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DEVELOPMENT AND EVALUATION OF A ROBOTIC PLATFORM FOR REHABILITATION OF ANKLE MOVEMENTS

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Abstract. *This paper presents the development and evaluation of a robotic platform for ankle rehabilitation of pos-stroke patients. Two virtual games are developed to interact with the patients through a set of tasks regarding dorsiflexion movements and muscle strength. The usability study presented in this paper was conducted in 19 hemiparetic and 19 healthy subjects, with the aim of evaluating ergonomics issues, safety, level of difficulty of the games, and platform ability to measure subjects' dorsiflexion range of motion and torque. Results from both games are presented and discussed.*

Keywords: *robotic rehabilitation, serious games, walking rehabilitation*

1. INTRODUCTION

Cerebrovascular diseases, including stroke, is the second leading cause of death worldwide and the leading cause of disability in the adult population. Due to the large number of individuals who survive a stroke, with different types of sequelae, new therapies have been proposed in recent years in order to promote a faster and more effective recovery of stroke patients, as for instance, the robotic therapy (Krebs, *et al.*, 2008).

However, while upper limb rehabilitation using robots in chronic or subacute stroke patients is already recommended by the American Heart Association (Miller, *et al.*, 2010), the lower limb robotic therapy has not been proven, and some studies have found no significant gains regarding this therapy compared to the conventional one (Hidler, *et al.*, 2009, Hornby, *et al.*, 2008). Therefore, alternative procedures for walking rehabilitation aided by robots continue to be proposed and studied.

Results from literature show that the use of robotic devices for rehabilitation of ankle movements associated with virtual stimuli, even in the sitting posture, enhances gains related to gait velocity, stride length and cadence of walking on a treadmill or on the ground. Several robotic devices have been developed with the aim of rehabilitating this joint, grouped into two broad categories: exoskeletons and robotic platforms. Zhang, *et al.* (2013) conducted a systematic review of these devices; the main results are obtained with the Anklebot and the Rutgers Ankle platform. The Anklebot is an impedance-controlled exoskeleton attached externally to the lower limb and can be used to evaluate therapeutic protocols in sitting position or on a treadmill (Forrester, *et al.*, 2011). The Ankle Rutgers platform is a Stewart platform which remains fixed to the ground and allows only training exercises the sitting position (Mirelman, *et al.*, 2008). According to Zhang, *et al.* (2013), few studies have evaluated the mechanisms by which ankle rehabilitation occurs.

This paper presents the development and evaluation of the Robotic Platform for Ankle Rehabilitation (RePAiR), an impedance-controlled robotic device to be used by pos-stroke subjects. Based on virtual therapy, two games are developed: the first one to stimulate and evaluate dorsiflexion range of motion, and the second one to deals with muscle strength. The proposed robotic platform and games were evaluated by 19 hemiparetic and 19 healthy subjects, during a one session evaluation, preceded by a conventional assessment. Results from both games are presented and discussed.

The paper is organized as follows: Section 2 presents the robotic platform for rehabilitation of ankle movements; Section 3 presents the set of serious games developed to evaluate dorsiflexion ROM and torque; Section 4 presents

details of the usability study perform with hemiparetic and healthy subjects; Section 5 presents the results obtained from the conventional evaluation and the RePAiR, and the indices generated by the game data; and Section 6 presents the conclusions.

2. ROBOTIC PLATFORM FOR ANKLE REHABILITATION

The Robotic Platform for Ankle Rehabilitation (RePAiR) was conceived to improve motor recovery in pos-stroke patients, requiring active motion from the patient during training sessions. The continuous use of the platform can increase muscle force, motor control and sensorimotor coordination, improving the walking pattern and avoiding the drop foot. Also, the proposed platform allows the development of an objective evaluation methodology to measure muscle force and range of movement, with the differential of evaluating pure joint motions. Furthermore, the RePAiR adds the benefits of virtual therapy as the high level of motivation and learning, with entrainment and fun.

The RePAiR is a one degree-of–freedom robotic system actuated by a compact series elastic actuator (CSEA), Figure 1. The patient is allowed to make motion of dorsiflexion and plantarflexion. The abduction/adduction degree-of-freedom is adjustable according to the patient evaluation by moving the platform base with relation the support part. However, no actuation or free-motion is provided in the degree-of-freedom.

