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Biomedical Serious Game System for Lower Limb Motor Rehabilitation of Hemiparetic Stroke Patients

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***Abstract*— Hemiparesis resulting from a stroke has a direct impact on patients' daily activities. New approaches for motor rehabilitation include Serious Games (SG) because they include (in a motivating way) the three fundamental elements for rehabilitation: intensive, repetitive and task-oriented training. This study aims to evaluate the therapeutic effects of a biomedical SG and a scoring system developed for lower limb motor rehabilitation of hemiparetic stroke patients. The SG was inspired by the classic videogame called Pong, where the goal is to control a tennis racquet, but using muscular strength. A knee extensor apparatus was adapted with a load cell and mechanical adjustments for measuring the muscular strength of the quadriceps femoris (QFG) and hamstrings (HSG). A scoring system was proposed to evaluate muscular control. Eleven hemiparetic stroke patients participated in an exercise program using the SG twice a week for ten weeks and only the paretic side was trained. Significant Effect Sizes (*d*) were found for QFG strength (*d*=0.5; *p*=0.021), QFG control (*d*=1.1; *p*<0.001), HSG strength (*d*=1.1; *p*=0.001), HSG control (*d*=1.5; *p*=0.003), functional mobility (*d*=0.3; *p*<0.001), gait speed (*d*=0.4; *p*=0.007) and motor recovery (*d*=1.0; *p*<0.001). Results indicate that the intervention of a SG with both proper apparatus and evaluation system may effectively promote lower limb motor rehabilitation of hemiparetic stroke patients.**

***Index Terms*— Stroke, Serious Games, Lower Limb Rehabilitation.**

I. Introduction

STROKE survivors are usually afflicted with some physical, cognitive or emotional impairment and require partial or complete assistance in the performance of activities of daily living [1].

Paresis is one of the most disabling and prevalent disorders in stroke victims [2]. The muscular strength deficit compromises daily live activity, making it difficult to transfer body weight to the impaired side, to emphasize incapacities and limitations, which are related to normal balance and mobility [3].

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In the past, there was the idea that post-stroke recovery occurred in the period between the first three months up to one year [4]. However, after years of evidence, it is clear that the rehabilitation exercises can improve functional skills even a few years after the stroke event [5]. American Heart Association / American Stroke Association recommendations emphasize the importance of physical activity for stroke survivors, including low to moderate intensity aerobic activity and muscle strengthening activity [6]. Strengthening programs can modify strength deficits, improving walking and functional mobility of patients [6], [7].

Many therapeutic strategies have been used in post-stroke rehabilitation, showing that intensive, repetitive and task-oriented training is beneficial for patients [8]. However, the repeatability may lead to a lack of motivation and patient engagement issues [9]. Therefore, the big challenge in rehabilitation is to make the process more motivating for the patient. In this sense, videogames are an alternative method for engaging post-stroke subjects in the rehabilitation process and enable greater repetition of movement compared to traditional therapy [10]. However, commercial games are not developed for rehabilitation [11], [12], but for entertainment of healthy people, which limits their therapeutic application [13]. In order to use these games for therapeutic purposes, adaptations are often necessary, which may involve procedural risks [14]. In addition, there are no adequate gameplay adjustments for different degrees of patient commitment [15] and the reduced motor function of the patient makes it difficult to control the game through traditional interfaces, such as a joystick or a mouse, as well as motion-based control interfaces [16].

An alternative to reduce the commercial games limitations is the development of games with specific purposes, called Serious Games (SG) [17]. The use of SG represents a modern and attractive therapeutic strategy which has being incorporated into specialized services [18], [19]. In neurorehabilitation, SG are developed to meet the needs of patients according to their functional limitations [20], which helps to increase the therapy compliance [21].

This paper presents a biomedical SG based on muscular strength for motor rehabilitation of the lower limb in hemiparetic patients' post-stroke. Our proposal combines game design and control interface design targeted to the function to be rehabilitated. Objectives of this study are to evaluate the therapeutic efficacy of the proposed biomedical SG and to investigate game metric properties for clinical evaluation of the patient's motor recovery.

