Mirror-Based Robotic Therapy for Ankle Recovery with a Serious Game: A Case Study with a Neurological Patient

Angie Pino[1], Daniel Gomez-Vargas[2], Andrea Garzón[3], Flavio Roberti[2], Ricardo Carelli[2], Marcela Múnera[1] and Carlos A. Cifuentes[4,5]

Abstract— **Neuromuscular disorders, such as foot drop, severely affect the locomotor function and walking independence after a brain injury event. Mirror-based robotic therapy (MRT) has been a promising rehabilitation strategy favouring upper limb muscle strength and motor control in the last years. However, there are still no studies validating this technique in lower limb experimental protocols. This paper presents an innovative visual and motor feedback strategy based on serious games and MRT modalities. Thus, a preliminary system validation with a healthy participant is performed. Moreover, the strategy's potential effects were investigated in a neurologic patient's short rehabilitation program. After six sessions, the results of the method favoured active ankle plantarflexion range of motion and muscle activation. Although the patient had a positive adaptation at the end of the game, it is necessary to improve the proposed strategy to enhance the robotic experience in the long term.**

Index Terms— **Mirror-based therapy, serious games, ankle rehabilitation, ankle exoskeleton**

I. INTRODUCTION

Foot drop is a locomotor impairment secondary to compressive disorders, traumatic injuries, or brain lesions. It has a reported prevalence of 19 per 100.000 people and is characterized by a weakness that hinders lifting the front part of the foot [1]. This condition, along with a hemiparesis, is highly manifested in Acquired Brain Injuries (ABI) where the central nervous system is unable to send signals to the muscles in charge of ankle dorsiflexion, which is mainly reflected during the swing phase of gait [2], [3]. Consequently, an asymmetrical gait pattern emerges, reducing the patient's stability and independence, raising the effort to walk, and increasing the risk of falling [4].

Patients who exhibit this pathology perform conventional physical rehabilitation with task-specific exercises to overcome these impairments and achieve autonomy. On the other hand, braces as an ankle-foot orthosis (AFO) are also the most common treatment to hold the straightened position of the foot in the frontal and transverse planes [5]. However, despite the partial independence in activities of daily living achieved by the previous techniques, some after-effects remain in patients reducing their quality of life.

Thus, robot-assisted ankle rehabilitation has emerged to support the therapeutic processes in intensity, long-time sessions, and person-centred therapies [6]. Therapeutic approaches, such as serious games, favour changes in plasticity and induce skills development over an interactive environment [7]. Another predominant rehabilitation approach to induce neuroplasticity is traditional mirror therapy. The strategy uses visual stimulation with a mirror placed in the person's midsagittal plane to stimulate the neural networks that control limb movement [8]. Thus, the movements performed by the unaffected limb are reflected in the mirror to simulate the hidden paretic limb motion. Other strategies employ mirror feedback within a virtual or gaming environment to generate a similar effect as traditional techniques [9]. For these cases, (1) the user perception due to the mirror and (2) concurrent brain activation by feedback loop strategies enhance motor recovery and promote neural reorganization. However, physical interaction does not induce neuroplasticity since the paretic limb is not assisted during the therapy [10].

Mirror-based robotic therapy (MRT) has arisen within the proprioceptive feedback concept, reflecting the functional joint motion of the impaired limb [11]. The coordinated bilateral movements (i.e., involving both limbs) increase the affected hemisphere's activation improving motor control and inducing neuroplasticity. Several studies have shown promising results in strength and motor control, especially for the upper limb of patients with hemiparesis. However, the literature reports few studies on applying this strategy in lower limb rehabilitation. Those studies' goal consists of presenting mechanical architectures and control strategies without an experimental protocol [11], [12].

Following the above, the present study aims to introduce a visual and motor feedback interface based on serious games and the MRT strategy for ankle rehabilitation. Moreover, it also seeks to validate the proposed strategy adaptation and effectiveness in terms of the robotic response and short-term functional impact. To do that, this study respectively detailed (1) a preliminary experimental validation with a healthy subject and (2) a short and increased-intensity rehabilitation program with a neurological patient.

