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Executive Summary of the Thesis

Validation and use of Teslasuit in a virtual-reality environment for neuromotor rehabilitation: a proof of concept study on healthy subjects

Laurea Magistrale in Biomedical Engineering - Ingegneria Biomedica

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1. Introduction

In the European Union, stroke is a major cause of mortality and disability, with an expected increase in cases due to population aging and improved survival rates. The 80% of stroke patients are affected by hemiparesis which leads to muscle weakness, loss of dexterity and poor motor control [4]. Proper rehabilitation during the acute phase is thus crucial. Current rehabilitation approaches focus on motor learning, including Constraint-Induced Movement Therapy (CIMT) and Mirror Therapy, which have been demonstrated to be simple and effective [2][3]. Technology-based interventions, such as Robotic Training and Functional Electrical Stimulation (FES), are also emerging as alternatives to perform controlled exercises and have shown to enhance neural plasticity. The combination of these methods with Virtual Reality (VR) can create motivating rehabilitation environments with potential benefits on patients' recovery [6]. Moreover, technology-based treatments generally include a monitoring system of the patient's movements, that is a crucial element in the rehabilitation process for quantitative and systematic standards of evaluation. However, technology-based treatments face the challenge of the time lost due to the process of dressing up and calibration, which in a clinical setting is a crucial time taken away from the patient's training. Therefore, having easily "wearable" and easily calibrated systems is essential. To this aim, in recent years, integrated devices like full-body suits were developed, which incorporate FES and Motion Capture (Mocap) systems for comprehensive rehabilitation and easy wearability. One example is the Teslasuit by VR Electronics Ltd. This thesis explores Teslasuit usability as a system for delivering FES and its potential integration with VR for post-stroke rehabilitation exercises. In particular, this study can be divided into 2 main parts: the device validation (both in terms of motion capture and electrical stimulation systems) and the development of an imitation-based exercise protocol for upper limb rehabilitation in a VR environment.

2. Materials and Methods

2.1. Matrials

2.1.1 Teslasuit

Teslasuit is a smart textile two-pieces full-body suit that consists of a jacket and trousers. This study relies on Teslasuit version 4.5.1 medical, size M, male users. "Medical" refers to the addition of zippers to facilitate the wearability of the suit. For the purpose of this study, only the jacket was used.
This version includes 2 major features: Motion Capture and Electrical Stimulation (ES) modules.
Motion capture module uses 10 Inertial Measurement Unit (IMU) sensors, embedded in the suit in fixed places. They track, record and monitor the movements and positioning of users.
Electrical stimulation module uses dry textile voltage-controlled electrodes, embedded in the suit in anatomic locations. The jacket contains 62 electrodes, including both anodes and cathodes, distributed across 48 channels. Each channel consists of both an anode and a cathode, although certain channels share the same anode. Some of these channels provide haptic feedback, while others are associated to muscles and provide Neuromuscular Electrical Stimulation (NMES). The stimulation frequency can range between 1 and 300 Hz, the voltage can range between 0 and 55V AC, the pulse width (PW) between 1 and 320μs, while current is 50 mA per 1 kOhm [1].
Two software are provided with the suit: Control Center and Studio.
Control Center contains the suit API needed to connect it to the computer.
Studio has 2 modules: Motion capture module and Electrical stimulation module. This thesis uses *Studio - Motion Capture module* interface to record subject data (quaternions referred to the limb's location, joint angles, velocities and accelerations) during the execution of specific tasks.
Teslasuit is also provided with a **Unity plug-in**, which reads in real time the data coming from the suit's API, and can control the electrical stimuli delivered by the suit. Consequently, virtual reality interfaces can be developed, allowing the interaction of the subject wearing the suit with the virtual environment.

2.2. Methods

Tests were run on subjects that voluntarily accepted to take part in the study and signed a written informed consent. All subjects matched the suit requirements: male, healthy and able to perform the designed tasks, chest measurement 96-101cm, waist measurement 84-89cm. All subjects tested in this work were aged between 22-25 years. The study was approved by Ethical Committee of Politecnico di Milano (Nr 13/2021).