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II. Materials and Methods

This quasi-experimental study was approved by the Ethics Committee for Research with Humans of the State University of Santa Catarina (CAAE 56995816.6.0000.0118). Eleven hemiparetic stroke subjects were selected (see Table I). The mean age was 59.0±11.9 years and the mean time since the stroke happened was 24.7±25.0 months. The inclusion criteria were: chronic hemiparesis for stroke (injury time > 6 months); 18 years old or more and; ability to walk independently although using a walking aid. The exclusion criteria were: hemiplegic patients; hemiparesis due to other pathologies; patients with severe visual and/or auditory impairment, sensory aphasia and cognitive deficit. Participants were tested for motor recovery, balance and physical mobility, functional mobility, strength of the paretic's quadriceps femoral muscle group (QFG) and strength of the paretic's hamstring muscle group (HSG) and an assessment protocol for both muscle control and strength by using the proposed SG. Three evaluations were performed on three alternate days before starting the rehabilitation program (pre-test) and three re-evaluations on three alternate days at the end of the program (post-test).

TABLE I
EPIDEMIOLOGICAL PROFILE OF THE PATIENTS

Subject	Age	Sex	Months since stroke	Paretic side
1	70	Male	9	Right
2	65	Male	34	Right
3	79	Male	17	Left
4	37	Female	7	Left
5	51	Female	13	Left
6	63	Male	29	Left
7	46	Female	16	Left
8	59	Male	18	Right
9	61	Female	96	Right
10	67	Male	22	Right
11	51	Female	11	Left

Motor recovery was assessed using the E section of the Fugl-Meyer Assessment Lower Extremity scale (FMA-LE), which consists of a cumulative numerical scoring system (0 to 28 points) that evaluates different motor aspects of the patient [22]. This choice was due to specificity of the training. The Fugl-Meyer assessment scale is one of the most widely recognized and clinically relevant measures of body function impairment after stroke [23].

Functional mobility was performed using the Timed Up and Go test (TUG). This test has been widely used in individuals who have had a stroke [24], which is considered the best predictor of participation in daily living activities for post-stroke patients [25].

The gait speed was assessed using the 10-meter Walk Test (10-MWT), which is commonly used as a prognostic tool for health status and functional decline, including hospitalization, prediction of hospital discharge and mortality [26].

Custom-made hardware and software were developed to acquire the patient's strength data. Fig. 1 shows the experimental setup and the SG used in this study.

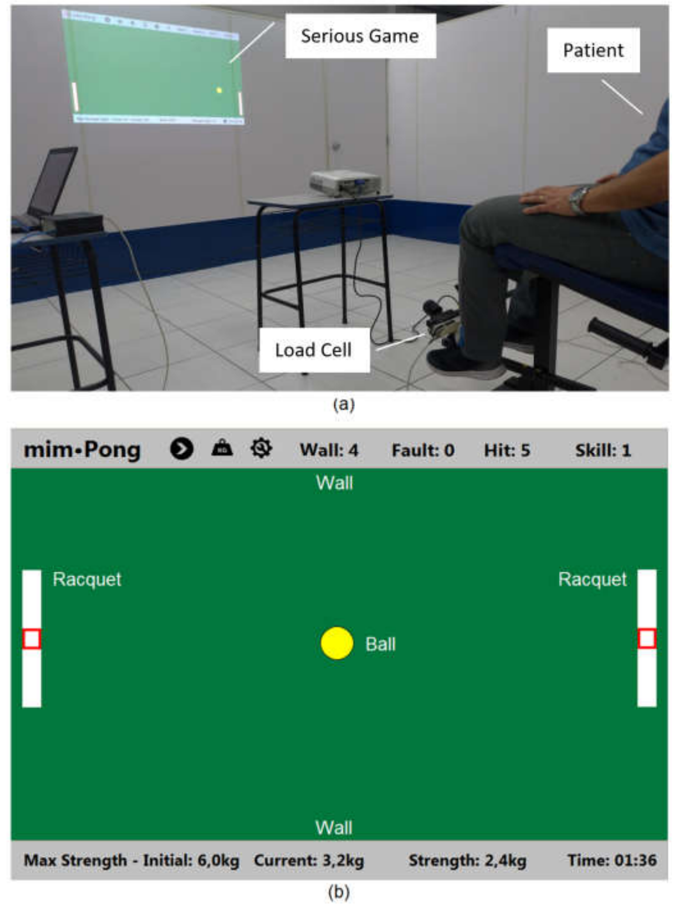

Fig. 1 – (a) A patient using the experimental setup. (b) The *mimPong* SG main screen.