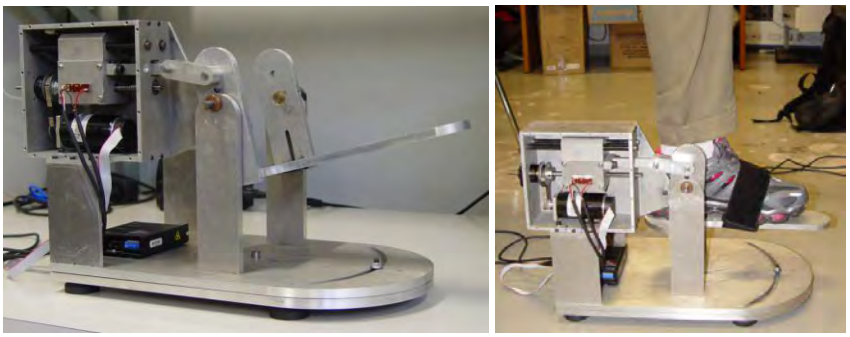

Figure 1. Robotic Platform for Ankle Rehabilitation.

The CSEA developed in Amaral (2011) allows to the therapist to select the level of the assistance provided by the device. Since it is possible to measure the force imposed by the user through the elastic element of the SEA, force and impedance controllers can be implemented. The impedance control is a suitable concept for human interaction with robotic devices, since it regulates the force/velocity ratio at the contact point. The impedance control concept has been applied for rehabilitation robotics by all commercial and non-commercial devices.

A series elastic actuator is essentially a spring element following a rigid actuator. The variable stiffness (or more generalized, the variable impedance) is defined by force and impedance controllers, with feedback of the spring deflection measurements. Figure 2 shows the typical configuration of a SEA for force control.

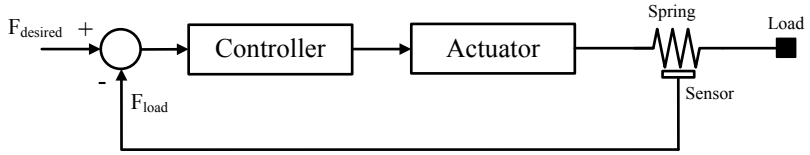

Figure 2 – Configuration of a SEA for force control.

In this study the RePAiR is applied for evaluating stroke and healthy subjects while seated, interacting with virtual games and improving both dorsiflexion range of motion and torque.

3. SERIOUS GAMES FOR ANKLE REHABILITATION

This section presents the set of serious games developed for ankle rehabilitation using the RePAiR. The idea is to take advantage of the benefits of the virtual therapy as the high level of motivation, promoting at the same time entertainment and fun. The games also provides resources to simulated funtional activities where the patient practice motions to be performed later in the real world. They also allow the therapist to reproduce identically the evaluations to all patients.

Two computational games are proposed. Both games were designed to stimulate dorsiflexion motions, one to evaluate range of motion of the ankle joint and one to measure applied forces to the platform. The games was developed using the RobRehab framework (Caurin, *et al.*, 2011). It provides the integration between the robotic system shown in

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the previous section with games developed in C # and XNA. The RobRehab framework is modular, since it can be easily used, modified and even replaced by any robotic system controlled by an EPOS (Easy-to-use Positioning) for DC and Brushless servomotors.

3.1 "O Guloso"

The first game, named "O Guloso" (*The Sweet Tooth*), was designed to stimulate and evaluate the range of motion of the ankle. In this game, the angular position of the ankle joint is associated with the vertical position of an animal picture on the game screen. Figure 3 shows the graphical interface of the game.

The goal is to collect as many as possible the food itens, which move from right to left. The vertical position of the itens on the screen is determined by a predefined routine, with periods where the position is determined randomly, short periods where the maximum dorsiflexion of the patient is stimulated, and resting periods. The predefined routine is defined as:

- Five (5) randomly-positioned itens;
- Five (5) maximum dorsiflexion itens, positioned at the upper area of the screen (adjusted to the initial range of motion of the patient);
- Three (3) resting itens, positioned at the lower area of the screen.

In the proposed assessment, this predefined set of itens is repeated six (6) times, totaling 78 itens and approximately 5 minutes.

Figure 3. Graphical interface, "O Guloso".

