Report for experiment

MȮTORE++

A new Rehabilitation Robot for the upper limb: refinement and experimental trials

D3.1 Test results

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1 Publishable Summary

The goal is to develop a rehabilitation robot named MOTORE++ aimed to restore upper limb functionality in patients with neurological diseases and to assess their performance. This is a new haptic portable device, the first suitable for home based rehabilitation. Starting from a prototype developed in the past years, the project aims at delivering a small omnidirectional robot capable of interacting with a patient, providing assistance and force feedback during rehabilitation sessions, offering several types of rehabilitation exercises. Biomechanical studies of the interaction with the robot and on the arm impedance during exercises will be part of the Echord++ experiment.

2 Work done at the RIF

Part of the work regarding the validation has been conducted in the rehabilitation clinic Auxilium Vitae, Volterra, which was was one of the RIFs proposed by the ECHORD++ consortium.

At the RIF two different studies have been conducted. One is intended for the identification and the validation of a metric for extensive patient assessment (an assessment campaign of patient treated with MOTORE++ will be conducted at the end of the project). In the meanwhile a second study has been conducted for a preliminary evaluation: the goal of this study is to evaluate the effects of upper limb rehabilitation treatment using the haptic device MOTORE++ in post-stroke subjects.

3 Brief description of the MOTORE++ device

As described in previous deliverables, MOTORE is a portable, mobile haptic interface using its wheels to deploy rehabilitation exercises. The haptic interface is equipped with a force sensor (a load cell in the handle) and omni-directional wheels, allowing force feedback interaction between the user and the robot. The analysis of the kinematics is available in [C. Avizzano, M. Satler, G. Cappiello, A. Scoglio, E. Ruffaldi,M. Bergamasco, et al. Motore: A mobile haptic interface for neurorehabilitation. In RO-MAN, 2011 IEEE, pages 383–388. IEEE, 2011]. An ad hoc developed sensor fusion policy that exploits an optimizes haptic rendering and a precise localization system, made with Anoto technology: MOTORE++ integrates an optical sensor that reads a known pattern printed on the desk to localize accurately the position and orientation of the device, and combines this information with internal data coming from moving wheels. As a consequence MOTORE++ can track its position with minimal error and provides a good choice in terms of control constructions and trajectory design. At the base of the fusion there is the measurement of the optical sensor position on the printed surface (with 0.03mm resolution) and its angular rotation. The information from the optical sensor and from the encoders readings is properly used in an Extended Kalman filter (EKF) filter running at 1kHz for estimating the absolute position of the device on the desk.

MOTORE++ has a multithreaded control systems that runs several loops in parallel. Two major control loops in the device provide the generation of the force feedback: an internal current controller running at 5KHz and a force position controller running at 1KHz. The internal DMA samples motor currents at 40KHz, then the current controller averages these samples and uses the estimated value to regulate the appropriate PWM duty cycle to the h-bridges. The controller structure also includes a feed-forward component that compensates for the expected current using the ideal switching model, and a feedback controller (a PI regulator) that uses the sensors' values to cancel the current error.

The force-position control loop developed for the execution of the exercise is governed by the following equations:

(1) $F p = (\alpha \cdot k \cdot (Pd - P) + (1 - \alpha) \cdot Fh)^T \cdot vp \cdot vp$
(2) $Fo = (k \cdot (Pd - P))^T \cdot vo \cdot vo$
(3) $Ft = F p + Fo$
(4) $Ft = Ma \cdot a + b \cdot v$

Where,

• Pd is the desired position as derived from the constrained motion policy/exercise;

• P is the actual position;

• k is the desired stiffness to gentle attract the user

towards the motion trajectory;

• $\alpha \in [0, 1]$ is a tunable parameter to switch between an admittance/impedance controller;

• vp is the versor parallel to the desired motion trajectory (computed in Pd);

• vo is the versor orthogonal to the desired motion trajectory (computed in Pd);

• Ma is the virtual mass to reflect in admittance operation,

• b is the apparent viscosity parameter,

• a is the estimated acceleration.

Below the specific function absolved for the control in each equation.

