Appendix 1
Robotic treatment protocol

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1. Introduction

In this appendix, the main characteristics of the robotic and sensor-based devices and their software, together with the rehabilitation protocols employed in the study for each device, are reported.

With respect to the rehabilitation protocols, the lists of exercises refer to a typical rehabilitation session of 45 minutes. To adapt the protocol to the patient's level of impairment, each patients was first categorized as "severe", "moderate", or "mild", according to the Fugl-Meyer Assessment (FMA): severe (FMA 0 – 28); moderate (FMA 29 – 42); and mild (FMA 43 – 66)[1].
Then, the corresponding treatment, with a raising level of difficulty, was delivered.

It is important to note that this appendix should not be intended as an exhaustive description of the devices and their software.

2. Motore (Humanware)

MOTORE (Figure 1) is a planar end-effector device equipped with an onboard computing unit, an odometry system (based on encoders) and a specifically designed global localization system (which recognizes patterns on the working surface). In fact, the device moves by means of transwheels on the planar working surface and it uses a 2DOF load cell in the handle to measure the interaction force with the patient. The device has 3 DC motors so that it can (a) help the patient when he/she is not able to accomplish the task, (b) prevent movements different from the ideal trajectories, (c) provide different weight and viscosity behaviors, (d) maintain a proper orientation on the plane. The device generates force feedback without any intermediate link to the ground or frame, thanks to the motion of the wheels and using the information obtained from the load cell. A Bluetooth connection links the device to a PC unit, where a software shows targets to be reached and trajectories to be followed as well as a user/therapist interface for the selection of the exercise parameters. The robot is controlled in admittance mode: forces measured by the load cell are used to determine the linear velocity of the device, based on two parameters (M, that is the apparent mass of the device, and b, that is the nominal viscosity) that can be modified to change the robot behavior.

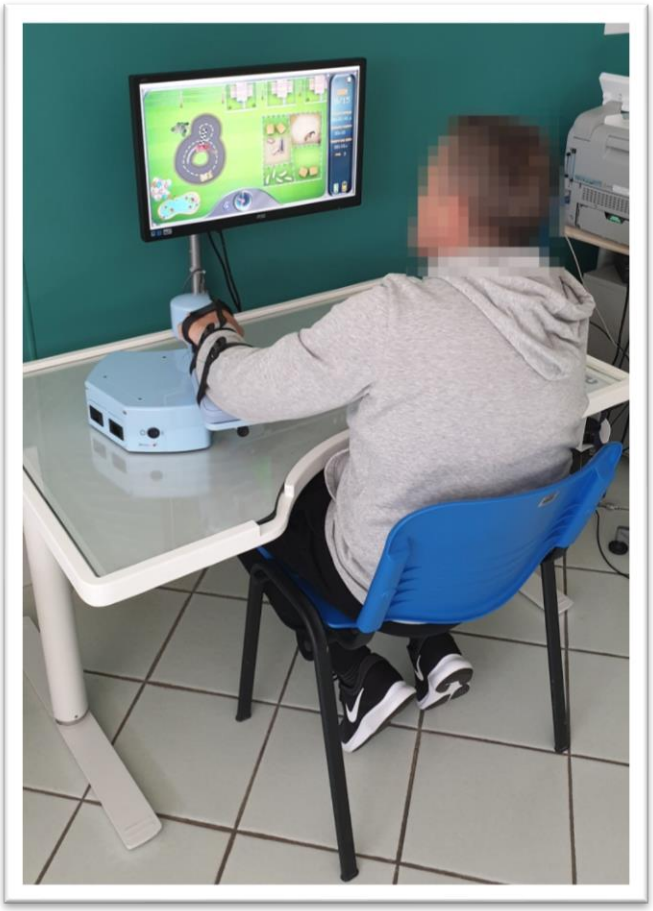


Figure 1 Motore (Humanware)

1.1. Assistance modalities used in the protocols

- **Passive patient**. The manipulandum guides the patient independently of the latter's ability; in practical terms, this allows the patient to perform the exercise in a passive way. This mode is also useful for showing the patient how to do the exercise correctly.
- **Automode**. Should the patient stay too far from the trajectory, the robot will exert an increasing resistant force to bring them back to the ideal trajectory. If the patient does not start or remains motionless, the robot accompanies the patient for a portion of the trajectory and waits; if the patient still does not start or remains motionless, the robot accompanies the patient for another portion of the trajectory.