The patients were submitted to a treatment period using the SG for 10 weeks, having two sessions a week on alternate days (total of 20 sessions). Each session was composed of three sets of two minutes with a one-minute break between each other, totaling 12 minutes of therapy (3 sets for the QFG and 3 sets for the HSG). It is worth pointing out that the proposed therapy is a unilateral exercise involving only the paretic lower limb. Participants did not undergo any other rehabilitation therapy that could have influenced the evaluation of the lower limb during this study.

A. Hardware Features

The strength value is obtained by a compression load cell of 60 kg. The signal from the load cell is amplified by the INA125 instrumentation amplifier (Texas Instruments, USA), digitized (12-bit) and processed by a microcontroller system based on Atmel's 32-bit ARM Cortex-M3 processor (Atmel Corporation, USA). The microcontroller program includes routines for communication with the computer, digital noise attenuation and scale adjustment.

B. The Serious Game

The proposed SG, called *mimPong*, was inspired by the classic videogame called *Pong* [27]. In this game, the goal is to control a tennis racquet to hit a ball. The visual aspects of the game are simple and focus the patient to hit the ball. Fig. 1b shows the main screen of the game, which the patient plays against himself using only the paretic leg. Racquets move simultaneously on the vertical sides of the screen based on the strength applied on the load cell. When no strength is applied, the racquets stay still at the bottom of the screen. The horizontal walls bounce the ball back. The upper limit of the racquets (at the top of the screen) is based on the maximum strength of each subject. Game parameters that can be changed included: racquet size, ball size, ball speed and color elements. These adjustments can be done in order to change the game dynamics according to the therapy goals. A scoring system has been proposed, which is based on clinical and motivational aims for maximizing accuracy and minimizing error.

An interface screen was made for evaluation and training purposes that allows the therapist to view the game's session graphic and to analyze parameters such as maximum strength, strength maintenance, visuomotor response time and muscular fatigue. In addition, the game data can be stored in the text file for post-processing, including ball center position, racquet center position, strength value, game settings and game score.

C. *Game usage procedures*

A knee extensor apparatus captures the strength measurements of the QFG (knee extensors) and HSG (knee flexors), for only the paretic limb. Device positioning depends on the muscular group analyzed. For the QFG (Fig. 2a), the patient sits in the chair with the trunk supported by the backrest, legs hanging, hip at 110º of flexion relative to the trunk and knees flexed at 90º [28]. The sensor is placed perpendicular to the distal third of the leg (just above the malleolar region), on the anterior face. For the HSG (Fig. 2b), the patient is positioned in the chair as in the QFG test, but with knees flexed at 60º [29] and the sensor is placed perpendicular to the distal third of the leg, on the posterior face.

Calibration is first performed because patients have different maximum levels of muscular strength. All patients perform a Maximum Voluntary Isometric Contraction (MVIC) with their muscle group of interest for five seconds. The strength peak value is used as a reference for the SG. In training mode, the upper limit of the racquet is set to the calibrated MVIC. A 60% MVIC threshold was used for the first half of the treatment, and 80% for the second half. These percentage values fulfill the guidelines of resistance exercises for post-stroke patients [30].

D. *Game metric properties*

We define game metric properties as the study on how game variables can be used as health indicators. Therefore, a game scoring system was proposed in order to evaluate lower limb motor recovery.

Fig. 2 – Adaptable knee extensor apparatus to measure both the strength of the QFG (a) and the HSG (b). White arrows show the strength direction.

