, functional and usability trials and they can be considered representative subjects exemplifying outlier (for better of worst) performance.

The following table summarises all experimental trials performed along the project both for the validation of partially integrated components (green sessions) and the proof of concept (yellow sessions). The table gives also details on the patients who participated in each experimental session as well as details on the specific aspects of the project that were analysed from data collected in each session.
In the table, those patients with code starting with B were recorded in Brussels (ULB), whereas those starting with V were recorded in Valencia (IBV). The column “TREMOR” indicates the type of tremor, which can be: Parkinson’s disease (PD), Parkinson plus (P+) essential tremor (ET), paraneoplastic cerebellar syndrome (PS), post-traumatic tremor (PT), extrapyramidal syndrome of vascular origin (ES), post-traumatic dystonic tremor (DT), or mixed tremor of unknown aetiology (MT).
2. Use and dissemination of foreground (Public)

A plan for use and dissemination of foreground (including socio-economic impact and target groups for the results of the research) shall be established at the end of the project. It should, where appropriate, be an update of the initial plan in Annex I for use and dissemination of foreground and be consistent with the report on societal implications on the use and dissemination of foreground (section 4.3 – H).

The plan should consist of:

• Section A

This section should describe the dissemination measures, including any scientific publications relating to foreground. Its content will be made available in the public domain thus demonstrating the added-value and positive impact of the project on the European Union.

• Section B

This section should specify the exploitable foreground and provide the plans for exploitation. All these data can be public or confidential; the report must clearly mark non-publishable (confidential) parts that will be treated as such by the Commission. Information under Section B that is not marked as confidential will be made available in the public domain thus demonstrating the added-value and positive impact of the project on the European Union.
### Section A (public)

<table>
<thead>
<tr>
<th>NO.</th>
<th>Title</th>
<th>Main author</th>
<th>Title of the periodical or the series</th>
<th>Number, date or frequency</th>
<th>Publisher</th>
<th>Place of publication</th>
<th>Year of publication</th>
<th>Relevant pages</th>
<th>Permanent identifiers</th>
<th>Is/Will open access provided to this publication?</th>
</tr>
</thead>
</table>

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1 A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

2 Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.
<table>
<thead>
<tr>
<th>4</th>
<th>“Fluctuations in isometric muscle force can be described by one linear projection of low-frequency components of motor unit discharge rates”</th>
<th>Negro F, Holobar A, Farina D.</th>
<th>Journal of Physio</th>
<th>October, 2009</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>“Adaptive band-pass filter for Tremor extraction from inertial sensor data”</td>
<td>Popović LZ, Šekara TB, Popović, MB.</td>
<td>Computer Methods and Programs in Biomedicine Journal</td>
<td>March, 2010</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>“Real-time estimation of pathological tremor parameters from gyroscope data”</td>
<td>Gallego JA, Rocon E, Roa JO, Moreno JC, Pons JL.</td>
<td>Sensor journal</td>
<td>10 March, 2010</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>“Distributed low-frequency functional electrical stimulation delays muscle fatigue compared to conventional stimulation”</td>
<td>Malešević NM, Popović LZ, Schwirtlich L and Popović DB</td>
<td>Muscle and Nerve journal</td>
<td>42(4) DOI 10.1002/mus.21736</td>
<td></td>
</tr>
</tbody>
</table>

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| 11 | “Learning arm/hand coordination with an altered visual input” | Denisia S., Iftime Nielsen, Strahinja Došen, Mirjana Popovic, and Dejan Popovic | Computational Intelligence and Neuroscience | ID 520781, 12 pages, doi:10.115 5/2010/520 781 | 2010 |
### A2: List of Dissemination Activities