1.2. Exercises used in the protocols

Exercise	Parameters	Figures
Trajectories The patient is asked to drive his car along one of the selectable tracks.	Shape: Oval Number 8, Letter P or D Track position: center or lateral Direction: clockwise (CW) or counterclockwise (CCW) Size: small or large	
Coins The patient is asked to grab some coins and bring them back to the centre of the worktop, where they will accumulate.	Direction: clockwise (CW) or counterclockwise (CCW) Size: small or large	
Washing dishes The patient is asked to wash the dishes according to a pre-established sequence of actions (bring the plate into the sink, open the tap, reach the sponge, etc).	-	

1.3. Rehabilitation protocols

Motore: 45-min protocol for a patient with a severe disability

Modality	Exercise	Parameters	Repetitions
Passive patient	Trajectory	Oval, lateral, CCW, small	10 laps
		Eight, lateral, CCW, small	10 laps
	Coins	CCW, small	100 movements
	Trajectory	Oval, lateral, CCW, small	10 laps
		Oval, lateral, CW, small	10 laps

Motore: 45-min protocol for a patient with a moderate disability

Modality	Exercise	Parameters	Repetition
Passive patient	Trajectory	Oval, Lateral, CCW, small or large	10 laps
	Washing Dishes	-	2 exercises
Automode (assisted by the unimpaired arm)	Trajectory	Oval, Lateral, CW, small or large	20 laps
		Oval, Center, CCW, small or large	10 laps
		D, Lateral, CCW, small or large	10 laps
		Oval, Lateral, CCW, small or large	10 laps
	Cleaning Dishes	-	1 exercise
Automode	Trajectory	Oval, Lateral, CCW, small or large	10 laps
	Coins	CCW, small or large	100 movements

Motore: 45-min protocol for a patient with a mild disability

Modality	Exercise	Parameters	Repetition
Passive patient	Trajectory	Oval, Lateral, CCW, small or large	10 laps
Automode	Trajectory	Oval, Lateral, CCW, small or large	30 laps
		Oval, Lateral, CW, small or large	10 laps
		Oval, Center, CCW, small or large	10 laps
		Eight, Center, CCW, small or large	20 laps
		D, Center, CCW, small or large	10 laps
		P, Center, CCW, small or large	10 laps
	Coins	CCW, small or large	100 movements
		CW, small or large	100 movements
	Washing Dishes	-	2 exercises

3. Amadeo, Tyromotion

Amadeo is an end-effector robot for fingers rehabilitation, with 5 DOFs. It provides the motion of one or all five fingers, thanks to a passive rotational joint placed between fingertip and an entity moving laterally (the thumb has got two passive rotational joints). All five translational DOFs are independent and provide large coverage of the fingers' workspace. The set-up involved securing a small magnetic disc to the pulp of each finger with cohesive tape for connection with the end-effecter, which would move back and forth in accordance with lanes aligned with the finger movement direction. The wrist is immobilized using a Velcro strap so that the elbow and shoulder are inhibited from moving. The robot can calibrate the full passive range of motion for each finger before the start of a session and supply the assistive force to patients to complete the remaining range of motion during an exercise. Moreover, the maximum flexion and extension force for each finger are recorded to calibrate the exercise where a strength control is required.

Figure 2 – Amadeo (Tyromotion)

2.1. Exercises and assistance modalities used in the protocols

Therapy	Parameters	Figures
Sensitivity training A vibratory treatment to increase proprioception	Frequency (always 60 Hz in the protocol)	
CPM Plus Fingers are moved passively by the device across the preset range of motion; patients are asked to collaborate by moving his/her fingers synchronously with the device. If spasticity happens, the gripping movement stops as soon as any finger exceeds the strength limit.	Passive Range of Motion	
Spasticity treatment Individual fingers are moved in spasticity treatment, just as for "CPM Plus". In spasticity treatment, only the finger that exceeded the limit is stopped, contrary to "CPM Plus". All other fingers continue the movement until the strength limit is exceeded or until reaching the end of the configured movement range.	Passive Range of Motion	
Assistive therapy This program gives the patient the option to actively perform the movement – as much as possible – with his/her own finger strength. The system takes over and completes the extension or flexion if the finger sliders are no longer moved actively.	Passive Range of Motion	