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[1]Angie Pino and Marcela Múnera are with the Department of Biomedical Engineering at the Colombian School of Engineering Julio Garavito, Bogota, Colombia.

[2]Daniel Gomez-Vargas, Flavio Roberti and Ricardo Carelli are with Institue of Automatics at the National University of San Juan, San Juan, Argentina

[3]Andrea Garzón is with the School of Medicine and Health Sciences, Universidad del Rosario, Bogota, Colombia.

[4]C. A. Cifuentes is with the Bristol Robotics Laboratory, University of the West of England, Bristol, UK. carlos.cifuentes@uwe.ac.uk

[5]C. A. Cifuentes is with the School of Engineering, Science and Technology, Universidad del Rosario, Bogota, Colombia. carlosan.cifuentes@urosario.edu.co

II. METHODOLOGY

A. Serious Game Interface

The serious game's strategy employed a non-immersive 3D virtual environment for path tracking exercise. Specifically, the game objective was to guide the trajectory of an aeroplane through some rings previously arranged in a triangular curve (see Figure 1). The game constantly received the angular orientation from the inertial sensor placed on the non-paretic foot tip. Thus, as dorsiflexion, the foot rotational changes on the sagittal plane reflected upwards on the avatar, while the plantarflexion implied the avatar descent. Therefore, the ideal gaming concept is to follow the trajectory guided by the tokens and in this way go through the rings, ideally in the middle of them. It is essential to emphasize that the user's range of motion was previously adjusted in an interface calibration stage as an individually adaptive approach for each session. Additionally, the game had three levels differentiated by the aircraft's sensitivity to generate rotational changes. Thus, the more advanced levels were less sensitive and required more effort.

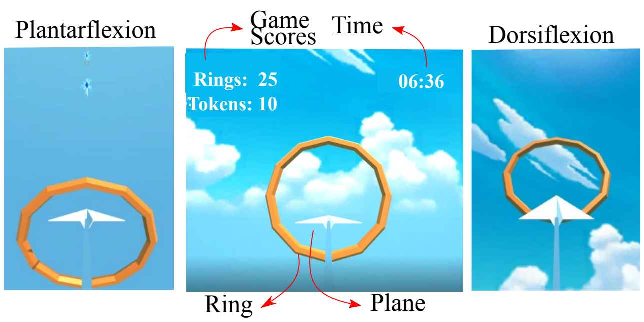

Fig. 1: Visual interface of the serious game implemented in the MRT system.

The interface also displayed the therapy time in regression, the number of rings passed and the total of tokens collected on a graphical level. These last were blue diamonds specifically arranged along the map to generate a visualized route towards the rings. The virtual environment and functionalities were performed with Unity software (Unity Technologies, Denmark). Besides, all graphic resources have initially been taken from a free and open-source game called "Glide" [13]. However, the functionality and playability were adapted to achieve the therapeutic objective of increasing the range of motion (ROM) of an impaired ankle.

B. Mirror-Based Robotic System

This work included a portable ankle exoskeleton, T-FLEX, based on variable stiffness actuators [14], as the motor feedback. T-FLEX comprises two high torque servomotors (MX106T, Dynamixel, USA) attached to composite tendons whose mechanical behaviour is similar to the human Achilles tendon [15]. The exoskeleton is placed on the user's shank to emulate the human functions during ankle movements, i.e., actuators as the user's muscles. T-FLEX can assist the dorsi-plantarflexion without restricting the other user's planes of motion [16]. Preliminary studies have been shown the potential of T-FLEX in assistive scenarios during gait rehabilitation programs [6], [17].

Control Architecture:

Considering the MRT concept and the serious games interface presented previously, Figure 2 shows the control strategy developed for T-FLEX. At the first stage, inertial sensors (BNO055, Bosch, Germany) placed on the user's feet, i.e., paretic and non-paretic, calculate the Euler angles ($e_{yH,P}$) relative to the ground employing an internal fusion algorithm. Subsequently, the user remains in a static position for 5 seconds to store the initial angle. Finally, the visual interface receives the non-paretic normalized angle value to control the aeroplane.