Admittance: the first equation computes commanded force in the direction of motion parallel the exercise trajectory. The equation introduces a switch (α) to variate the style of motion. When $\alpha = 1$, a completely passive motion is considered and the robot moves to the desired position by ignoring the force exerted on the handle; when α

= 0 , the motion is completely guided by user force exerted along the exercise direction on the device.

Impedance: the second equation computes the rendering force profile in the direction of motion orthogonal the exercise trajectory. In this case we implement a pure impedance force that is proportional to the distance between the actual device position and the trajectory.

Total commanded force: the overall force is the combination of admittance and impedance force.

Velocity command : internally MOTORE++ uses a unique velocity controller obtained from the integration of estimated acceleration information. Hence in eq. (4) we combine viscous effects and the Ft to estimate the velocity at device handle.

The logic of MOTORE++ is managed using additional loops: a control monitor (1KHz) implements diagnostics and basic behaviors of the robot, and a higher level control (100Hz) manages external communication with a remote virtual environment and allows to accept/reject external commands for the execution of rehabilitation tasks. The force position controller is also composed of the aforementioned EKF to reconstruct the robot location at 1KHz, thus providing a constant position estimation for the internal velocity/position controller (internal loop).

4 Assessment of patient with MOTORE++ and wearable sensors

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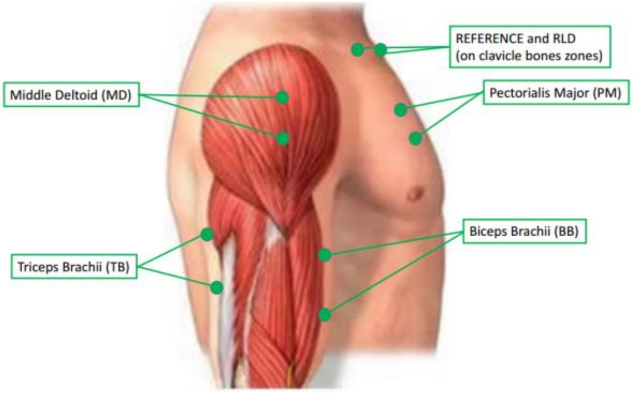
The first work addressed upper-limb rehabilitation after-stroke, performed with the 2D planar device MOTORE++. To obtain a set of parameters that evaluates and adapts the robot behavior for each patient condition, we have developed and presented a method that assembles and processes data from a set of sensors operating in two different devices: a wearable suit and the table-top rehabilitation device MOTORE++. On one side the suit is intended to provide an estimation of arm posture and muscular stress, while the latter, MOTORE++, performs a series of exercises by exerting and monitoring guidance forces in accordance with the position of the device.

The method is based on sensor fusion to achieve a valid metric for the evaluation of the patient condition with the integrated system. In accordance with common practice in literature we extract three evaluation parameters: ForceDirectional Error (FDE), Work Efficiency (WE) and Mean Work (meanW). The wearable sensors, instead, return information of joint angles and 8 EMG signals, useful to evaluate muscular activity/weakness(MVC) and the co-activation ratio (CoA), parameter to detect abnormal intra-limb synergies through principal component analysis [P.-C. Kung, C.-C. Lin, and M.-S. Ju. Neuro-rehabilitation robotassisted assessments of synergy patterns of forearm, elbow and shoulder joints in chronic stroke patients. Clinical Biomechanics, 25:647–654, 2010.].

The wearable suit has been originally designed for the purpose of assessment of musculoskeletal disorders during daily work activity [L. Peppoloni, A. Filippeschi, E. Ruffaldi, and C. Avizzano. A novel wearable system for the online assessment of risk for biomechanical load in repetitive efforts. International J. of Industrial Ergonomics, 52:1–11, 2016] with upper limb motion tracking [L. Peppoloni, A. Filippeschi, E. Ruffaldi, and C. Avizzano. A novel 7 degrees of freedom model for upper limb kinematic reconstruction based on wearable sensors. In 2013 IEEE 11th International Symposium on Intelligent Systems and Informatics (SISY), pages 1–11. IEEE, 2013] combined with wearable electromyographic measurements.