<table>
<thead>
<tr>
<th>NO.</th>
<th>Type of activities</th>
<th>Main leader</th>
<th>Title</th>
<th>Date</th>
<th>Place</th>
<th>Type of audience</th>
<th>Size of audience</th>
<th>Countries addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Web</td>
<td>TCN, all partners involved</td>
<td>Project web-site</td>
<td>Start of Project</td>
<td>-</td>
<td>Research/General public</td>
<td>-</td>
<td>Global</td>
</tr>
<tr>
<td>2</td>
<td>Press release</td>
<td>IBV</td>
<td>Communication in medical magazine: Gaceta Médica Digital</td>
<td>July, 2008</td>
<td>-</td>
<td>Research/media</td>
<td>200</td>
<td>Spain</td>
</tr>
<tr>
<td>3</td>
<td>Web</td>
<td>CSIC</td>
<td>Introduction of information related to TREMOR project into Wikipedia</td>
<td>July, 2008</td>
<td>-</td>
<td>General public</td>
<td>-</td>
<td>Global</td>
</tr>
<tr>
<td>4</td>
<td>Seminar</td>
<td>CSIC</td>
<td>Organization of the International Seminar on Brain-Computer Interface (BCI). Participation of J. del Millán (coordinator of EU IP project TOBI)</td>
<td>Septe mber, 2008</td>
<td>Research</td>
<td>100</td>
<td>Global but most of the participants are from Spain</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Conference</td>
<td>UNA/AAU</td>
<td>Participation on 2008 Symposium on Neural Network Applications in Electrical Engineering (NEUREL) with the paper “External control of movements and artificial neural networks”</td>
<td>25-27 September, 2008</td>
<td>Belgrad e</td>
<td>Research</td>
<td>-</td>
<td>Global</td>
</tr>
</tbody>
</table>

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5 A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