3.2 "O Atleta"

To assess the dorsiflexion torque measurement capability of the RePAiR, the game "O Atleta" (*The Athlete*) was designed. Figure 4 shows the graphical interface of the game. The screen shows the athlete running from left to right and when it approaches the obstacles, the patient should perform dorsiflexion torque to jump them. The right sidebar shows the amount of torque exerted by the patient and the required torque for the athlete to jump the obstacle.

Figure 4. Graphical interface, "O Atleta".

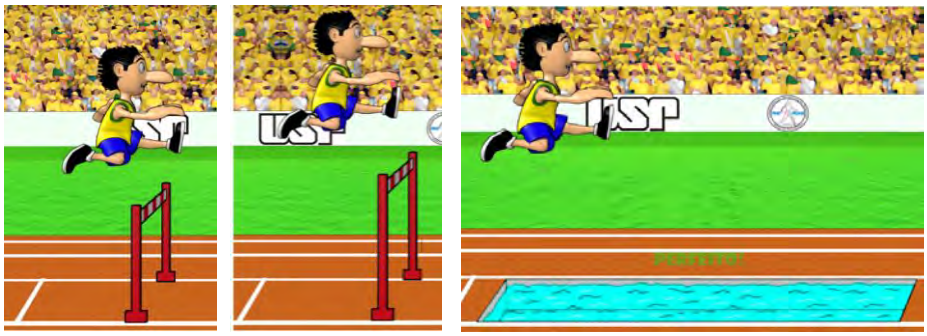

Figure 5. Obstacles (lower hurdle, higher hurdle, and pool).

Three obstacles are used to assess the patient's muscle strength: the lower hurdle, corresponding to 30% of the maximum dorsiflexion torque performed by the patient at the initial evaluation before the game start; the higher hurdle, equivalent to 50% of maximum torque; and the pool, in which the patient should maintain the torque above 30% of the maximum for the entire length of the pool, Figure 5.

A predefined routine, repeated 2 times during the assessment, is defined as:

- Four (4) lower hurdles;
- One (1) pool;
- Three (3) lower hurdles;
- One (1) higher hurdles;
- Three (3) lower hurdles.

The total assessment takes approximately 2 minutes, where the patient must handle 24 obstacles.

4. USABILITY STUDY

The present study was developed as part of the agreement between the University of São Paulo at São Carlos and the SORRI-Bauru Rehabilitation Center, located in Bauru, state of São Paulo, where the tests were performed. The assessment project was approved by the Ethic Committee of the School of Nursing, University of São Paulo (certificate no. 08477512.5.0000.5392, November, 2012).

The proposed study aims to evaluate the usability of the RePAiR regarding ergonomics, safety, level of difficulty of the games, and platform's ability to measure subjects' dorsiflexion range of motion and torque. It was evaluated in two populations: stroke patients in clinically stable condition at least for 6 months, and healthy subjects, usually the caregivers of the first group.

The inclusion criteria for the stroke group specifies male or female subjects, regardless of race, age 30-85 years, hemiparesis with preserved cognition and without sensitivity deficit, and active range of motion of ankle dorsiflexion greater than 5 degrees. For the healthy individual group, the inlcusion criteria allows for male or female subjects, regardless of race, age 30-85 years, without cognitive deficit, no change in sensitivity, without motor impairment of muscle strength, and range of motion of ankle dorsiflexion in normal ranges (0-20 degrees).

According to the exclusion criteria (for both groups), subjects who presented the following characteristics were not able to participate in the research: atrophy and deformities of the lower limb, by limiting the range of motion of the ankle; cognitive deficits and psychiatric disorders that preclude understanding the test proposed in this study; any kind of visual impairment that compromises the performance of therapy; previous diseases that may interfere in the assessments, such as severe rheumatic disease, amputations and orthopedic disorders; and vestibular system impairment.

After subject recruitment, a conventional physiotherapy assessment was conducted. At the same day, the participants received information regarding the research and performed the informed consent procedures. Subsequently, the tests with the RePAiR were scheduled, where both groups performed the predefined routines for the "O Guloso"and "O Atleta" games. A previous acquaintance game session was conducted where the therapist introduces food itens or obstacles according to the subjects performance.