On the other hand, the angle error for the exoskeleton is estimated from the difference between non-paretic and paretic Euler angles. Then, a constant gain ($K_G = 0.4$) multiplies the error to find the desired angle increment for each actuator. Both actuators perform contrary rotations to minimize the error, achieving that the paretic foot follows the healthy foot's trajectory. The control gain was calibrated manually to reach the set-point in the minimum time.

C. Participants

Initially, a healthy subject (i.e., male, 26 years old, without cognitive and motor-related pathologies) participated in the preliminary validation of the robotic system.

However, the short rehabilitation case study was evaluated for a 42-year-old male diagnosed with left spastic hemiparesis secondary to a frontal subdural hematoma due to a fall from his proper height in January 2019. The sequelae of these episodes included a motor deficit of the left half of the body with brachial predominance, absence of motor control in dorsiflexion, and failures in balance and equilibrium. Following the acute management, the participant received inpatient and outpatient rehabilitation. This way, he could perform a hemiparetic gait with the external assistance of a 4-point base cane support and a rigid AFO at 90 degrees. Nevertheless, his gait was significantly slow, asymmetrical, and short in step length. In addition to the motor symptoms, the patient was described as having mild mental and behavioural impairments secondary to the injury. The above included a moderate adaptive disorder with a depressing mood and mild attention deficit.

Before the therapy procedures, the participants provided informed consent to follow the protocol previously approved by the local Research Ethics Committee of the Colombian School of Engineering Julio Garavito.

D. Experimental Procedure

As previously mentioned, the preliminary validation of the system was performed by a healthy subject in a single session to validate the control strategy with the exoskeleton and without considering the results of the game. Next, the rehabilitation protocol was carried out in six sessions over three weeks (i.e., two sessions per week) to evaluate the effects of the MRT with a serious game in a 20-min test. Throughout

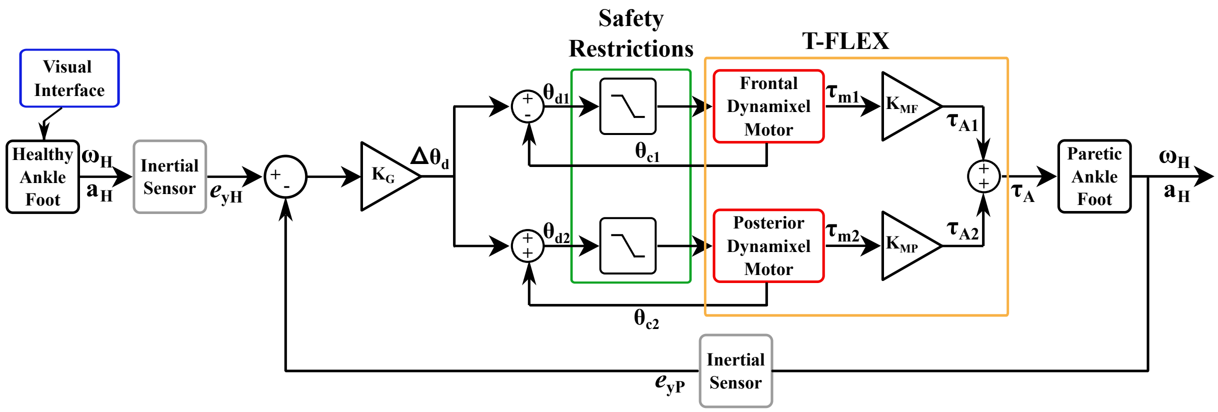

Fig. 2: T-FLEX's control architecture for a mirror-based therapy. The orange box represents the mechanical design of T-FLEX, including the torque of the actuators (τ_m) and angle (θ_c) outputs, the gain derivated from the tendons composition and user's dimensions (K_{MF}), and the total torque applied to the ankle (τ_A). The green box denotes the safety restrictions for the angle set-points (θ_d). K_G refers to the control gain that multiplies the error estimated between sagittal Euler angle of paretic and non-paretic feet (e_{yH}).

the session, the patient's non-paretic limb was sensed to control the dorsi-plantarflexion movements of the impaired extremity. Following MRT's concept, only the affected limb wore the assistance device. Simultaneously, the patient was engaged in a serious game where the task instruction was to perform ankle bilateral flexion and extension training movements. The therapy intensity progressively increased according to the game levels to progressively induce greater muscle activity and effort. The above was considered since previous studies with T-FLEX orthosis demonstrated the same training did not produce enough effort to generate high electrical activity [6].