2.2.1 Motion Capture Validation

The aim of these tests was to evaluate the validity of upper limb angles, that are shoulder angle of elevation (AOE) and plane of elevation (POE), and elbow flexion-extension (FE), with respect to the optoelectronic system data, assumed as the gold standard.
This study relies on an optoelectronic system based on 8 SMART DX 400 (BTS SPA, IT) cameras with an acquisition frequency of 100Hz, passive markers, and *Smart analyzer* software.
5 subjects were acquired in this phase. The acquisition protocol can be summarized in 4 phases, described as follows.
The 1st one is **Markers and Teslasuit set up** where 8 passive markers are positioned on the right arm. Their placement was chosen to allow the 3D reconstruction of the upper limb joint angles [5]. The Teslasuit setup, instead, only requires the user to wear the suit and connect it to its power bank.
Next, the **Teslasuit motion capture system calibration** followed, using the *Studio* interface and asking the subject to stand still in I-Pose for 2s.
Lastly, the **Execution of the tasks** was carried out to assess the behavior of elbow and shoulder angles. In particular, the performed movements are: *Reach to grasp* (reaching of an object positioned in front of the subject); *3D pointing* (lateral pointing); *Hand to nose* (reaching of the subject's nose); *Shoulder lateral flexion* (shoulder abdo-adduction on the frontal plane); *Elbow flexion-extension* (elbow flexion-extension in the sagittal plane).
Supposing that there is symmetry in the behavior of the two sides for a healthy subject, all the tasks were executed only with the right arm. The initial position consists of sitting in front of

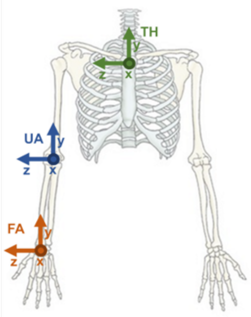


Figure 1: ISB reference systems [7]

a table, then each task is performed 10 times.
During the task execution, the optoelectronic system records data through *SMART-Tracker* software at a rate of 100Hz. These data consist of 3D coordinates representing the positions of markers, and they are then processed in *Smart Analyzer* to obtain local reference systems coordinate representing the position of upper arm, forearm, and thorax with respect to the global reference system (room).
Teslasuit, instead, acquires data through *Studio* at a variable rate, that is approximately about 60Hz. These data are the quaternions representing the rotation of upper arm, forearm, and thorax with respect to the root bone (Hips).
Optoelectronic and Teslasuit data are then processed to obtain joint angles according to International Society of Biomechanics (ISB) convention [7].
ISB reference systems are shown in Figure 1.

Elbow movements are described by FE, i.e. the relative angle between the upper arm (UA) y-axis and the forearm (FA) y-axis.
Shoulder movements are described by AOE and POE. The former is defined as the relative angle between the thorax (TH) y-axis and the upper arm y-axis. The latter, instead, is computed as the relative angle between the thorax z-axis and the projection of the upper arm y-axis onto the plane defined by the thorax x-axis and z-axis. FE is defined as positive while flexing, AOE while elevating and POE when moving the arm frontally.

For every task acquisition, Teslasuit and Smart data are synchronized and segmented in their respective 10 repetitions.
The used evaluation metrics are Range of Motion (ROM) and Root Mean Square Error (RMSE). The ROM of AOE, POE and FE is evaluated for each repetition of each task for both systems. RMSE, instead, is computed for each repetition of the task for the angles having an optoelectronic ROM bigger than 15. Eventually, the RMSE of each repetition of a task are averaged, resulting in a single value for each subject for each task.