6 A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias ('multiple choices' is possible.)
<table>
<thead>
<tr>
<th>No.</th>
<th>Event Type</th>
<th>Organizing</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Conference</td>
<td>UNA</td>
<td>Presentation of the paper: “Estimation of forearm rotation with a “virtual stick” at ETRAN</td>
</tr>
<tr>
<td>14</td>
<td>Conference</td>
<td>URT</td>
<td>WC 2009. Presentation of paper: “The role of the sEMG signal processing in the field of the Human Movement Analysis”.</td>
</tr>
<tr>
<td>15</td>
<td>Conference</td>
<td>CSIC / TCN</td>
<td>Presentation of the paper: “On the Use of Inertial Measurement Units for Real-Time Quantification of Pathological Tremor Amplitude and Frequency” at Eurosensors Conference</td>
</tr>
<tr>
<td>16</td>
<td>Conference</td>
<td>CSIC / TCN</td>
<td>Presentation of the papers: “Caracterización y Compensación del Temblor Patológico Mediante Brain Neural Computer Interface (BNCI)” and “Estimulación Eléctrica Funcional en rehabilitación: introducción, aplicaciones, futuro” at the XXX Jornadas de Automática</td>
</tr>
<tr>
<td>17</td>
<td>Conference</td>
<td>URT</td>
<td>Presentation of the paper: “Real-time adaptive neural predictors for upper limb gestures blind recognition” at EMBEC Munich 2009 Conference.</td>
</tr>
<tr>
<td>18</td>
<td>Conference</td>
<td>CSIC / TCN / AAU / UM</td>
<td>Presentation of the paper: “Evaluation of matrix electrodes for control of functional movement of the knee joint with mechanical braces” at IFESS 2009 Annual Conference</td>
</tr>
<tr>
<td>No.</td>
<td>Type</td>
<td>Media</td>
<td>Description</td>
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<tr>
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<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>19</td>
<td>Media</td>
<td>IBV / TCN</td>
<td>Appearance in Spanish TV: La Sexta Noticias. Interview to CSIC team on advances on interfacing the human and the rehabilitation robots</td>
</tr>
<tr>
<td>20</td>
<td>Conference</td>
<td>CSIC</td>
<td>“Muscle Fatigue of Quadriceps in Paraplegics: Comparison between Single vs. Multi-pad Electrode Surface Stimulation” IEEE EMBC</td>
</tr>
<tr>
<td>21</td>
<td>Conference</td>
<td>CSIC / all partners involved</td>
<td>SIAMOC 2009. Presentation of the paper: “Tremor detection and tracking through sEMG analysis”</td>
</tr>
<tr>
<td>22</td>
<td>Conference</td>
<td>URT</td>
<td>Detection of the “will to move” for an ambulatory system for tremor suppression based on functional electrical stimulation, 9th Congress of Clinical Neurophysiology with international participation</td>
</tr>
<tr>
<td>23</td>
<td>Conference</td>
<td>CSIC / TCN / AAU / UM</td>
<td>Participation on the ISSNIP Biosignals and Biorobotics Conference 2010 with the papers “Tremor suppression. Estimation of tremor time series parameters” and “Advances in Surface EMG: Applications for Better and Safer Living”</td>
</tr>
<tr>
<td>24</td>
<td>Media</td>
<td>IBV / TCN</td>
<td>Radio interview on advancements in tremor treatment.</td>
</tr>
<tr>
<td>No.</td>
<td>Type</td>
<td>CSIC / Partner Involved</td>
<td>Activity Description</td>
</tr>
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<td>----------</td>
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<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>25</td>
<td>Symposium</td>
<td>CSIC / all partners</td>
<td>Presentation of the paper: “Muscle Selectivity Algorithm For Superficial Matrix Electrodes” at 9th International Symposium Computer Methods in Biomechanics and Biomedical Engineering.</td>
</tr>
<tr>
<td>26</td>
<td>Workshop</td>
<td>CSIC / all partners</td>
<td>Participation in TOBI workshop: “TREMOR. An ambulatory BCI-driven tremor suppression system based on FES”</td>
</tr>
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<td>27</td>
<td>Workshop</td>
<td>URT</td>
<td>Participation in TOBI workshop: “Development of a real-time algorithm for ERD/ERS detection for the discrimination between voluntary and un-voluntary activity”</td>
</tr>
<tr>
<td>28</td>
<td>Workshop</td>
<td></td>
<td>Participation in TOBI workshop: “Voluntary movement detection method from tremor patients EEG on the single-trial basis”</td>
</tr>
<tr>
<td>29</td>
<td>Media</td>
<td>IBV</td>
<td>Radio interview: Introduction of TREMOR project</td>
</tr>
<tr>
<td>30</td>
<td>Media</td>
<td>CSIC / TCN</td>
<td>Appearance in Spanish TV: La Sexta Noticias. Interview to CSIC team on advances on wearable robots: a special mention to TREMOR will be done.</td>
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<tr>
<td>No.</td>
<td>Type</td>
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<td>Event Title</td>
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<tr>
<td>31</td>
<td>Conference</td>
<td>AAU/UNA</td>
<td>Presentation of the paper: “Estimation of Instantaneous Tremor Parameters for FES-Based Tremor Suppression” IEEE International Conference of Robotics and Automation” ICRA 2010 Conference</td>
</tr>
<tr>
<td>32</td>
<td>Conference</td>
<td>AAU/UNA</td>
<td>Presentation of the paper: “Soft Robotics: External control of muscles” IEEE International Conference of Robotics and Automation ICRA 2010 Conference</td>
</tr>
<tr>
<td>33</td>
<td>Workshop</td>
<td>CSIC</td>
<td>Workshop on Interfacing the Human and the Robot organised by CSIC in the framework of ICRA 2010</td>
</tr>
<tr>
<td>34</td>
<td>Workshop</td>
<td>CSIC / all partners involved</td>
<td>Workshop on Softening Rehabilitation Robotics organised by CSIC in the framework of ICRA 2010 with some papers of the consortium.</td>
</tr>
<tr>
<td>35</td>
<td>Conference</td>
<td>CSIC</td>
<td>Presentation of the paper: “Functional Electrical Stimulation: Alternative actuators in rehabilitation robotics” at ACTUATOR 2010 Conference</td>
</tr>
</tbody>
</table>

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The conference will be hosted by Aalborg University and chaired by Dario Farina, member of TREMOR in AAU’s team. E. Rocon and J.L. Pons, both members of TREMOR in CSIC’s team, will chair the session.

TREMOR consortium is organizing a special session on Tremor Management in the framework of ISEK 2010 conference. Some of the most active researches in the field of Tremor management were invited and will participate in the session. Several papers from the Consortium were presented.