2.2. Rehabilitation protocols

Amadeo: 45-min protocol for a patient with a severe disability

Exercise	Repetition/times
Sensitivity therapy	5 minutes
Spasticity treatment	120 repetitions
Sensitivity therapy	5 minutes

Amadeo: 45-min protocol for a patient with a moderate disability

Exercise	Repetition/times
Sensitivity therapy	5 minutes
Spasticity treatment	30 repetitions
CPM Plus	60 repetitions
Spasticity treatment	30 repetitions
Sensitivity therapy	5 minutes

Amadeo: 45-min protocol for a patient with a mild disability

Exercise	Repetition/times
Sensitivity therapy	5 minutes
Spasticity treatment	30 repetitions
CPM Plus	60 repetitions
Assistive therapy	25 repetitions
Sensitivity therapy	5 minutes

4. Diego, Tyromotion

The Diego system (Figure 3) is a mechatronic shoulder-arm rehabilitation device. It consists of two ArmUnits that hang above the patient and allow separate therapeutic treatments for each arm. Two dangling ropes pull the patient's arm upward at two locations (attached to the wrist and elbow). The attractive upward force can be adjusted individually. The system can be operated with one or two ArmUnits. Both arms can be treated simultaneously if the operation for two ArmUnits is enabled. Each ArmUnit contains two electric motors, which allow an independently adjustable weight easing of one arm at the patient's elbow and wrist. The device can be applied unilaterally or bilaterally and employs “intelligent gravity compensation” to un-weight the limb and facilitate motion in three dimensions, much like a mobile arm support.

Figure 3 Diego (Tyromotion): bimanual (left) and unimanual (right) treatment

3.1. Exercises and assistance modalities used in the protocols

3.1.1. Movement therapies

- **Assistive therapy.** During this program, patients can use their own strength to actively move their arms as much as possible. The system eventually takes over and completes the movements against gravity if the patient no longer exerts any force on the ropes.
- **Symmetry therapy.** Both arms should be in a symmetrical position or perform a symmetrical movement (as symmetrical as possible). One arm prescribes the position or movement while the other is pulled to the correct height with the adjustable assistance function (against gravity).

3.1.2. Serious games therapies

Active training in a virtual environment by carrying out various target-oriented tasks; the patients has to move the shoulder joint in order to accomplish several goal-oriented tasks (catch an apple with a basket, move a balloon avoiding obstacles, etc., see Table 7). The device can help the patient by un-weighting the limb and to assist movement against gravity. Some of these therapies are also provided with a simplified graphic ("basic version").

The exercises can be performed:

- by using the affected arm only;
- or bilaterally.

There are different categories of exercises, then can be summarized as:

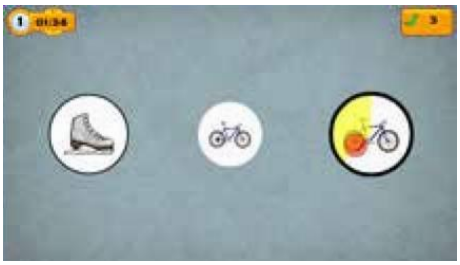
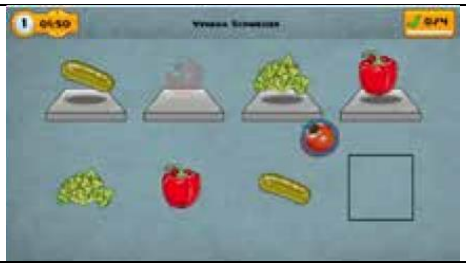
- "*1D precision*" or "*1D reaction*" (selective movements, i.e. shoulder flexion/extension or shoulder abd/adduction);
- "*2D motricity*" (combined movements on both sagittal and frontal planes, or on transverse plane);
- "*2D cognitive*" (movements on both sagittal and frontal planes, or on transverse plane, with cognitive requests);
- "*Virtual Reality*" (movements on a 3D space).

