Research Article

A Novel Study on Natural Robotic Rehabilitation Exergames Using the Unaffected Arm of Stroke Patients

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We design and implement a low-cost rehabilitation glove to meet the needs of those patients who have paralysis in their affected hand. The novelty of this glove is that it is to be worn on the unaffected hand which acts as a natural robotic arm during the rehabilitation session. The glove is equipped with FSR sensors that measure the forces exerted by the affected hand on the unaffected hand. A virtual reality rehabilitation game is developed using Microsoft Kinect to facilitate the exercises and motivate the patients. The system is tested on three patients for six weeks. Objective measurements showed that patients have significantly improved over the study period. Moreover, the patients themselves gave positive feedback on the whole system; wearing the glove on the unaffected hand made their life easier and let them enjoy the rehabilitation sessions.

1. Background

A stroke occurs when the blood flow to the brain is interrupted due to a blood clot or when uncontrolled bleeding occurs in the brain. The former, which is the most common, is called ischemic stroke (about 80 percent). The latter is called hemorrhagic, which is less common (about 20 percent) but more severe than the ischemic stroke. Warning signs and symptoms of stroke may include, but are not limited to, sudden dizziness, numbness of the face, leg, or arm, un consciousness, and trouble with walking, speaking, and understanding. Statistics reveals that stroke is the third leading cause of death in North America, just comes after the cancer and heart disease, and it is the leading cause of disability. In Canada alone, there are about 315,000 Canadians that live with the effects of stroke [1]. They cost the Canadian economy more than 3.6 billion dollars a year in hospitals and rehabilitation centers. Moreover, the patients spend more than 639,000 days in acute care in Canadian hospitals and 4.5 million days in rehabilitation centers [2].

Stroke patients are admitted to an intensive rehabilitation program in order to restore their motor functions. The duration, capacity, and effectiveness of the rehabilitation program have a huge impact on the patient’s progress. Such program is a continuum. It starts when the patients are admitted to the hospital and continues for several years depending on the severity of the stroke attack. However, patients may have problems getting into these rehabilitation centers because these centers are usually located in cities, far away from patients that live in rural areas. Moreover, the economic impact of stroke is very high, which prevent some patients from continuing their rehabilitation program. To overcome these problems, therapists recommend that patients perform their daily exercises at home. However, the home rehabilitation tools are usually passive devices that lack interactivity with the patient. In addition, and with the absence of adequate feedback from these devices, the therapists face a big challenge in the evaluating process of the patient's progress.

In contrast to the traditional stroke rehabilitation centers, home-based rehabilitation provides a cost-effective and
Table 1: Patients statistics.

| Patient          | Stroke side | Age | Stroke date   | Dominant hand | Gender |
|------------------|-------------|-----|---------------|---------------|--------|
| Patient one      | Right       | 79  | Jan 05, 2014  | Left          | Male   |
| Patient two      | Left        | 67  | March 20, 2014| Right         | Male   |
| Patient three    | Left        | 60  | Jan 10, 2014  | Right         | Female |

convenient environment for the patients to recover. Such an environment improves empowerment, minimizes costs, and makes the treatment available anytime and anywhere [3]. However, passive devices such as dumbbells, elastic bands, stress balls, and tubing that have been widely used for home-based arm rehabilitation [4] do not provide therapists with the information needed to monitor the patient’s progress, identify any impairment, and suggest treatments [3]. Moreover, the lack of interactivity of these devices turns the rehabilitation exercises into a boring, unpleasant task [5].

The best solution of the aforementioned problems is to use innovative tools that can be effectively controlled by the patients. Researchers have adopted new technology, in particular augmented reality games with intuitive and natural user interfaces and modified them in a way that benefits the treatment program of the patient and at the same time changes boring exercise into more enjoyable ones. In addition, many studies show that patients partaking in virtual environment rehabilitation programs have restored their motor skills faster than those in a real environment [6–8]. This is because in a real environment the patients do not enjoy the course of treatment and quickly become frustrated. Besides, games for rehabilitation can be customized to fit the patient’s needs at different stages of the treatment.