For the hemiparetic group, both limbs were tested in order to evaluate the concept that the unaffected hemisphere also introduces changes in the gait and therefore must be considered within a rehabilitation program. For the healthy group, only one randomically defined limb was tested.

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5. RESULTS

This section presents the assessment results, specifically the comparison between the convetional measureaments of range of motion and muscle force and the data obtained from the RePAiR. It is also shown a case study where a set of possible evaluations from the game and robotic data is addressed.

The initial proposal was that both groups were composed of 20 subjects. However, one hemiparetic individual, previously assessed by conventional tests, gave up the assessment due to personal issues. Hence, a total of 19 stroke patients and 19 healthy individuals participated in this study.

5.1 Hemiparetic Group

From the 19 individuals, 9 are males and 10 females, with ages varying from 45 to 82 years (61.2 ± 8.7 years, all data presented as mean ± standard deviation, where applicable). The stroke group consisted of hemiparetic patients who had their first event from 2 to 114 months ago (38.1 ± 35.0 months), note that the lesion time is not considered as an inclusion or exclusion criterion in this study. Regarding the topography of lesion, 9 individuals presented right hemiparesis (6 males and 3 females) and 10 left (3 males and 7 females).

All subjects had not applied botulinum toxin type A in the triceps surae muscle groups, where often spasticity is present, and did not use any of kind of orthosis. All hemiparetic individuals also showed preserved sensitivity, proven by means of conventional susceptibility testing. Regarding the mini-mental score, the minimum value was 23 and the maximum was 30, indicating the absence of cognitive impairment or cognitive decline.

In this group the RePAiR was evaluated in both lower limbs (impaired and preserved).

5.2 Healthy Group

From the 19 individuals, 10 are males and 9 females, with ages varying from 32 to 84 years (55.7 ± 13.7 years); 11 individuals did not perform regular physical activity and 8 performed regularly. All individuals had preserved sensitivity and mini-mental score from 21 to 30, indicating the absence of cognitive impairment or cognitive decline.

The RePAiR was tested on only one leg, randomly selected, totaling 11 tests in the right lower limb (RLL), 6 males and 5 females, and 8 tests in the left lower limb (LLL), 4 males and 4 females.

5.3 Range of Motion (ROM) Analysis

Regarding the conventional method, the healthy individuals presented active dorsiflexion ROM of: 18.8 ± 1.8 degrees, RLL, and 18.4 ± 3.9 degrees, LLL. For the hemiparetic group, the individuals presented in the active case, unimpaired limb: 17.4 ± 4.6 degrees, RLL, and 17.6 ± 3.9 degrees, LLL; impaired limb: 14.4 ± 6.4 degrees, RLL, and 12.4 ± 5.5 degrees, LLL. All passive measurements have shown a slight increase in the mean values of dorsiflexion ROM for both groups.

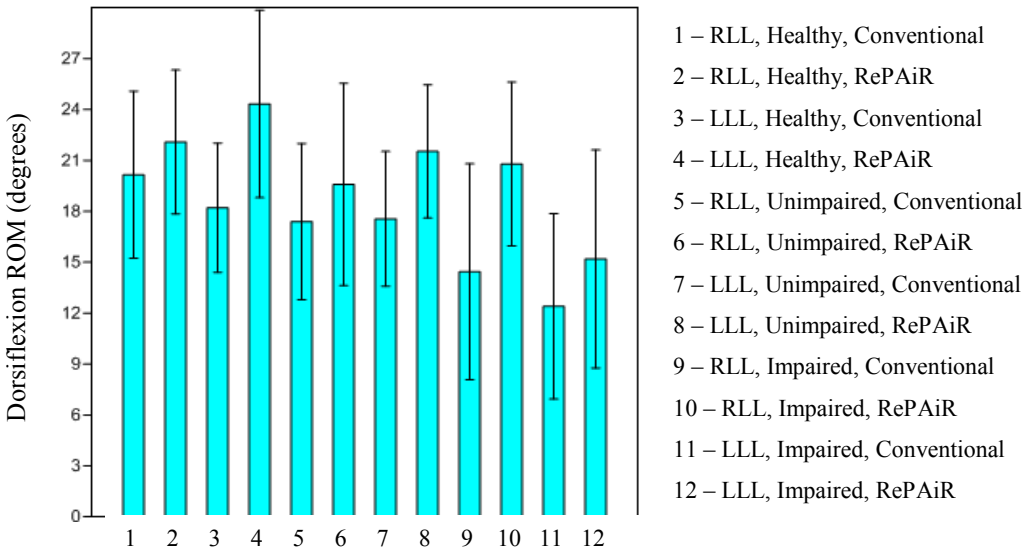

Figure 6 – Active dorsiflexion range of motion, conventional and RePAiR measurements.