The motion reconstruction is achieved with the implementation of a kinematic model based on Denavit-Hartenberg method at 5 or 7 Degree of Freedoms (DoFs), depending if the tracking of wrist movements is required or not. In the 7 DoF configuration 7 joint-angles are registered: (i) shoulder abduction/adduction angle, flexion/extension angle, prono-supination angle; (ii) elbow flexion/extension angle, prono-supination angle; (iii) wrist flexion angle and abduction/adduction angle. The wearable device is composed of 3 or 4 IMUs respectively for the 5 and 7 DoFs model, each equipped with tri-axial gyroscope, accelerometer and magnetometer (Invensense 9250). Due to the non linearity of the kinematic model, an Unscented Kalman Filter (UKF) has been employed. The device exploits a system for the capture of surface EMG signals to assess arm muscular activity and the possible abnormalities. Surface button electrodes have been connected to each of 8 channels for EMG registration and 2 channels have been used for the reference EMG and RLD.

To reach our analysis aims, we have chosen a Point-to-Point reaching exercise (PtP) in Free/Constrained Target mode. The exercise has been structured in 4 tasks: horizontal, vertical and two diagonal directions movements. Each task is composed of 2 passive and 2 active trials. To assist the user in the active phase of motion an help modality has been added: in the case the user is keeping staying in the same point of the trajectory for more than 10 seconds, the robot enters in a passive modality for a short stretch of the trajectory. The three sensor units for the arm motion reconstruction are placed respectively on forearm, arm and chest. The EMG electrodes are positioned in pairs on the epidermic area corresponding to the Pectoralis Major(PM), Biceps Brachii(BB), Middle Deltoid(MD) and Triceps Brachii(TB) muscles as shown in the following picture.



The intent of this task is to develop a metric of assessment of affected people based on the comparison with healthy persons performance if subject to the same test. We choose to conduct a wide spectrum analysis on upper limb force capability together with muscular synergies and activity. On the human-robot force exchange side we focused our attention on 3 indexes: Mean Work (MW), Work Efficiency(WE) and Force Directional Error(FDE) [R. Colombo, I. Sterpi, et al. Measuring changes of movement dynamics during robot-aided neurorehabilitation of stroke patients. IEEE Trans. on Neural Systems and Rehab Engineering, 18:1:1534–4320, 2010]. On the muscular side EMG inspection of weakness was conducted through Maximum Voluntary Contraction (MVC) analysis and synergies evaluation achieved via Principal Component Analysis (PCA) and Co-Activation Ratio formulation [M. Perez and M. Nussbaum. Principal components analysis as an evaluation and classification tool for lower torso semg data. J. of Biomechanics, 36:1225–1229, 2003].

All data produced by the system is timestamped for synchronization and sent via TCP over Wireless 802.11n to a data fusion and extraction node running on a computer. This node collects wearable sensors's data IMU at 100Hz, and EMG at 500Hz. The data from the MOTORE++ device is acquired at 200Hz including position, velocity, force and device status. Such data is used for pose reconstruction and EMG filtering, then combined with the MOTORE++ information for the computation of the metrics.

4.1 Force Analysis

The device uses a global reference system centered in the geometrical center of the working surface with axis aligned to the borders (X going from left to right, Y going from bottom to up). Data of active and passive subjects' force profiles of planar XY components were extracted by MOTORE++ during the exercise execution.

<u>Force Directional Error</u>. Parameter evaluating direction of forces exerted on the XY directions. It is quantified as the relation between the singular affected subject force vector and the mean force vector registered in healthy people tests (eq. 7). The force vector is obtained as the contribution of voluntary force profile during each phase of motion averaged on the total trials (eq. 6). Voluntary force profile is obtained as the

difference between the force profiles registered during active phases of motion and the mean of passive test phases(eq. 5).

$$p^j(t) = \frac{1}{trp} \cdot \sum_{i=1}^{trp} p^j_{i=1}(t) \tag{5}$$

$$F^j = \frac{1}{trt} \cdot \sum_{i=1}^{trt} \frac{\sum_{t=t_0}^{t_f} a_i^j(t) - p^j(t)}{N} \tag{6}$$

$$FDE = \arccos\left(\frac{\overrightarrow{F}_{subj} \cdot \overrightarrow{F}_{healthy}}{|\overrightarrow{F}_{subj}| \cdot |\overrightarrow{F}_{healthy}|}\right) \tag{7}$$

with t_0 = initial time, t_f = final time, j = index indicating force component considered (x and y in our case), i = index indicating the tasks, trt = sum of passive and active trials, N = samples total number, $F_{sub\ j}$ = force vector of tester, $F_{healthy}$ = mean value of healthy testers force vector.