The score aims to give a clinical feedback that allows the physical therapist to evaluate the patient's clinical evolution and helps the patient to recognize his own improvement. The game score was defined based on the model for game score designing proposed by Noveletto et al. [31]. According to the model, the score is defined empirically based on game elements and should be related to the therapeutic requirements (i.e. the physical effort to hit the ball in the racquet center). Correlation analysis between game score and the clinical scale of interest (FMA-LE) is done in order to clinically validate and a strong correlation means that game score can be used as a health indicator. Weak correlations can mean that the game mechanics are not fit to the therapeutic requirements and will have to undergo a major adjustment.

1) *Control and muscular strength assessment*

The *mimPong* SG has an assessment protocol to evaluate control and muscular strength (Fig. 3), which consists of a task of hitting a ball at five different levels (from 0 to 4). These levels are associated with the MVIC obtained during the calibration. At level 0, the patient should produce strength equivalent to 20% MVIC in order to hit the ball in the racquet center. Respectively, levels 1 to 4 represent of 40, 60, 80 and 100% of the MVIC.

The patient's performance (*EvalScore*) is calculated according to equation (1). *HitLevel* represents the hit position on the racquet, as shown in Fig. 3. The factor (10 + 5i) is a weight parameter related to the effort required to hit the ball at a certain level. The lower levels require less muscular strength and so represent a smaller weight in the score composition.

$$EvalScore = \frac{1}{5}\sum_{i=0}^{4}(10 + 5 \times i) \times HitLevel_i \qquad (1)$$

The score in the evaluation mode is used as a clinical score and it ranges from 0 to 100 points. Score values were correlated to motor evaluation clinical scales to investigate score usage as a clinical motor assessment tool.

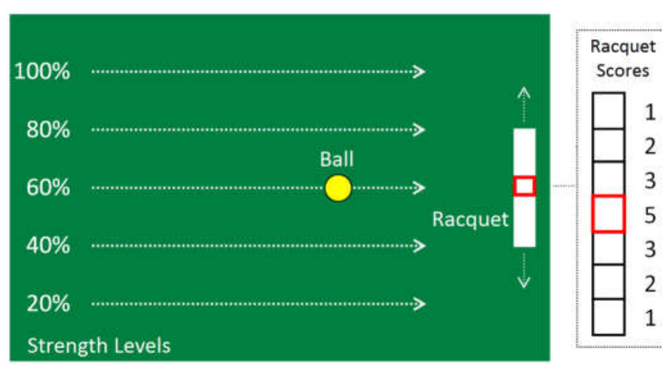

Fig. 3 – Assessment protocol for muscular control and muscular strength. The horizontal dotted lines represent the ball displacement at each strength level. These levels are related to the MVIC obtained in the calibration. One ball leaves every 10 seconds, starting with the lowest strength level (20% MVIC) up to the maximum level (100% MVIC). The hit score values on the racquet are shown zoomed in at the right side. The closer to the racquet center, the higher the score. The score is equal to zero if the ball does not hit the racquet.

2) Performance assessment while training

The score patient's during training considers aspects related to gameplay.

Equation (2) establishes the overall game difficulty according to game variables. For instance, the greater the *BallSpeed*, the harder it is to play, but the bigger the *RacquetSize*, the easier it is to play. All variables range from 1 to 10. The weight of each variable is based on its importance in the game difficulty. In this work, the game setting was the same for all patients.

Equation (3) represents the game dynamics, where *GameHit* is the number of times the ball hits in any racquet position, *GameSkill* is the number of times the ball hits in the racquet center (represented by the highlighted red square in the Fig. 1b), *GameFault* is the number of times the ball is missed and *GameWall* is the number of times the ball touches the screen's horizontal walls. The weight of variables is based on their importance in game performance.

Equation (4) shows how to compute the total score of the game (*GameScore*), where its maximum value changes according to the elapsed time using the game while the session therapy. Since the *GameScore* reckon patient effort and accuracy at a given difficulty level, it acts as a motivational driver for the patient.

$$Setup = 10 \times \left(\frac{BallSpeed}{2} + \frac{4}{RacquetSize} + \frac{1}{BallSize}\right) \quad (2)$$

$$\begin{aligned} Performance = {} & 10 \times (GameHit + GameSkill) \\ & - 3 \times GameFault - GameWall \end{aligned} \quad (3)$$

$$GameScore = Setup \times Performance \quad (4)$$

Higher scores are also used to motivate and challenge the patient himself to increase his performance, but without comparing with other patients, because there is a wide range of patients limitations, than the comparison among them is unfeasible and may lead to patient demotivation.