2.2.2 Electrical Stimulation Validation

The aim of these tests was to verify whether the specific Electrical Stimulation channel can induce the expected movement and range of motion. This study analyzed channels referred to: anterior deltoid, posterior deltoid, biceps and triceps.
5 subjects were acquired for this section.
The acquisition protocol can be summarized in 4 phases, each one repeated for the right and left arms.
The first one is the **VR avatar calibration** during which the subject is asked to stand still in I-Pose for 1s.
After that, the **Voluntary execution of the movement** follows, where the voluntary movement related to the examined channel (shoulder abduction-adduction for anterior and posterior deltoid, elbow flexion-extension for biceps and triceps) is repeated 5 times.
The third phase is the **Calibration of the pulse width range** for the examined ES channel, consisting in the delivery of an increasing ramp of pulse width values, from 0 to 100% of the suit pulse width range. Each pulse width value is delivered for 1s and the minimum (value at which a muscle contraction is visible) and the maximum value (pain threshold) of pulse width are identified.
The last step is the **Execution of ES-induced movements** in which the stimulation is characterized by an increasing pulse width ramp of 0.5s from the minimum to the maximum, a 2s plateau keeping the maximum value and a 2.5s pause between the end of the plateau and the start of the following ramp. The stimulation is always provided as a train of pulses with 40Hz frequency and a total of 5 repetitions is recorded.
Apart from the voluntary execution of the movement, the entire protocol is repeated twice:

soon after the suit was worn, and again after a 30-minute interval. This is done to evaluate the stimulation repeatability over time. The two sets of acquisition will be referred to as *test 1* and *test 2*.

During each movement, pulse width range values and quaternions related to upper body segments are recorded through the *Unity interface*.
As described in the previous section, quaternions are used to compute biomechanical angles. For each stimulation channel, only the angle referred to the expected movement is analyzed: FE angle for biceps and triceps, AOE angle for anterior and posterior deltoid. POE is not taken into consideration due to its poor performance as it will be shown later in the results section.
Each acquisition is segmented into its 5 repetitions, and for each repetition the used evaluation metrics are percentage ROM and pulse width integral over time.
The percentage ROM is computed as the ratio between the ROM of ES-induced movements and the one of voluntary movements. The integral of the pulse width over time is used as an indicator of the charge administered to the subjects.
Lastly, for both metrics, the median values across the 5 repetitions, calculated for all subjects, are compared between test 1 and test 2 by means of Wilcoxon signed-rank test.

2.2.3 Imitation-based exercise

Inspired by the concept of Mirror Therapy, the following protocol suggests a series of exercises based on the execution of a movement with one arm (the healthy one in the case of post-stroke patients). This movement is recorded through the suit and replicated on the other arm (the impaired one) using FES.
The proposed exercises use angles and channels that have been considered valid based on the results of the initial motion capture and ES module validation tests. Specifically, the considered angles are AOE and FE, while the channels of interest are those associated with anterior deltoid, biceps, and triceps.
The exercise implementation methodology can be broken down into 4 specific phases:

- **Acquisition of the target trajectory**: upon pressing the "start" button, the subject is asked to perform a movement with one arm. Meanwhile, AOE and FE are recorded and saved as target trajectories. The recording stops when the subject returns to the initial I-pose position (i.e. both the FE and AOE angles are below a threshold set to 5°).
- **Reconstruction of the target trajectory using a beta-function**: all acquired trajectories are divided into ascending, plateau, and descending phases. The ascent phase begins when the trajectory derivative overcomes 10°/s and terminates at 80% of the trajectory's maximum. From this point on there is the plateau phase which continues until reaching 80% of the maximum along the descending phase. Subsequently, the descent phase follows, ending when the trajectory derivative goes below -10°/s. Lastly, to simplify the obtained trajectory, this was reshaped as a beta-function.
- **Construction of the stimulation pattern**: the ES-induced movement of the other arm is regulated at each repetition with an Iterative Learning Control (ILC) algorithm. This takes as input the error between the target and the ES-induced trajectory acquired during the previous repetition and gives as output the pulse width values to be used in the following repetition. The error, referring to the k-th repetition is defined as:

$$error^k(i) = \theta^k_{target}(i) - \theta^k_{acquired}(i) \quad (1)$$

where i identifies the time frame and goes from 0 to the length of the target trajectory. This error is used to adjust the pulse width value for each frame of the following k+1 repetition:

$$PW^{k+1} = PW_{min} + \frac{PW_{max} - PW_{min}}{ROM} * \bar{u}^{k+1} \quad (2)$$

$$\bar{u}^{k+1} = \bar{u}^k + \lambda * \bar{Q} * \bar{error}^k \quad (3)$$

where λ is an adimensional scalar learning gain (set to 0.2) and Q is a 1x9 smoothing filter. The ILC algorithm is involved only during anti-gravity movements (elbow flexion, anti-gravity elbow extension, shoulder abduction). Gravity-assisted movements (gravity-assisted elbow extension, shoulder

adduction), instead, are simply accompanied by a descending pulse width ramp.
The obtained PW values are anticipated of 375ms to correct the muscular and system response delay observed during experiments and to enhance the time synchronization between the target trajectory and the response one.

- **Stimulation and acquisition of the ES-induced trajectory**: the subject receives the stimulation defined by the ILC algorithm while the ES-induced trajectory is acquired to compute the tracking error. A pause of 1.25 seconds is given between two subsequent stimulation patterns. The stimulation is always delivered as a train of pulses with a 40Hz frequency.

Regarding the imitation-based exercise protocol, 5 subjects were acquired. This protocol can be summarized in 3 phases, described as follows.
The first one is the **VR avatar calibration** already explained in Section 2.2.2.
The second is the **Calibration of ES values and Computation of ES-induced ROM**. The Calibration of ES values consists in the delivery of the increasing ramp of pulse width values described in Section 2.2.2, while the maximum ES-induced ROM is computed as the joint angle described by the stimulated limb when the subject specific maximum PW value is delivered.
Then, the third one is the **Execution of imitation-based exercises** where subjects perform movements in two virtual environments, each one with two interaction modalities with objects, resulting in a total of four exercises. Each exercise starts from the I-pose, the subject is asked to voluntarily perform the scene-specific movement with one arm and then to stay passive and let the other arm execute the movement through the FES-induced contractions for a total of 15 repetitions. Throughout the whole execution of the exercise, AOE and FE angles are acquired. Two virtual environments were developed in this study.
The former is named **Kitchen scene** and here the subject is asked to perform a *hand to mouth* exercise, by "grabbing" one mug on a table in front of him and bringing it to his mouth. Two velocities of interaction are tested: *slow speed* and *self-selected speed*. This kind of movement only involves biceps and anterior deltoid.
The latter is the **Supermarket scene** in which the subject is asked to perform a *lateral reaching* exercise by grabbing a target object on a lateral shelf. Two different movement heights are tested by using two targets placed at different heights: a bottle of milk on a higher shelf (*wide movement*) and a cereal carton on a lower shelf (*small movement*). Both modalities of this exercise involve the biceps and the anterior deltoid muscle, the *high lateral reaching* also involves the triceps, during the anti-gravity extension of the elbow.

To assess the performance of the ILC algorithm controlling the electrical stimulation, the study considered the RMSE for each subject and for every repetition of each exercise. The median was then extracted over the 5 subjects, obtaining one value for each iteration of each exercise.

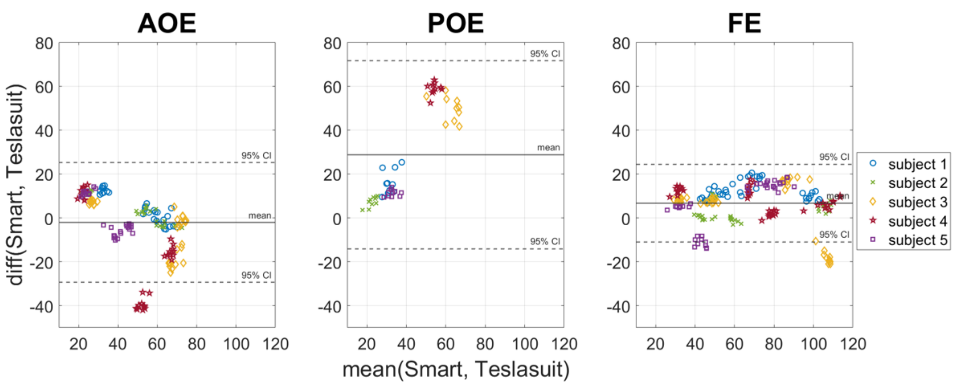


Figure 2: Bland-Altman plots which show the measurement error between the Teslasuit motion capture system and the optoelectronic system for the 3 DOFs