Using the RePAiR, only active measurements were performed. The ROM values are found by computing the mean of three successive measurements of the maximum dorsiflexion taken before the before the beginning of the game. This value is also used to adjust the vertical size of the game screen.

The following dorsiflexion ROM values were obtained for healthy subjects: 21.9 ± 4.4 degrees, RLL, and 24.2 ± 5.1 degrees, LLL. For the hemiparetic group, unimpaired limb: 19.6 ± 5.9 degrees, RLL, and 21.5 ± 3.9 degrees, LLL; impaired limb: 20.8 ± 4.8 degrees, RLL, and 15.2 ± 6.4 degrees, LLL.

Figure 6 presents a comparison between the conventional and the robotic platform measurements, for both limbs and groups, and regarding the active case. It is used the ANOVA test to compare the data to detect significant differences across the methods for the active measurement. The significance level was set at $p < 0.05$. Table 1 shows the values of p. It can be noted that three of six values have presented significant differences between conventional and RePAiR measurements.

Table 1 – p for ROM analysis, conventional versus RePAiR measurements.

Conventional x RePAiR	***p***
RLL, Healthy	0.27
LLL, Healthy	0.0037 *
RLL, Unimpaired	0.37
LLL, Unimpaired	0.048 *
RLL, Impaired	0.029 *
LLL, Impaired	0.31

* Statistically significant difference ($p < 0.05$).

5.4 Dorsiflexion Torque Analysis

Three measurements of maximum dorsiflexion torque are performed at the beginning of the virtual game "O Atleta" by the RePAiR. The mean value is set as the maximum dorsiflexion torque and used to define the training requirements (30 % for the lower hurdle and pool, and 50% for the higher hurdle). Table 2 shows the mean and standard deviation of maximum dorsiflexion torques obtained from RePAiR for the hemiparetic group.

Table 2 – Maximum dorsiflexion torques from RePAiR, hemiparetic subjects (Nm).

Lower Limb	**Impaired**	**Unimpaired**
Right	13.1 ± 3.9	16.4± 4.1
Left	9.2 ± 6.3	12.2 ± 5.2

Regarding the healthy group, Table 3 shows the maximum dorsiflexion torques for both right and left limbs, comparing male and female results.

Table 3 – Maximum dorsiflexion torques from RePAiR, healthy subjects (Nm).

Lower Limb	**Male**	**Female**
Right	19.2 ± 4.3	10.5 ± 3.3
Left	17.2 ± 5.6	10.3 ± 2.7

The conventional evaluation of dorsiflexion torque is a subjective test, with a scale values from 0 to 5. It was not possible to compare the results from the RePAiR and the conventional tests since a small number of subjects was used and the measured data from the platform presented a significant variance.

5.5 Game Results

This section presents a preliminary analysis of the data provided by the games. The main goal here is to shown that the available data can be useful to define patient condition and how he/she is evolving over the therapy sessions. For example, Figures 7 and 8 show typical responses for the games "O Guloso" and "O Atleta", respectively. In Figure 7, the item appears to the patient at the right hand side of the screen approximately at time 167 s and position corresponding to 22º. After a short period of time, the patient starts moving to that dorsiflexion angle and properly intercepts the item. From the data used to plot this graphic, it is possible to estimate travelled distance, maximum

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velocity, maximum acceleration, mean jerk, response time, and others kinematics measures related to the quality of the motion.

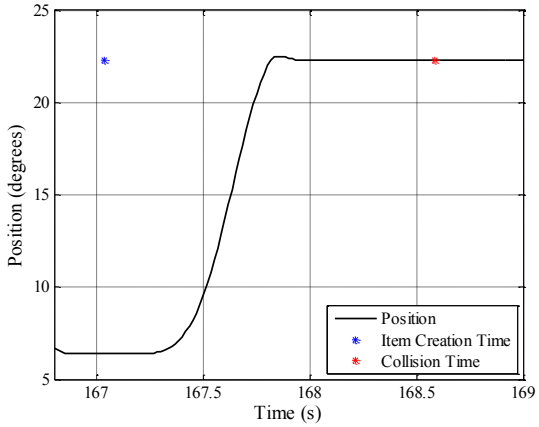

Figure 7 – Typical position response for a given item, game "O Guloso".