E. Statistical Analysis

The statistical analyses were performed with Minitab Statistical software - Release 17 (Minitab Inc., EUA). All parameters were presented in terms of mean and standard deviation. After checking the normality of parameters, the differences between the pre and post-test were conducted with a paired Student's *t*-test with a significance level set at 0.05. A Pearson Correlation Coefficient (*r*) test was conduct in order to measure the association between parameters. Finally, *Cohen's d* - effect sizes (*d*) were calculated to evaluate if differences observed corresponded to important clinical effects [32]. Effect sizes of 0.2, 0.5 and 0.8 were regarded as small, medium and large degrees of differences, respectively.

III. Results

Table II shows the results of the pre/post-intervention. The effect size analysis showed that there was clinical improvement in all measured variables.

TABLE II
RESULTS OF THE PRE/POST-TESTS

Variables	Pre	Post	*p*-value	*d*
FMA-LE	19.3(4.5)	23.3(3.5)	<0.001	1.0
TUG [s]	29.0(16.0)	24.1(14.9)	<0.001	0.3
10-MWT [m/s]	0.51(0.34)	0.68(0.51)	0.007	0.4
STQ-P [kgf]	13.4(6.5)	17.9(10.9)	0.021	0.5
STH-P [kgf]	5.1(2.7)	9.1(4.4)	0.001	1.1
STQ-NP [kgf]	23.2(5.8)	26.1(11.1)	0.190	0.3
STH-NP [kgf]	11.7(4.2)	14.8(5.6)	0.002	0.6
SQ-P	66.9(21.2)	86.1(14.3)	<0.001	1.1
SH-P	54.6(24.0)	82.8(13.1)	0.003	1.5
SQ-NP	77.2(9.6)	85.9(3.1)	0.019	1.2
SH-NP	69.4(14.4)	81.9(12.8)	0.003	0.9

All parameters are expressed in terms of Mean and Standard Deviation (SD). Effect Sizes (*d*) are expressed in module. FMA-LE= Fugl-Meyer Scale – lower limb section; TUG= Timed Up and Go Test; 10-MWT= 10-meter Walk Test; STQ= Strength of quadriceps; STH= Strength of hamstrings; SQ= Game score of QFG; SH= Game score of HSG; P= Paretic side; NP= Non-paretic side.

Since FMA-LE is a relevant measure of body function impairment after stroke [23], we conducted a post-hoc analysis in order to determine if the sample size was enough to reasonably detect a minimal beneficial therapeutic effect. Sufficient statistical power has been validated, where a power of 0.99 (α=0.05; *dz*=-1.95; two tails t-test) was obtained for FMA-LE. An increment of 23.0±15.6% in the FMA-LE with a large effect size was observed, which indicate a reduction in the patient's motor impairment.

Functional mobility tests (TUG) showed an improvement of 19.7±10.1%, as well as the functional capacity assessed by the 10-MWT (30.8±14.3%).

A muscle strength increase was observed in all measured muscular groups (trained and non-trained). Fig. 4a-b shows a bar graph with the pre/post-test values of strength for the QFG and HSG of each patient (paretic side). The strength asymmetry between the paretic and non-paretic sides showed a reduction after the intervention period. The strength difference between the paretic and non-paretic sides of the QGF was reduced from 44.7±18.6% (p=0.001) to 34.3±24.0% (p=0.097), and from 50.4±37.6% ($p<0.001$) to 35.3±37.9% (p=0.015) for the HSG.

Data from game were analyzed in the evaluation and training phases for both muscular control and strength. Only the paretic side was submitted to the intervention in the training phase. Pre/post-intervention game scores showed an evolution for both muscle groups (paretic and non-paretic side) with large effect sizes. Fig. 5a-b shows a bar graph with the pre/post-test values of game score for the QFG and HSG of each patient (paretic side). A significant difference ($p<0.001$) was obtained in the training phase assessed by the *GameSkill* variable.