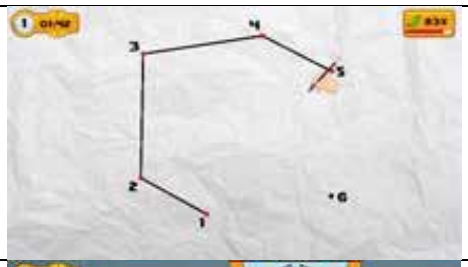
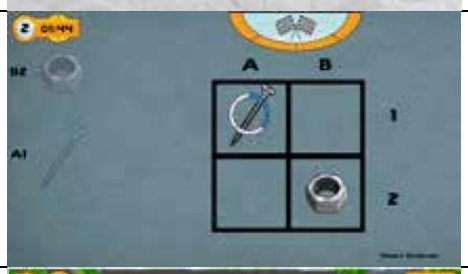
Each game has several levels, with an increasing difficulty (e.g., in the Applehunter game, the number of falling apples, as well as their velocity, increase, and the basket size decrease progressively). The game goes to the next level if the patients perform the required requests predefined in the software.

The movement range and the support against gravity provided by the device are set daily for each patient, according to his/her: (a) shoulder pain; (b) range of motion; (c) spasticity; and (d) strength.

Table 1 – Diego (Tyromotion) – available games

Game names	Categories	
Elevator Operating an elevator in a building; people must be picked up and taken to the correct floor.	1D precision	
Ballon Manoeuvring a balloon through a course and past obstacles	1D precision	
Applehunter Falling apples must be caught with a basket	1D precision	
Firefighters Flaring flames must be extinguished with a water jet as precisely as possible, achieving and maintaining the required strength and/or motion level	1D precision	
Cars Steering a vehicle in traffic	1D precision	
Shooting Cans Cans move past a fixed reticule on the screen. Pulling the trigger at the right time will shoot the cans: timely activation of strength and/or motion impulses	1D reaction	

Recycle Pick up different pieces of waste with a gripper and deposit them in the corresponding container: Achieving and maintaining the required strength and/or motion level	1D reaction	
Dinner Correct placement of the plates, glasses, knives, forks and spoons on the place mats (as if standing in front of the table).	2D motricity	
Get green The patient controls a dot and must guide it into the green circles and avoid the red circles.	2D motricity	
Chicken and worm A chicken must be controlled while it is picking worms from the ground.	2D motricity	
Crab A crab is running around on the beach. Direction and speed are controlled by the patient. The goal is to catch as many of the ants, which try to run away from the crab.	2D motricity	
Symbols Identifying of identical symbols and moving the red dot (cursor) to the identical symbol in a selection of symbols and staying there. Then returning to the centre of the playing surface in order to activate the next symbol.	2D cognitive	
Missing symbols A symbol is missing in the line below, and the patient must select it from the line above and place it in the correct location.	2D cognitive	

Draw by numbers The patient controls the pen and must connect the dots in the correct order.	2D cognitive	
Grid Place the symbols in the designated grid positions	2D cognitive	
Swimming The swim motions must be performed to move forward	Virtual reality	
Box and blocks Small cubes must be lifted over an obstacle	Virtual reality	
Hang up the laundry Laundry items and clothes pins must be taken from the table and attached to the clothes line.	Virtual reality	

3.2. Rehabilitation protocols

Diego: 45-min protocol for a patient with a severe disability

Uni/bilateral	Shoulder Movement	Exercise	Levels/Repetition
Unilateral (with assistance from the unimpaired arm)	Flexion/extension	1D precision	Increasing / Depending on patients' ability
	Abd/adduction	1D precision	

Diego: 45-min protocol for a patient with a moderate disability

Unilateral/bilateral	Shoulder Movement	Exercise	Levels/Repetition
Unilateral or bilateral*	Flexion/extension	1D precision	Increasing / Depending on patients' ability
	Abd/adduction	1D precision	
	Combined	2D motricity	
	Combined	2D cognitive	

Diego: 45-min protocol for a patient with a mild disability

Unilateral/bilateral	Shoulder Movement	Exercise	Levels/Repetition
Unilateral or bilateral*	Flexion/extension	1D precision	Increasing / Depending on patients' ability
	Abd/adduction	1D precision	
	Combined	2D motricity	
	Combined	2D cognitive	
	Combined	Virtual reality	

* during a single session, only a modality (unilateral or bilateral) is used.