3. Results and Discussion

3.1. Motion Capture Validation

The overall results show good performances for AOE and FE, with respectively a median RMSE of 5.5° (1.7°) (target ROM: $\sim$ 55.4°) and 6.2° (1.9°) (target ROM: $\sim$ 58.9°).
POE is evaluated only for the *3D pointing* task, where its median RMSE is 26,6° (32,7°) (target ROM: 24,7°). This poor outcome is due to problems faced during its computation, therefore POE could not be validated and thus it was not used in further exercises of this work.
Figure 2, shows the Bland Altman plot realized by putting together all users and all tasks in which the the angle is considered relevant, according to the criteria mentioned in 2.2.1. Regarding AOE and FE, the data largely fall within a confidence interval with a width of about 40°, almost centered around 0. However, this same trend is not observed in the POE data, which, as anticipated, displays a greater variability.

3.2. ES Validation

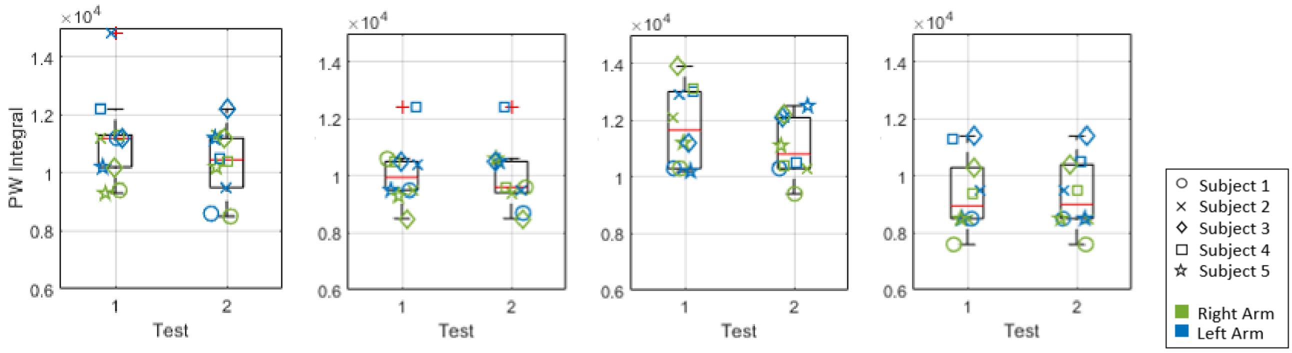
Figure 3 shows the results in terms of ROM percentage and PW integral over time, highlighting the differences between subjects, limb side and tests.
Regarding the pulse width integral, a relevant variability among subjects in all channels for both tests was noticed. No significant differences or specific trends were observed between Test 1 and Test 2; this behavior is particularly evident in the channels associated with the biceps and triceps.
Considering the percentage ROM, excellent performance was observed in the channels associated with the biceps and triceps, with values very close to 100%. The anterior deltoid also demonstrated good execution but with greater variability among subjects. The channel linked to the posterior deltoid, despite showing less variability, was the one with the poorest performance, likely due to electrode placement on the suit. In all channels, no significant differences were identified between Test 1 and Test 2; only a slight trend toward a decrease in performance from Test 1 to Test 2 was noticed, probably associated with muscle fatigue.