Mean Work and Work Efficiency. MW is a parameter obtained averaging through the exercise tasks the value of positive work done by the upper arm during the test (eq. 8). WE indicator has values in the range [0,1](η = 1 represents the optimal ideal performance) and it has been calculated as the ratio (eq. 10) of positive work respect potential work (eq.10).

$$W_i = \sum_{t=t_0}^{t_f} \left\{ \sum_{j=1}^{2} max\left\{ [a_i^j(t) - p^j(t)] \times \Delta_i^j(t), 0 \right\} \right\} \tag{8}$$

$$\Theta_i = \sum_{t=t_0}^{t_f} \left\{ \sqrt{\sum_{j=1}^{2} [a_i^j(t) - p^j(t)]^2} \times \sqrt{\sum_{j=1}^{2} [\Delta_i^j(t)]^2} \right\} \tag{9}$$

$$\eta_i = \frac{W_i}{\Theta_i} \tag{10}$$

with t0 = initial time, t_f = final time, j = index indicating force component considered (x and y in our case), i = index indicating the tasks, trp = number of passive trials, Δ^j_i = vector containing the piece of trajectory traveled from the previous to the current sample time.

4.2 EMG Analysis

EMG signals were extracted by wearable sensors during the exercise execution. Below post-processing of data and laws implemented.

Co-Activation Ratio. Detector of abnormal co-contraction in antagonistic proximal muscles (PM-BB and MD-TB) if positive values are assumed [P.-C. Kung, C.-C. Lin, and M.-S. Ju. Neuro-rehabilitation robotassisted assessments of synergy patterns of forearm, elbow and shoulder joints in chronic stroke patients. Clinical Biomechanics,

25:647–654, 2010]. First the data are filtered with a bandpass filter Butterworth filter (order 8, frequencies range [10-250]Hz) and an adaptive FIR filter based on LMS algorithm and on a noise model formulated ad hoc for our device. Then 4 of the 8 raw

EMG signals collected during the exercise are chosen (1 for every muscle bundle of interest) and the PCA [M. Perez and M. Nussbaum. Principal components analysis as an evaluation and classification tool for lower torso semg data. J. of Biomechanics, 36:1225–1229, 2003 - H. Sadeghi, F. Prince, S. Sadeghi, and H. Labelle. Principal component analysis of the power developed in the flexion/extension muscles of the hip in able-bodied gait. Medical Engineering & Physics, 22:703–710, 2000] computed. First and second Principal components are used to compute our indicators (CoA ratios) having values in [-1,1] and calculated on every motion direction (8)-(9):

$$c_{1i} = (P_{1i}^{PM} + P_{1i}^{BB})(P_{1i}^{MD} + P_{1i}^{TB}) \qquad (11)$$
$$c_{2i} = (P_{2i}^{PM} + P_{2i}^{BB})(P_{2i}^{MD} + P_{2i}^{TB}) \qquad (12)$$

with c_{1i} , c_{2i} = CoA ratios respect to 1st and 2nd PC if the i-th task (motion direction, P_{1i}^{X} = correlation coefficient between 1st principal component and EMG of X muscle in the i-th task).

MVC analysis. Root Mean Square algorithm followed by Power Spectral Density analysis were conducted in order to evaluate the percentage of muscular activation of the limb during the test. We detect weakness for each muscle as percentage under the ranges established on the based of normal limb activity registered on healthy subjects. In this case we determine Maximal Voluntary Contraction not as maximal isometric muscular contraction possible for the subject, but in terms of maximal contraction applied by the tester while executing the exercise.