The patient was seated with 90° knee flexion and elevated lower limbs throughout the interventions to avoid contact with the floor. Moreover, a screen is arranged in front of the patient showing the visual feedback provided by the serious game (see Figure 3). All experimental procedures were performed under the supervision of a physiotherapist at the Center for Biomechatronics at the Colombian School of Engineering Julio Garavito.

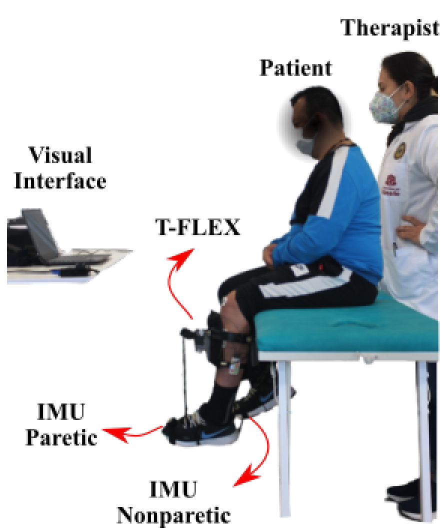

Fig. 3: Experimental setup for the MRT strategy using T-FLEX exoskeleton.

E. Outcomes

One of the main goals of this study was to validate the MRT performance in terms of adaptation and effectiveness. The robotic actuators' response to angular input variations was initially assessed in a non-pathological participant to certify this goal. In this sense, actuators data (i.e., desired and current positions) and the Euler angle error were stored using the rosbag tool under the Robot Operating System (ROS) framework. The actuator controllers and the inertial sensor acquisition codes are available in a public repository at `https://github.com/GummiExo/t_flex`.

After the preliminary validation, the strategy was thoroughly tested to understand its functionality and effects on the neurological patient. The impact on the user's motor functionality was divided into therapy results and pre and post functional tests.

1) Therapy Results: Throughout all sessions, the paretic ankle dorsal and plantar flexion muscular activity (i.e., tibialis anterior and gastrocnemius muscles) were recorded with the Shimmer3 (Shimmer, Boston, USA) surface EMG sensor. The acquired data passed through a notch filter (60 Hz), a Butterworth bandpass filter (10 and 100 Hz), and a rectification stage. Subsequently, the signals were normalized according to the maximum voluntary contraction (MVC) and finally smoothed to extract the RMS value as the main feature throughout each session.

On the other hand, the results of the serious game were fundamental in describing the patient's performance. These data presented the number of rings passed and not passed, the total tokens collected, and the type of collision with the ring (i.e., upper, ideal, or lower). An ideal collision with the ring is to pass through the middle of the circle, while the upper and lower collisions refer to collisions close to the upper and lower edges of the ring, respectively.

2) Pre and Post Functional Assessments: The physiotherapist validated the consequences before and after the six-session strategy. This way, the modified Ashworth scale and the passive and active range of motion (ROM) were

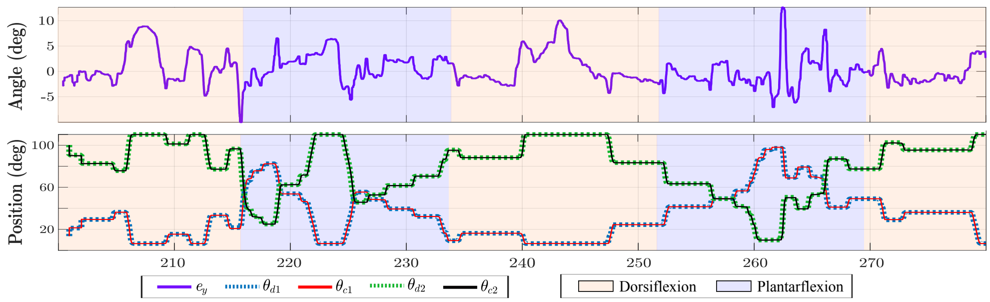

Fig. 4: Control signals for MRT strategy using T-FLEX exoskeleton. The upper figure shows the error (i.e., Euler angle) during the session. The lower part shows the set-points (θ_d) and the current angles (θ_c) for the actuators. In addition, the angle represents the actuator rotation concerning zero, being 120° the maximum rotation range.

performed in the lower limbs. Likewise, a 6-minute walk test (6MWT) evaluated the maximum distance covered and the physiological performance (i.e., heart rate, breathing rate, SpO2, and Borg Breathlessness Scale).