The initial value (average of the first three sessions) was 6.2±2.6 and the final value (average of the last three sessions) was 10.7±4.2, representing a large effect size (d=1.3; $p<0.001$). Fig. 6 shows the correlations of both strength and game score with the FMA-LE for the paretic side (trained). Results showed that can be feasible the clinical evaluation based on game data.

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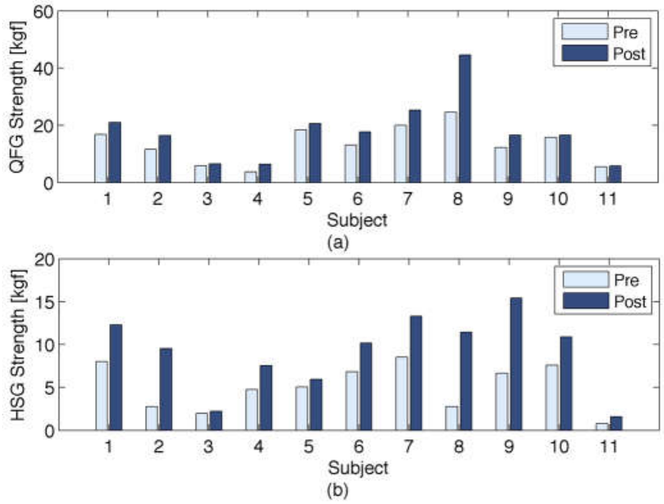

Fig. 4. Pre/post-test paretic strength values for the QFG (a) and HSG (b).

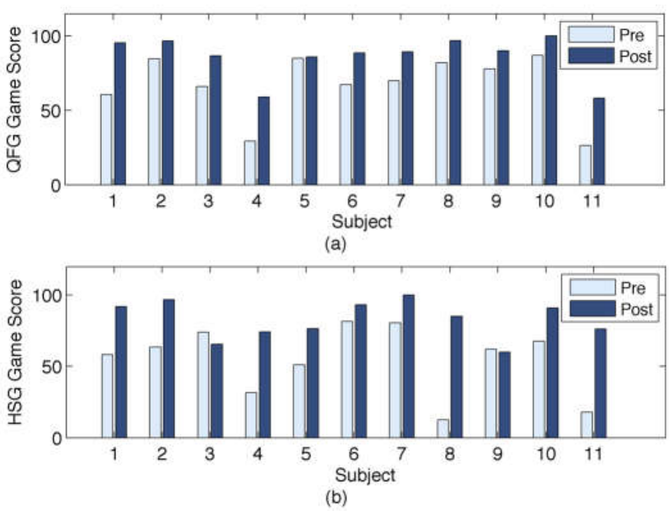

Fig. 5. Pre/post-test paretic game scores for the QFG (a) and HSG (b).

A stratified analysis by the dominant side was conducted in order to evaluate their influence over the patient's performance. Game scores of the patients with the dominant side affected were slightly better than patients with the non-dominant side affected, but without statistically significant difference between them (p=0.143).

IV. Discussion

The exercise program with the *mimPong* SG focused on training and evaluation of muscle strength and control of the paretic lower limb. Additionally, it was designed by mixing the motivational and the clinical aspects.

The therapeutic effect analysis for muscular strength showed that the intervention was beneficial for both sides. For the paretic side (trained), the effect size was medium for the QFG (d=0.5; p=0.021) and large for the HSG (d=1.1; p=0.001). Although not trained, the strength of the non-paretic side was also increased after the intervention, which may be related to the increase in activities performed by the patient due to the muscle strength improvement in the paretic limb.