Therapists recommend patients performing daily life activities, such as coffee making, in order to improve their upper limb movements. Since such tasks might be dangerous for a patient with arm injury, researchers have developed virtual and augmented reality systems where tangible objects are associated with a virtual object that simulates the real object [9, 10]. The current technological advancements have brought new perspectives to the rehabilitation process. Researchers have designed computerized rehabilitation robotic tools associated with virtual environments and games aimed to be used at home. Therapists use these tools to track the patient’s progress. However, two of the common inconveniences for many of these rehabilitation devices are related to their bulky shape and the complexity of their deployment [11]. Consequently, these shortcomings make them impractical for home training because they require the presence of an expert. Cost is also an important factor for many patients when acquiring such devices. For these reasons, most of the robotic-assisted therapy devices are commonly used in clinic centers or hospitals.

In this study, we present a low-cost virtual environment rehabilitation glove system for stroke patients. The system helps those patients with severely damaged upper limb to decrease the dysfunction. The novelty of this glove is that it is to be worn on the unaffected hand that acts as a natural robotic arm during the rehabilitation session. The glove is equipped with FSR sensors that measure the forces exerted by the affected hand on the unaffected hand. Results show that patients have significantly improved over the course of the rehabilitation program. Moreover, the patients themselves gave a positive feedback about the whole system; wearing the glove on the unaffected hand made their life easier and let them enjoy the rehabilitation sessions.

2. Methods

2.1. Participants. The study was approved by the Ethical Committee of the Hamshary Hospital in Lebanon, and a consent form was signed by each participant. Three poststroke patients of average age $66.6 \pm 9.6$ years were recruited to take this experiment. All patients (Table 1) were diagnosed with chronic stroke (<10 months). Exclusion criteria were serious cognitive problems, ability to move the affected hand without the support of the unaffected hand, fully bounded to a wheelchair, and in patients (the patients had not been hospitalized for 24 hours a day during the time of conducting the experiments). Patients did not attend any other rehabilitation treatment during the entire study; the only form of treatment that they got was provided by our proposed rehabilitation system.

Patient’s one description is as follows: a 79-year-old male who had a left Middle cerebral artery (MCA) ischemic stroke six months prior to the start of the experiment. Mr. S was sitting close to a chimney, drinking his cup of tea in a cold night of the winter of 2014. Suddenly, he felt dizzy, and both his face and right arm were numb. When he tried to stand up, he fell on the floor. Mr. S had hypertension and he was on medication during that time. Mr. S arrived to the hospital; he was diagnosed with ischemic stroke on the right side of his body. The right arm became very weak to the extent that he could not move it or control in any more. The stroke did not affect his cognitive abilities. Mr. S had not had stroke previously.

Patient’s two description is as follows: a 67-year-old male who had a right middle cerebral artery (MCA) ischemic stroke four months prior to the start of the experiment. Mr. M was practicing some exercises and when he turned his head down he suffered from intense and sudden headache with blurry vision. Few hours later, Mr. M started to feel numbness in his left side. He had not suffered from migraine or any other disease before, so he thought it was a temporary symptom and it was going to fade soon. The next day, Mr. M woke up in the morning with his left side of his body paralyzed. He did not lose his conscious, but he could not speak properly or had a clear vision. Mr. M was diagnosed with ischemic stroke and stayed in the hospital for three months.

Patient’s three description is as follows: a 60-year-old female who had a right middle cerebral artery (MCA)
ischemic stroke six months prior to the start of the experiment. Mrs. F was suffering from diabetes and she was a heavy smoker too. In the night, she had a stroke and she was feeling dizzy whenever she tried to walk. She woke up at four in the morning to go to the washroom. She moved one step from her bed and collapsed. Mrs. M’s son rushed her to the hospital where she was diagnosed with severe ischemic stroke. Mrs. F could not move her left upper limb prior to the time of the start of the study.