4.3 Validation of exercise

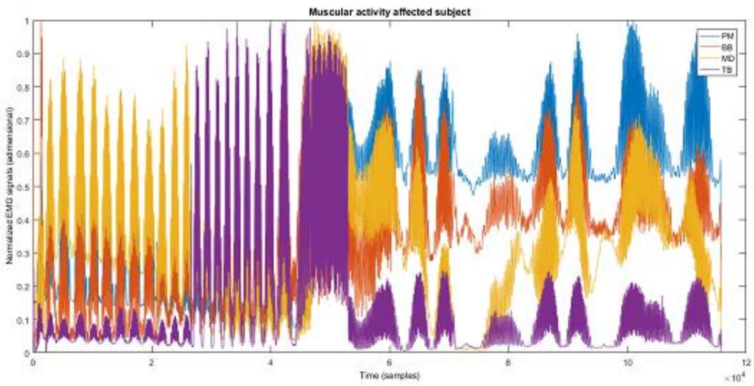
Joints angles have been collected from wearable sensors. Their temporal evolution along the different tasks suggest a validation protocol of the exercise. If the exercise is well-executed, a particular behavior is expected otherwise the subject has moved the chest and hold the arm at the same position: in horizontal direction (TASK 1) the shoulder abduction angle significantly variable and elbow flexion angle almost constant or little changing; while in vertical direction (TASK 3) the shoulder and elbow flexion angle significantly variable.

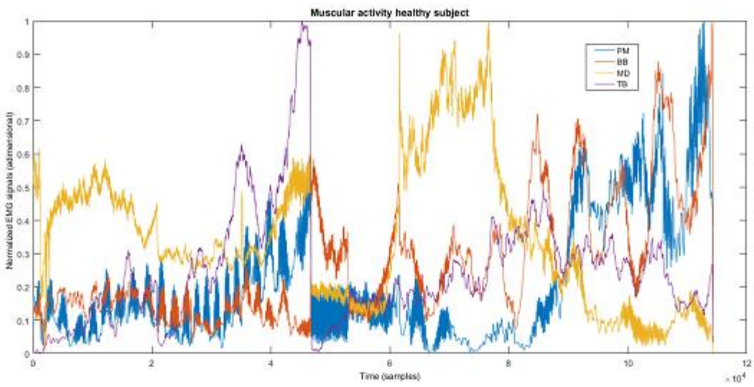
4.4 EXPERIMENTAL RESULTS

The validation at the RIF in Volterra was performed with 18 healthy subjects (8M/10F with average age 30) and 10 affected subjects (4F/6M with age 65 ± 12).

Results Table															
Subj	**SINERGY**								**WEAKNESS (% musc.activity)**				**FORCES**		
	c_{11}	c_{12}	c_{21}	c_{22}	c_{31}	c_{32}	c_{41}	c_{42}	**PM**	**BB**	**MD**	**TB**	**FDE**	**WE**	**W**
1	0.006	0.01	0.002	0.004	-0.001	-0.001	0	0	0.168	0.301	0.237	0.299	180	0.642	5
2	-0.109	-0.112	-0.255	-0.066	-0.038	-0.059	-0.011	-0.016	0.027	0.233	0.145	0.334	180	0.563	17
3	-0.005	0	0	0	0	-0.001	-0.005	-0.008	0.013	0.008	0.017	0.054	122	0.323	7
4	-1.001	0.032	-0.025	-0.007	-0.184	-0.234	-0.008	-0.025	0.13	0.049	0.361	0.262	71	0.543	18
5	-0.001	-0.003	0	-0.001	-0.017	-0.044	-0.012	-0.034	0.157	0.232	0.252	0.146	0	0.6	21
6	-0.144	-0.351	-0.002	-0.003	0.003	0.008	-0.101	-0.319	0.253	0.421	0.22	0.475	0	0.634	29
7	-0.841	-0.034	-0.065	-0.06	-0.164	-0.145	-1.001	0.031	0.473	0.3	0.265	0.297	99	0.627	43
8	0	-0.002	-0.013	-0.02	-0.04	-0.007	-0.077	-0.009	0.102	0.299	0.046	0.256	85	0.584	47
9	-0.14	-0.013	-0.133	-0.014	-0.065	-0.132	-0.126	-0.019	0.231	0.33	0.144	0.156	0	0.572	9
10	-0.003	-0.003	-0.093	-0.001	-0.005	-0.011	-0.024	-0.029	0.018	0.062	0.04	0.221	136	0.341	4
Fit Subj.	VALUES in $[-1, 0)$ Common range: [-0.6 -0.2]								Values in [0 1] Common ranges: [0.3 0.45]				FDE: Low Val.(≥ 0) WE in [0 1] WE range: [0.65 0.8] W range: [8 30]		