3.3. Imitation-based exercise

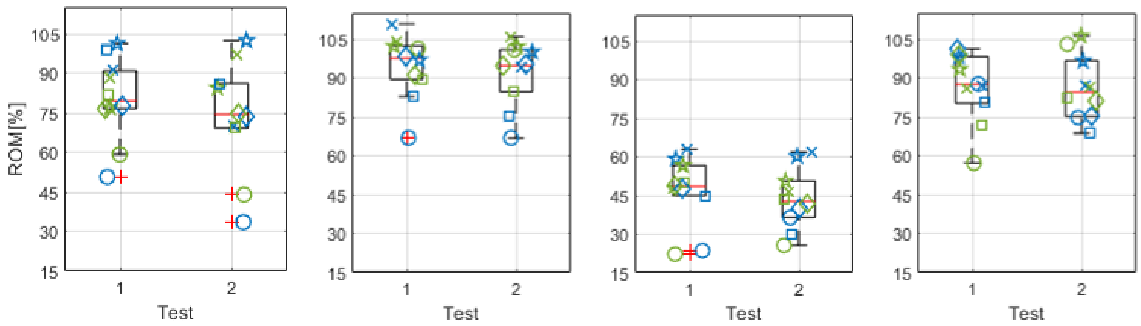
Figure 4 depicts the median RMSE trend over the 15 repetitions for each task and each involved muscle. Generally, an enhancement in the movement performance can be noticed around the fifth repetition of each exercise, followed by a subsequent deterioration in the final repetitions, most likely associated with muscle fatigue. Considering the specific angles, an excellent performance has been observed in the AOE, with its median across repetitions consistently below 10° for each task, as shown in Table 1 The flexion angle associated with the biceps also exhibits a good performance, with RMSE values all below 20°. Both angles also maintain a limited variability across repetitions. The extension angle associated with the triceps, instead, exhibits the poorest performance, both in terms of RMSE and variability among repetitions. This is likely due to the fact that flexion and extension movements are referred to the same trajectory but to different muscles, hence any error coming from the stimulation of the biceps consequently affects the stimulation-induced trajectory and error associated with the triceps.

4. Conclusions

This work has proven the possibility of using Teslasuit jacket as a support device in neuromotor rehabilitation of shoulder and upper arm. First, the validity of the motion capture system incorporated into Teslasuit was assessed, proving a good accuracy in the AOE and FE calculation when compared to the gold standard system while further exploration is required for the POE.
The electrical stimulation system was also demonstrated to be effective, with the ROM of ES-induced movements being comparable to the one of voluntary movements (except for the posterior deltoid channel).
Once demonstrated the reliability of Teslasuit features, a VR-based rehabilitative exercise program intended for post-stroke patients was developed, with different scenarios adaptable for their use in diverse settings.
Thus, it is possible to conclude that this system offers promising opportunities for the implementation of flexible rehabilitation therapies.