5. Pablo, Tyromotion

Pablo (Figure 4) is a sensor-based device for unilateral and bilateral training. It is equipped with an accelerometer and a dynamometer, embedded in a "sensor handle". Therapies can be controlled either by means of force or motion. Therapies are controlled by the tilt (i.e., the rotation) of the sensor handle or by the strength applied to it. Before the training start, it is required to calibrate the sensor. Specifically, the patient is required to extend and flex the fingers as much as possible. With respect to the motion, the possible movement are: elbow extension/flexion; wrist dorsal extension/palmar flexion; shoulder joint abduction/adduction; lower arm supination/pronation; shoulder joint flexion/extension.

For weaker patients, two additional devices can be used:

- the Multiball, that trains pronation and supination of the forearm as well as extension and flexion of the wrist;
- the Multiboard, that help the patient to perform repetitive movements involving the whole upper limb, both distally and proximally.

Figure 4 - Pablo (Tyromotion) used with the *Sensor Handle* (left), the *Multiboard* (center) and the *Multiball* (right).

4.1. Exercises and assistance modalities used in the protocols

Owing to the characteristics of the device (absence of actuators), all the movements are unassisted.

Training is delivered by serious games therapy (see Table 1 – as Pablo shares most of the games with Diego), i.e. active training in a virtual environment by carrying out various target-oriented tasks. The patient has to move the sensor handle (or the Multiboard or Multiball), or grasp the handle with a variable

strength, to accomplish several goal-oriented tasks (catch an apple with a basket, move a balloon avoiding obstacles, etc.).

For each patient, the physical therapist set the range of movements, according to (a) shoulder pain; (b) range of motion; (c) spasticity, and the strength limits, according to the maximum strength of the patient.

4.2. Rehabilitation protocols

Pablo: 45-min protocol for a patient with a severe disability

Supporting device	Movement	Exercise	Levels/Repetition
Multiboard (with the hand fixed by a strap)	Elbow flex/extension	1D precision	Increasing / Depending on patients' ability
or			
Multiball (with unimpaired arm assistance)	Forearm prono/supination	1D precision	Increasing / Depending on patients' ability
	Wrist flex/extension	1D precision	

Pablo: 45-min protocol for a patient with a moderate disability

Supporting device	Movement	Exercise	Levels/Repetition
Multiboard	Elbow flex/extension	1D precision	Increasing /depending on patients' ability
	Elbow flex/extension and trunk lateral flexion	2D motricity	
	Elbow flex/extension and trunk lateral flexion	2D cognitive	
or			
Multiball	Forearm prono/supination	1D precision	Increasing /depending on patients' ability
	Wrist flex/extension	1D precision	
	Forearm prono/supination and wrist flex/extension	2D motricity	
	Forearm prono/supination and wrist flex/extension	2D cognitive	
or			
Sensor handle	Grasping	1D precision	Increasing difficulties/depending on patients' ability
	Elbow flex/extension	1D precision	

Pablo: 45-min protocol for a patient with a mild disability

Supporting device	Movement	Exercise	Levels/Repetition
Multiboard	Elbow flexion/extension	1D precision	Increasing /depending on patients' ability
	Elbow flexion/extension	1D reaction	
	Elbow flexion/extension and trunk lateral flexion	2D motricity	
	Elbow flexion/extension and trunk lateral flexion	2D cognitive	
or			
Multiball	Forearm prono/supination	1D precision	Increasing /depending on patients' ability
	Forearm prono/supination	1D reaction	
	Wrist flexion/extension	1D precision	
	Forearm prono/supination and wrist flex/extension	2D motricity	
	Forearm prono/supination and wrist flex/extension	2D cognitive	
or			
Sensor handle	Grasping	1D precision	Increasing /depending on patients' ability
	Elbow flex/extension	1D precision	
	Elbow flex/extension	1D reaction	

6. References

1. Woytowicz EJ, Rietschel JC, Goodman RN, et al. Determining Levels of Upper Extremity Movement Impairment by Applying a Cluster Analysis to the Fugl-Meyer Assessment of the Upper Extremity in Chronic Stroke. *Arch Phys Med Rehabil*. 2017;98(3):456-462. doi:10.1016/j.apmr.2016.06.023.
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