3) Data Processing: All data were imported and processed into Matlab (The Mathworks, Inc., Natick, MA, USA). Specifically, tibialis anterior and gastrocnemius muscles were recorded for all the proposed conditions and normalized to each session recorded maximum voluntary contractions (MVCs).

III. RESULTS

A. Control Strategy

A preliminary validation with a healthy subject was carried out in the first stage. Thus, the control strategy was tested to validate the functionality and performance during an MRT. Figure 4 shows the error signal and the actuators angle during the session.

The controller shows an error angle reduction during the session while the user uses the visual interface. The maximum error exhibited concerning the dominant foot was 12 degrees for dorsiflexion and 10 degrees for plantar flexion. On the other hand, the actuators followed the angle set-points to compensate for the movement in the non-dominant foot (see Figure 4).

The neurologic patient accomplished six sessions using the T-FLEX exoskeleton and the visual interface for the second stage. In terms of the error signal, the patient exhibited a maximum error of 38 degrees in dorsiflexion and 20 degrees in plantarflexion. Specifically, the actuators could not correct the angle error for the dorsiflexion movements instant several times. In this sense, the actuators exhibited saturation (i.e., safety conditions), so the paretic foot did not follow the healthy foot just in these cases (see Figure 5).

B. Therapy Results

Figure 6 shows the mean RMS values for each therapy session. More significant muscle activations were initially expected as the therapy intensity increased (i.e., higher game level). Nevertheless, the tibialis anterior and gastrocnemius muscles showed fluctuating and no meaningful activity during the initial levels (i.e., levels one and two).

Finally, the session results with the serious game were presented in Table I. As can be observed, the patient obtained a better performance throughout level 3 with mostly top and ideal ring collisions. Moreover, the user adaptation to the game was evident with the progressive increase in tokens collected during the levels.

TABLE I: Serious game results in patient performance

	Level 1		Level 2		Level 3	
	Ses 1	**Ses 2**	**Ses 3**	**Ses 4**	**Ses 5**	**Ses 6**
Hits	24	27	36	15	44	35
Failures	43	40	31	52	23	32
Precision (%)	35.8	40.3	53.7	22.4	65.7	52.2
Tokens	6	12	12	15	20	25
Top Collisions	10	8	18	2	40	13
Ideal Collisions	6	15	7	58	4	12
Down Collisions	8	4	11	2	0	10

C. Pre and Post Functional Assessments

In terms of functional tests, the patient's muscle tone, evaluated with the Ashworth scale, remained with no changes in a two-score for the gastrocnemius muscle and +1 in tibialis anterior, hamstring, and left quadriceps muscles. In contrast, the ROM measurement in Table II reported changes in most of the active motions of the left paretic limb. The highlighted values denote variation above 10% for both increases (green) and decreases (red). There were increases in hip abduction, knee flexion and extension, plantar flexion of the ankle, and inversion of the foot. Moreover, this study showed a 14% and 10% decrease in the active and passive dorsiflexion, respectively. The other measures exhibited less than 10% variations compared to the initial assessment.