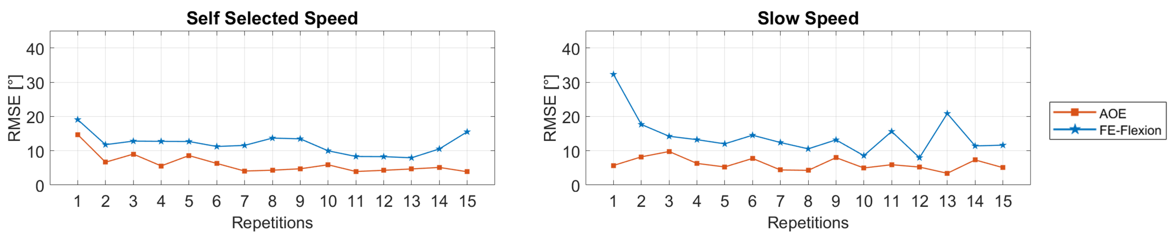


(a) *Anterior deltoid* (b) *Biceps* (c) *Posterior deltoid* (d) *Triceps*

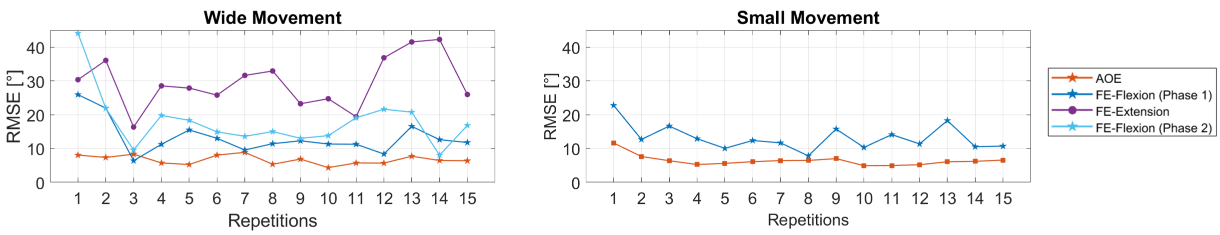


(e) *Angle of elevation (AOE)* (f) *Flexion (FE)* (g) *Angle of elevation (AOE)* (h) *Extension (FE)*

Figure 3: Results of the FES validation tests: the top panels report the integral of the PW provided to each stimulated muscle, while the bottom panels show the ROM of the resulting movement



(a) *Hand to Mouth*



(b) *Lateral Reaching*

Figure 4: Performance of the control algorithm: RMSE between the target and the actual angle of the two different exercises

		Angle of elevation (AOE)	Flexion (FE)		Extension (FE)
			Phase 1	Phase 2	
		Median (IQR) [°]	Median (IQR) [°]	Median (IQR) [°]	Median (IQR) [°]
Hand to mouth	Self selected speed	5.10 (2.27)	11.76 (3.19)	-	-
	Slow speed	5.68 (2.65)	13.16 (3.89)	-	-
Lateral Reaching	Wide movement	6.43 (2.27)	11.77 (3.62)	16.82 (6.86)	28.53 (10.32)
	Small movement	6.18 (1.20)	12.35 (4.79)	-	-

Table 1: Performace of the control algorithm: median RMSE between the target and the actual angle of the two different exercise among all the repetitions.

5. Acknowledgements

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References

[1] Teslasuit user guide.

[2] Ameen Barghi, Jane B Allendorfer, Edward Taub, Brent Womble, Jarrod M Hicks, Gitendra Uswatte, Jerzy P Szaflarski, and Victor W Mark. Phase ii randomized controlled trial of constraint-induced movement therapy in multiple sclerosis. part 2: effect on white matter integrity. *Neurorehabilitation and neural repair*, 32(3):233–241, 2018.

[3] Lynne V Gauthier, Edward Taub, Christi Perkins, Magdalene Ortmann, Victor W Mark, and Gitendra Uswatte. Remodeling the brain: plastic structural brain changes produced by different motor therapies after stroke. *Stroke*, 39(5):1520–1525, 2008.

[4] Samar M Hatem, Geoffroy Saussez, Margaux Della Faille, Vincent Prist, Xue Zhang, Delphine Dispa, and Yannick Bleyenheuft. Rehabilitation of motor function after stroke: a multiple systematic review focused on techniques to stimulate upper extremity recovery. *Frontiers in human neuroscience*, 10:442, 2016.

[5] George Rab, Kyria Petuskey, and Anita Bagley. A method for determination of upper extremity kinematics. *Gait Posture*, 15(2):113–119, 2002.

[6] Matijević Valentina, Šečić Ana, Mašić Valentina, Šunić Martina, Kolak Željka, and Znika Mateja. Virtual reality in rehabilitation and therapy. *Acta Clinica Croatica*, 52(4.):453–457, 2013.

[7] Ge Wu, Frans C.T. van der Helm, H.E.J. (DirkJan) Veeger, Mohsen Makhsous, Peter Van Roy, Carolyn Anglin, Jochem Nagels, Andrew R. Karduna, Kevin McQuade, Xuguang Wang, Frederick W. Werner, and Bryan Buchholz. Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part ii: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, 38(5):981–992, 2005.