Regarding the "O Atleta" game, Figure 8 shows the dorsiflexion torques provided by the patient for two obstacles, the lower hurdle and the pool. For the hurdles (lower and higher), the patient is requested to applied dorsiflexion torque during a period of time (defined by the blue line in the left graphic) immediately before the obstacle. If the torque in this period is higher than the predefined threshold (defined by the *y* value of the blue line, 4 Nm in this example), the patient avatar jumps them. Otherwise, the patient hits the hurdles.

In the pool example (right graphic), the patient must start the torque application before the obstacle (blue line) and maintain it above the threshold level for the entire length of the pool (defined by the reline).

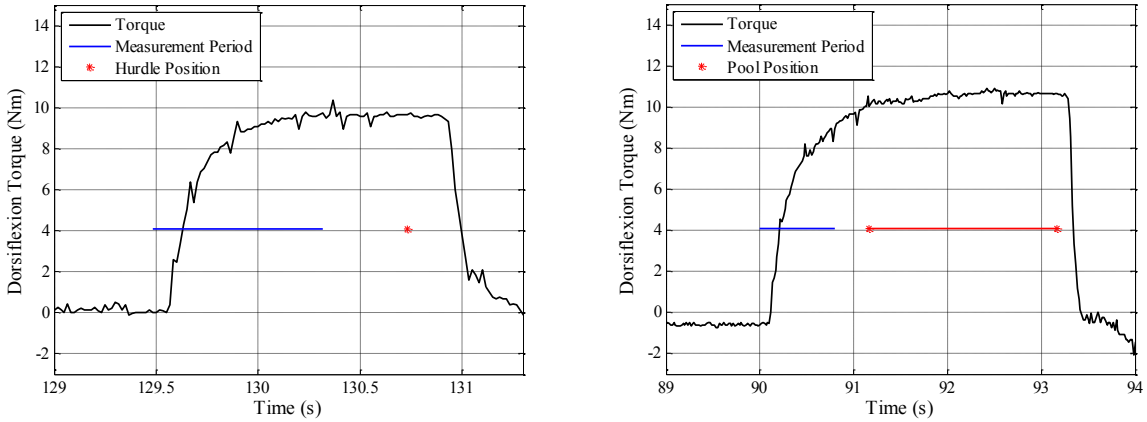

Figure 8 – Typical force responses for lower hurdle (left) and pool (right) , game "O Atleta".

Tables 4 and 5 show a brief example of how the game results can be used to evaluate patient conditions. Both tables compare game results (mean values) for the hemiparetic group, regarding only the impaired limb. It can be noted that left hemiparetic patients have greater difficulties to perform the games tasks, which can be related to the lower values of dorsiflexion ROM and torque presented by the same group, Figure 6 and Table 2.

Table 4 – Game results, "O Guloso", hemiparetic subjects.

Lower Limb	No. of Hits (of 108)	No. of Challenge Hits (of 30)	Travelled Distance (º)	Maximum Velocity (º/s)
Right	105.4	29.8	978.0	84.7
Left	96.8	26.4	698	67.8

Table 5 – Game results, "O Atleta", hemiparetic subjects.

Lower Limb	No. of Transposed Obstacles (of 24)	No. of Transposed Pools (of 2)
Right	22.9	1.1
Left	22.2	0.6

6. CONCLUSIONS

Results from literature show that robotic devices for rehabilitation of ankle movements associated with virtual games are effective in promoting gains in walking indices. This paper presents the RePAiR, a compact and easy-to-use robotic platform, which can provide assistive as well as passive therapy through its impedance-controlled solution. The proposed device is tested by two groups: 19 pos-stroke subjects and 19 healthy individuals, which have performed a one session evaluation of two virtual games, developed to stimulate and evaluate dorsiflexion range of motion and torque. The results show the proposed platform can be used as an alternative device for rehabilitation of ankle movements.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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