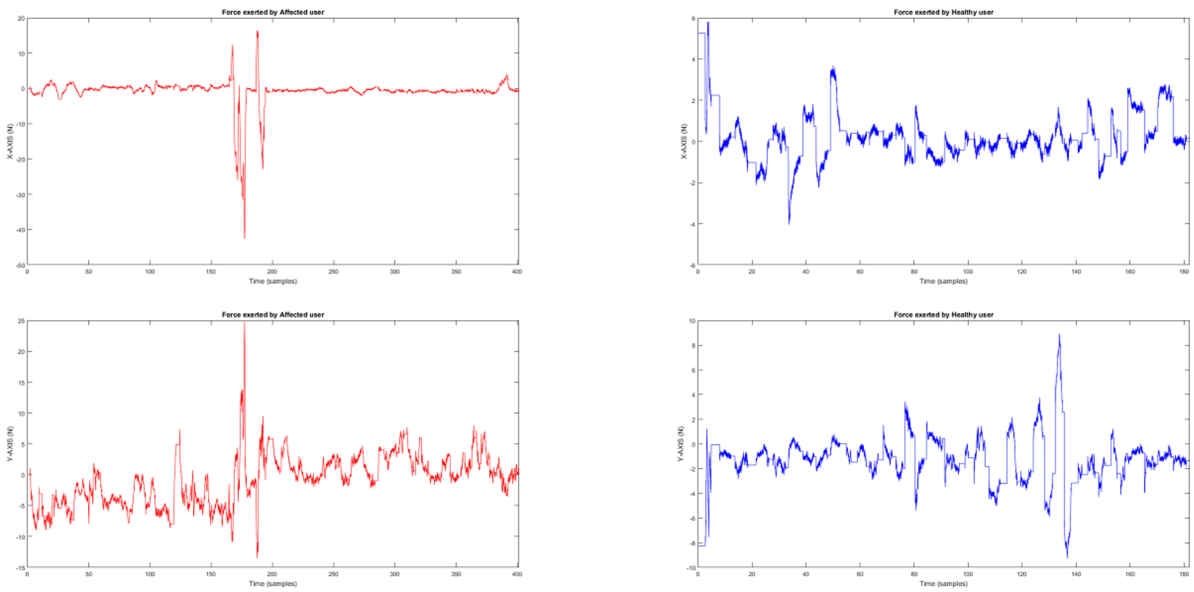
The previous table summarizes the relevant results. The columns represents: c_{ij} = the Co_A Ratio of i-th task relative to j-th PC; then the percentage of activation during the exercise for each muscle; Fx,Fy = mean force among all exercises, FDE = force directional error, WE = work efficiency, W = positive work. Expected ranges, from healthy subjects, were reported in the last row and used as comparison parameter for anomaly detection. Abnormal synergies and muscular weakness have been detected in some subjects and are reflected also in the EMG profiles processed with RMS in frequency domain (see following picture).





In most cases, subjects demonstrated a lower level of muscular activation during the execution of the exercise when compared with the expected ranges. As an example, apart of a general altered EMG profile of the stroke subject and the frequent co-activation of antagonistic fibers, we notice that the initial Pectoralis Major muscle contribution is very low. This phenomenon is associated to the low value of weakness parameter registered for PM in the table of results, Subject 1. Other subjects, instead, have shown great weakness (up to 1% of muscular activation) even in more than a singular muscular fiber but not a synergy relevant anomaly. This is probably due to the variegate sample of illnesses having neurological or mechanical post-traumatic events, and different aging since the trauma.