TABLE II: Range of Motion (ROM) for both lower limbs in MRT

		Initial				Final			
		Passive (°)		Active (°)		Passive (°)		Active (°)	
Joint	**Mov**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**
Hip	**Flex**	110	118	110	116	110	118	**76**	110
	Ext	18	20	10	20	18	20	10	20
	Abd	40	40	10	40	40	40	**24**	36
	Add	22	22	12	22	22	22	**18**	22
	Int R	30	30	20	30	30	30	20	30
	Ext R	30	30	16	30	30	30	16	30
Knee	**Flex**	120	124	12	120	120	124	**40**	114
	Ext	4	4	-10	-6	**6**	**6**	**-8**	-6
Ankle	**Dorsi**	14	28	-12	24	**10**	30	**-14**	22
	Plant	58	50	12	40	56	50	**24**	**48**
Foot	**Inv**	30	24	0	22	30	24	**4**	22
	Ever	4	12	0	12	4	12	0	12

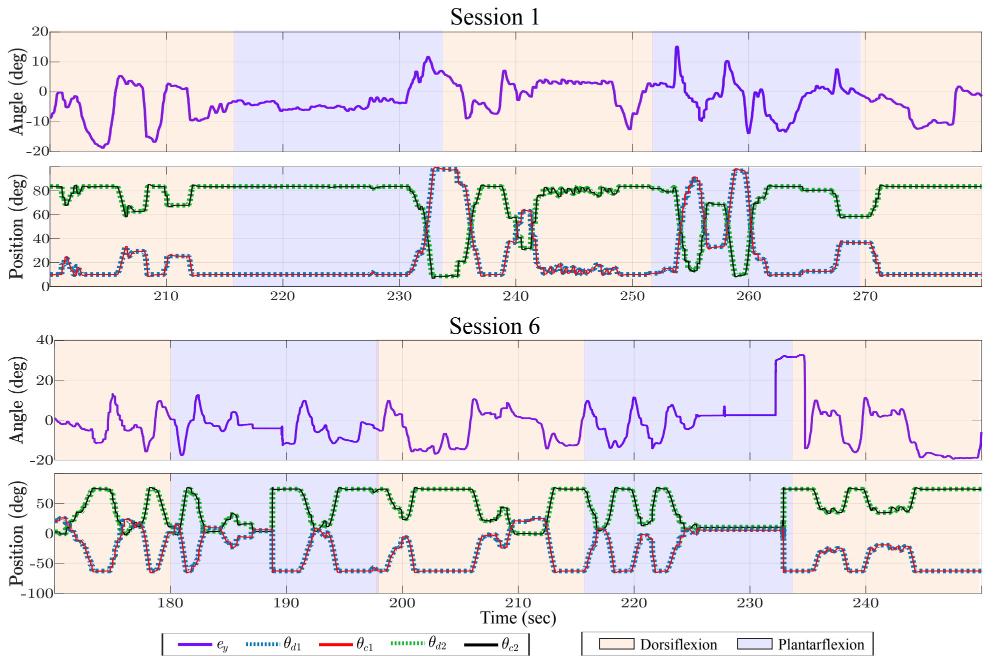

Fig. 5: Patient control signals using T-FLEX with the MRT strategy. The upper figure shows the error (i.e., Euler angle) during the session. The lower part shows the set-points (θ_d) and the current angles (θ_c) for the actuators. In addition, the angle represents the actuator rotation concerning zero, being 120° the maximum rotation range.

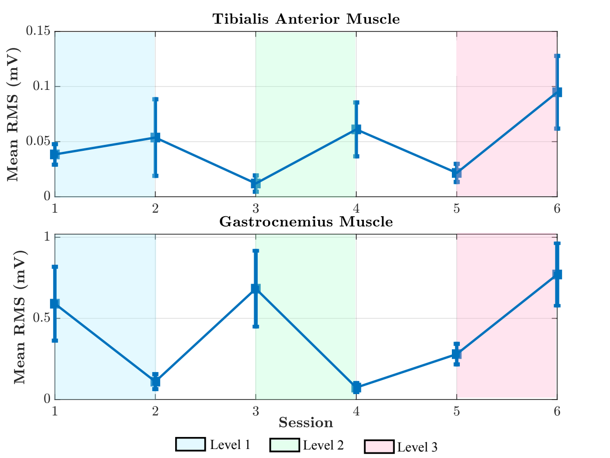

Fig. 6: Mean RMS values per session. The upper graph focuses on tibialis anterior muscle activity while the lower graph reports the gastrocnemius.

On the other hand, the 6MWT results did not show differences greater than 10% for the covered distance and physiological condition values (see Table III). Nevertheless, the fatigue perception decreased after performing the gait test.