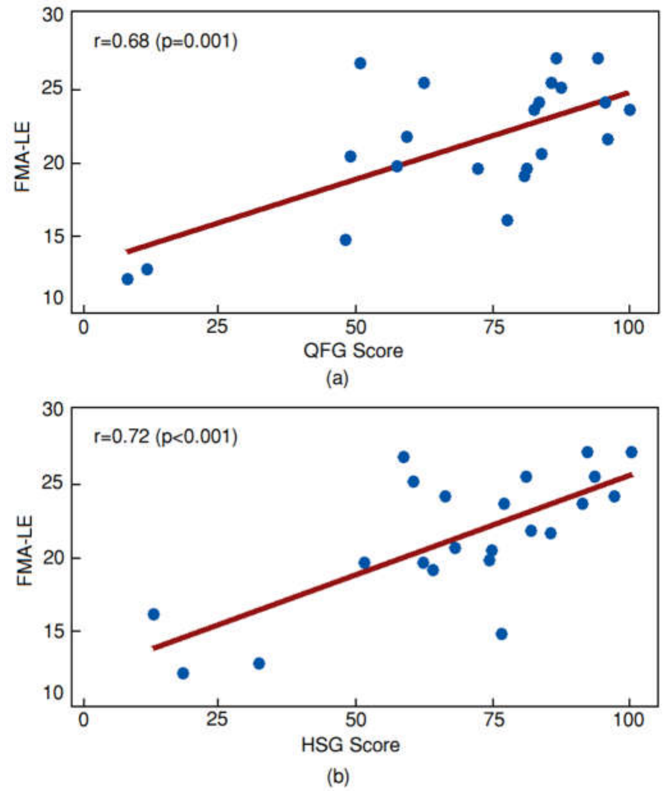

Fig. 6. Correlation coefficients between game scores and the FMA-LE for the paretic side.

This might be related to the increase in the walking regularity and distance as well as, in activities such as sitting down, standing up, and climbing stairs up and down [33].

The strength asymmetry between the paretic and the non-paretic sides was reduced for both muscular groups after intervention and this is positive because in a recent study by Kostka et al. [34], it has been shown that the strength of paretic HSG and the difference in the HSG strength between limbs (paretic and non-paretic) are the best predictors of functional performance for post-stroke subjects.

As shown in the Fig. 7, the exercise program developed for the *mimPong* SG allows patients to use different strength levels during a session of therapy, given that the ball can be bounced at any vertical height on the screen.

Motor control is evaluated by the game, where the closer to the racquet center the patient hits the ball, the higher the score. The game dynamics provide an increase in strength and control using different muscular activation strategies.

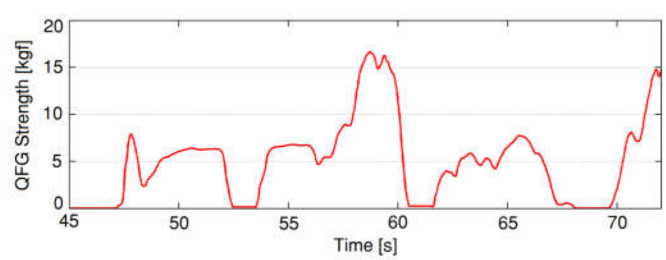

Fig. 7. Graphic that shows different levels of strength during a training session.

Therefore, there were significant improvements in the motor control (shown by game score) of the patients after the treatment. For the trained limb (paretic), improvements may be attributed to the game dynamics, such as: intensive training, repetitive exercises, task-oriented training, increased attention and motivation. Improvements were also found in the non-trained limb, which can be due to the learning process (sensorimotor and cognitive), where the individual is more likely to perform activities due to prior experiences [35].

Results obtained in our study showed improvement in gait speed (d=0.4; p=0.007). Similar results were also found in the meta-analysis study [36], which examined resistance training efficacy in gait speed for chronic post-stroke patients (d=0.3±0.12; p<0.013). They concluded that strength training can improve comfortable gait speed and distance.

Functional mobility was assessed by the TUG test, showing improvements for the patients. A study conducted by Persson et al. [37] was performed at different stages during the first-year post-stroke and they found improvements only in the first three months (acute phase). We have found patient's improvement in functional mobility in the chronic phase, with a gain of 19.7±10.1% (p<0.001). Our data suggest that a motivating motor program can lead to functional mobility improvements after the acute phase.