Underlined disorders in the direction of forces exerted by the ill subjects or a Work Efficiency under the ranges of healthy people correspond to an altered user forces profile over time. For instance, Subject 2 was victim of a spasmodic status during the execution of the test with the consequent alteration in measured force direction (FDE index) and in the efficiency of total work. In many cases it emerges a correlation between force abnormalities (in particular FDE) and electromyographic evaluation (i.e. Subject 1 in VI). These phenomena depend on the link between force registered and muscular activity: information on force directions and entities can be extracted from EMG signals in terms of contractions of singular muscle fibers and co-contraction between different muscles. The co-contraction of antagonistic muscles can cause undesired deviation of force direction as common in spasmodic events. However, upper limb rehabilitation is applied on illnesses due to different occurred trauma of neurological or mechanical post-traumatic origin and neither all considered factors nor a particular combination coexist coherently in every case. Moreover, the samples of ill people tested differ also in time passed from the traumatic event to the assessment analysis. As a consequence, correct evaluation of illness seems to requires both analysis (forces and muscular activity) because there is not a most indicative index, but every specific pathology could present even only one alteration of all that we have considered in our metric.



In the previous picture was shown in red the affected subject force profile (Subject 2). Module of forces of stroked subject reaches 40 N showing the presence of a spasm. The event is reflected in score values of FDE and WE. In blue is shown Healthy subject force profile. Module of forces never exceed 10N

In conclusion as result of the work a set of seven weakness and force indicators were automatically extracted by the system during the operation. A clear distinction was highlighted by the scored indexes not only between healthy and the affected subjects but also within each specific subject when any sort of spasmodic event occurs. The preliminary results shows high confidence to use this metric for extensive patient validation.

Future improvements aims to refine joint arm pose estimation between wearable sensors and localization sensor for the mobile device thus removing related issues on slow yaw-drift of the IMUs due to magnetic interference.

5 Preliminary results on rehabilitation with MOTORE++

Five subjects from the RIF Auxilium Vitae in Volterra (age range 61-76, mean age 70.40±6.27, four men and two women) experienced the acute event 25±7 days prior to the study. Three had a history of right hemiparesis, and two had incurred in left hemiparesis. Five subjects (age range 42-66, mean age 57.00±9.67, five men) experienced the acute event at least one year prior to the study and had incurred in left hemiparesis. The local ethics committee approved the experimental protocol and each subject signed a consent form. MOTORE++ was used to provide 2DOFs force feedback implementing an "assist-as-needed" control strategy. Each subject was asked to perform five sessions of upper limb robot-assisted rehabilitation for four weeks. During each session 45 minutes of robot-assisted reaching tasks emphasizing shoulder and elbow movements were carried out. These test lasted for the first months of the experiment MOTORE++ using the intermediate prototype (which was in fact effective as the last refined prototype). The intermediate prototype was also used as test bed for the final refinement.

An increase of the FM values after the robot-assisted upper limb treatment was observed in subacute subjects (T0: 44.9±11.9; T1: 54.2±6.1, ns). A statistically significant improvement was found in chronic subjects (T0: 23.8±15.0; T1: 36.8±16.9, $p<0.05$). MAS-S and MAS-E values in subacute subjects did not change after the upper limb rehabilitation treatment. A decrease, even though not statistically significant, was observed in chronic subjects both in MAS-S (T0: 1.40±1.14; T1: 1.20±0.45) and MAS-E (T0: 2.60±1.34; T1: 2.00±1.22). A significant increase of the B&B test was observed only in subacute subjects (T0: 44.9±11.9; T1: 54.2±6.1, $p<0.05$).

The preliminary results presented in this study, which have to be confirmed by further studies involving a control group and a larger pool of patients, show that the upper limb rehabilitation treatment based on a novel portable haptic device may reduce the motor impairment in stroke patients

6 Deviations and mitigation

Due to the late delivery of the prototypes (because of a delay in supplying the components), the clinical activity has been postponed. As a consequence the number of subjects monitored is smaller than expected. For this reason the MOTORE++ team asked for an extension of the experiment. At the moment of writing the tests in Auxilium Vitae are still ongoing and new tests with the wearable sensors are planned. The consortium has interest in collecting this kind of data in order to give evidence of the effectiveness of the device for its marketing.