TABLE III: Six-minute walk test (6MWLT) results

Parameters	Initial		Final	
	Pre-6MWT	Post-6MWT	Pre-6MWT	Post-6MWT
Distance (m)	-	47.1	-	43.9
Heart rate (bpm)	70	72	69	72
Breathing rate (breaths/min)	15	16	16	18
SpO2 (%)	91	92	90	93
Borg Score	1	3	1	**2**

IV. DISCUSSION

The experimental design of this study intended to perform a preliminary validation of the strategy performance in the healthy subject to subsequently assess the short time effects in increased intensity sessions with the neurologic patient. The system worked ideally with the healthy user in terms of the robotic and control strategy. However, it presented considerable control errors with the patient possibly related to an abnormal posture (i.e., extending the knee and back) during the sessions. In this case, while the healthy user kept the same posture, i.e., back straight and 90° knee flexion, during the preliminary validation, the patient tended to perform compensatory movements to accomplish the ankle ROM due to his spasticity. Therefore, Euler angle measurements were affected because the angle estimation was relative to the ground. Accordingly, it is necessary to propose another type of movement intention detector (e.g., including an additional inertial sensor on the shank) or another experimental setup that adapts the proposed system to the spastic condition.

According to the functional results after the therapy, the variations exhibited in the active patient ROM were greater than 10% compared to the initial assessment. In this case, the bilateral plantarflexion movements considerably improved in addition to the active flexion and extension of the knee. These findings are highly positive because they demonstrated motor control improvements to perform voluntary movements. According to Mark et al., an increase in active ROM movements theoretically reflects a strengthening of the neural connections to execute the motor activities [18]. These results potentially favour the initial intent of the strategy to induce neuroplasticity. Partially demonstrate that combining the visual-motor interface with T-FLEX helps generate own ankle changes. Despite the benefits, decreases in hip flexion and adduction were also found. These changes are probably a consequence of the previously discussed posture and compensatory movements to operate the game. Remarkably, the patient evidenced greater effort in performing plantar flexion movements to visualize the aircraft decline in the game. This is possibly why the results favour plantarflexion to a greater extent.

On the other hand, variability of muscle activity presented at levels one and two contrasted with the findings at level three, where muscles had a greater activation and reached maximum RMS values in the last session. These findings suggest the game difficulty strategy only generated a substantial effort at this level. Therefore, the perception of having the lowest sensitivity to control the aeroplane rotation seemingly produced a higher range of motion and in turn, a greater muscle activation. However, a larger number of sessions is required to validate this outcome.

The patient demonstrated a positive adaptation to the last session's game results (i.e., number of hits and tokens). Further, he always remained attentive and focused on achieving the game's objectives despite being diagnosed with a mild attention deficit. Hence, it is possible to deduce that the serious game fulfils the aim of focusing the user's attention on the therapy and demonstrates its potential influence even in patients with mild attention deficit. Moreover, the present single-case study provides preliminary and favourable evidence of patient active ROM improvements and high muscular activation after six sessions of the MRT and serious game treatment. The above suggests the strategy can potentially be used in ankle rehabilitation therapies, where neurological and chronic patients may benefit from similar outcomes. However, due to disease variability, further studies with an improved system, a long-term study, and a larger patient sample are required to measure the effectiveness of the strategy objectively. Compared to other studies, this study found and reported relevant changes in active movements after a short-term rehabilitation program applying visual and motor feedback based on serious games [19], [20], [21].

V. CONCLUSIONS

This paper presented the MRT strategy during the interaction of a serious game of trajectory tracking. The preliminary robotic control validation with the healthy subject demonstrated ideal results for carrying out the bilateral technique. However, this same strategy with the patient suggests proposing another sensory or control strategy to suit the pathological condition. On the other hand, the functional results favoured both ankle plantarflexion ROM and increased muscle activation in the last session. This is supposed to be an approach to the induction of neuroplasticity and the relearning of lost motor functions.

Future work includes improving the robotic and visual strategy to promote motor recovery. Additionally, long-term studies with a larger sample size should be performed to validate the benefits found in this study.

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