A large effect size of 1.0 (p<0.001) was observed in the motor impairment reduction assessed by the FMA-LE. The value of the FMA-LE changed from 20.7±4.8 to 24.1±3.5 points after the intervention. Similar results were found by Pandian et al. [38] (20.2±4.3 to 25.6±5.0) using conventional therapy for lower extremity for chronic hemiparetic post-stroke patients. Results found in our study are promise since our patients were older and more chronic, the intervention time was shorter, and the FMA-LE range used was lower (0 to 28 points). The motor impairment reduction observed in our study is stressed by the significant correlations of the FMA-LE with TUG (r=-0.59; p=0.004), 10-MWT (r=-0.65; p=0.001), muscle strength and game score. Correlations between FMAS-LE and game score is an important finding of this study. It is an indication that the metric properties of *mimPong* SG are related to motor function.

For functional mobility, a better correlation with the QFG strength was found. In fact, the specific requirements of the TUG test (standing up, sitting and walking) are directly related to muscle strength [37], in particular to QFG.

Regarding gait speed (10-MWT), better correlations with both muscle strength and game score for the HSG was found. This result is positive since reduced knee flexion (HSG) is a leading feature of post-stroke gait and is associated with muscle control [40].

The game scoring system is a contribution of this study. It works not only as a motivational aspect for the patient but also as an assessment index for the therapist. Additionally, it works not only for strength but also for motor control as well. Game scoring usually applied to rehabilitation is only related to player performance and motivation and has no clinical function [39]. No references were found in the literature for game scoring as a clinical evaluation tool. This justifies the empirical method used in the *mimPong* SG score design, where both gameplay and motor aspects related to muscle strength and control were considered. The hypothesis was that there is a relationship between game data and the motor assessment scales (TUG, 10-MWT and FMA-LE). Our results indicate that this hypothesis holds true for the scoring system used in *mimPong* SG.

The game score is an empirical representation of muscular control, but certainly does not fulfill all mechanisms involved in the process. Hollands et al. [41] emphasize that therapies based on the practice of specific and repetitive tasks, such as the *mimPong* SG, are among the most promising interventions to improve gait coordination. However, they also pointed out that gait control is strongly related to patient neurological aspects (e.g. neuroplasticity) involved in the process. Correlations between game data and the FMA-LE were also significant, particularly to the HSG strength. In fact, most tasks in the E section of the FMA-LE involve the HSG strength, which may explain a better correlation with the HSG muscular strength.

It must be emphasized that the settings of the game allowed the therapist to maintain the patient's flow condition. The score system maximizes correct task execution and minimizes error. In addition, visual and auditory messages related to patient effort are used to reward his performance, motivating him to be engaged in the treatment. It should be mentioned that motivation is often used as a determining factor for rehabilitation outcomes [42]. According to Drummond et al. [43], the combination between the motivation for the learning activity itself (intrinsic motivation) with the future desirable outcome motivation (extrinsic motivation) is essential for SG. All these neuropsychological elements should be present in the game design in order to increase therapeutic dosage, which is recommended in the neurological rehabilitation [44].

An important aspect of the game score found in this study is related to the patient's improvement awareness. Patients usually have little sense of their rehabilitation progress [45], which can lead them to abandon the treatment. For this reason, the relationship between the game and the therapy must be clear for the patient. Using *mimPong* SG, patients were motivated by the score increase during the treatment, and they related feeling better since now the score is greater than the beginning of the treatment.

A. Study Limitations

Although the results found in this paper are quite promising, some limitations should be considered for further experiments. The first limiting factor is the heterogeneity of deficits caused by strokes. Secondly, although the pre/post-test differences were significant, the small sample size does not allow us to extend our results to the whole population. As far as we know, there is no similar study found in the literature which can be used for comparison purposes. A control group was not included in the study. Overall, it was observed that the proposed SG was beneficial for the patients who undertook this study.

V. Conclusions

A biomedical SG, called *mimPong*, was developed for lower limb motor rehabilitation of patients having hemiparesis as a result of stroke. The clinical results showed that the treatment was beneficial for the patients. The scoring system of the *mimPong* SG enabled both therapist and patient to follow the

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treatment evolution in a simpler way. Correlations between the game score and the clinical tests indicate that the game metrics accurately correspond to clinical outcome, allowing its use as a coadjuvant clinical tool.

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