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<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Date</th>
<th>Location</th>
<th>Organizers</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>Conference</td>
<td>July 2010</td>
<td>Torino, Italy</td>
<td>CSIC / all partners involved</td>
<td>Organization of a networking session on “Interfacing the Human and the Rehabilitation Robot” in the context of the upcoming ICT2010 event</td>
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<tr>
<td>38</td>
<td>Conference</td>
<td>September 2010</td>
<td>Brussels</td>
<td>CSIC / all partners involved</td>
<td>Participation in a joint proposal for a BNCI Village in the context of the upcoming ICT2010 event</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>No.</th>
<th>Event Type</th>
<th>Organizers</th>
<th>Details</th>
<th>Location</th>
<th>Year</th>
<th>Type</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Conference</td>
<td>CSIC</td>
<td>Presentation of the paper: “Activacion muscular selectiva mediante matrices de electrodos transcutaneous” at the XXXI Jornadas de Automática</td>
<td>Jaén, Spain</td>
<td>2010</td>
<td>Research</td>
<td>Spain</td>
</tr>
<tr>
<td>41</td>
<td>Conference</td>
<td>AAU, UNA</td>
<td>Participation on Zdravniski Vestnik with the paper “New trends in neurorehabilitation of subjects with central nervous system lesions”.</td>
<td></td>
<td>2010</td>
<td>Research</td>
<td>Global</td>
</tr>
<tr>
<td>42</td>
<td>Symposium</td>
<td>UNA</td>
<td>Participation on 2010 10th the Symposium on Neural Network Applications in Electrical Engineering (NEUREL) with the paper “Classification of muscle twitch response using ANN: Application in multi-pad electrode optimization”</td>
<td>Belgrade, Serbia</td>
<td>Sept 2010</td>
<td>Research</td>
<td>Global</td>
</tr>
<tr>
<td>No.</td>
<td>Event Type</td>
<td>Organiser</td>
<td>Location</td>
<td>Paper Details</td>
<td>Date</td>
<td>Research Scope</td>
<td>Global Scope</td>
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<tr>
<td>44</td>
<td>Conference</td>
<td>UM</td>
<td>Portorož, Slovenia</td>
<td>Participation on the Nineteen International Electrotechnical and Computer Science Conference, with the papers “CKC Validation on Shorter Surface EMG” and “Nineteen International Electrotechnical and Computer Science Conference”</td>
<td>Septembe r, 2010</td>
<td>-</td>
<td>Global</td>
</tr>
<tr>
<td>46</td>
<td>Conference</td>
<td>URT</td>
<td>Portorož, Slovenia</td>
<td>Participation on GNB2010 with the paper “Modelling arm behaviour under surface electrical stimulation”</td>
<td>November, 2010</td>
<td>-</td>
<td>Global</td>
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<tr>
<td></td>
<td>Conference</td>
<td>CSIC/All partners</td>
<td>Participation on the 5th International IEEE/EMBS Conference on Neural Engineering with the paper &quot;Analysis of kinematic data in pathological tremor with the Hilbert-Huang Transform&quot;.</td>
<td>April, 2011</td>
<td>Research</td>
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<td>Global</td>
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<tr>
<td>50</td>
<td>Conference</td>
<td>CSIC</td>
<td>Participation on the 2011 IEEE International Conference on Robotics and Automation with the paper &quot;A soft wearable robot for tremor assessment and suppression&quot;.</td>
<td>May, 2011</td>
<td>Research</td>
<td>-</td>
<td>Global</td>
</tr>
<tr>
<td>51</td>
<td>Conference</td>
<td>CSIC</td>
<td>Participation on the International Work Conference on Artificial Neural Networks, Special session on New applications of Brain-Computer Interfaces held in Spain with the paper “An EEG-based design for the online detection of movement intention”.</td>
<td>June, 2011</td>
<td>Research</td>
<td>-</td>
<td>Global</td>
</tr>
<tr>
<td>53</td>
<td>Summer School</td>
<td>CSIC</td>
<td>TREMOR project collaborated in the organization of the 2011 IEEE Summer School on Neurorehabilitation and specially in the organization of two workshops: -Development of a BCI system - Design and test a FES system</td>
<td>Sept 2011</td>
<td>Salamanca (Spain)</td>
<td>Research</td>
<td>100</td>
</tr>
</tbody>
</table>