2.2. FSR Glove. The glove is a lightweight, inexpensive measurement device designed to find the force exerted by the affected hand on the unaffected hand. The glove is equipped with eight FSR sensors, five of which are mounted close to the middle of the fingers and three are mounted on the palm (Figure 1). The rest of the design is similar to the one appeared in [12]. A wireless connection is established between the glove and the computer via a BlueSMiRF bluetooth modem. A microcontroller processes the received analog signal from the sensors and sends a relevant serial output raw data to the computer. The glove circuit is powered by a 3.3 V rechargeable battery.

2.3. FSR Sensors Position. For the glove to provide a reliable reading, the sensors should be placed in particular positions that give a weight measurement close to the actual weight of the affected hand. An artificial arm (hand + forearm) with a known weight is used in our experiment. We started changing the positions of the sensors on the glove and compared the force exerted by the stick on the hand that wore the glove. It is worth to note that, we followed the guidelines recommended by the therapists; we placed the sensors on a way that they read the exerted force naturally without adding the grip force of the fingers. That would allow the blood to circulate normally in the arm; the patients would not be at risk at any time.

2.4. Virtual Environment System. The proposed virtual environment system consisted of three main components: upper limb tracking unit, motion analysis unit, and multimodal feedback unit (Figure 2). The system combines recent rehabilitation approaches with efficient, yet affordable skeleton tracking input technologies, and multimodal interactive computer environment. Kinect, a skeleton tracking sensor from Microsoft for Xbox, is used as a 3D motion capturing and tracking of the upper limb. Affordability and controller-free are the main advantages of the Kinect sensor. The motion analysis unit evaluates the received data by comparing it with the data previously taken from the same patient. Therapists depend on this evaluation in order to assess the progress of the patient and determine the effectiveness of the treatment paradigm. The motion analysis unit sends requests to the game controller system to update the difficulty level of the exergame whenever needed. The system also provides the users with both visual feedback and auditory feedback. The visual feedback is represented by a predefined visual path that guides the user during the rehabilitation exercises. Moreover, a progress bar is displayed on the left bottom of the screen that shows the progress of the patients depending on the real-time data received from the glove (red means the unaffected hand is doing all the job and green means the affected hand is performing the exercise without the need of the support of the unaffected hand). The auditory feedback depends on (1) the events that are taking place during the exercise and (2) the data measurement received from the glove. At the end of the exercise the system plays an audioclip from prerecorded audioclip list. The program chooses a clip to play that reflects the overall performance of the user.

2.5. Data Capturing Setup. The recorded analog signals by eight sensors were converted into digital signals and their average value was sent to the computer. The sample rate of the data was 29 samples per second where the baud rate was 9600. The captured data is synchronized by a virtual cup that when it is touched, it triggers a signal to a specific module which opens a file and starts saving both the kinematics values and the force values.

During each task, we captured the values of five parameters: the displacement, the velocity, the acceleration, the jerkiness, and the exerted force of the affected hand on the unaffected hand. At the beginning of the first session, we took baseline measurements of these parameters and we used them to monitor the progress of the patient. The parameters were calculated according to the following formulas:

\[ f = \frac{g \times r}{255}, \]

\[ d_i = d_i - d_{i-1}, \]

\[ v_i = \frac{d_i - d_{i-1}}{t_i - t_{i-1}}, \]

\[ a_i = \frac{v_i - v_{i-1}}{t_i - t_{i-1}}, \]

\[ J = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{1}{2} \times \int_{0}^{T} a'^2(t) \, dt \right), \]

where \( f \) is the equivalent force of the value captured by the glove, \( g \) is the gravity force (9.8 Newtons), \( r \) is the actual reading of the glove, \( d_i \) is the position of the joint at time \( t_i \), \( v_i \) is the velocity in cm/sec, \( a_i \) is the acceleration in cm/sec², \( J \) is the jerkiness cost, \( N \) is the number of times the user has
performed the movement, $T$ is the time interval, and $a'(t)$ is the rate of change of the acceleration.

2.6. Clinical Study. Prior to this study, a professional physiotherapist has evaluated the severity and impact of stroke on the three patients. Action Research Arm (ARM) test, which is considered as a strong and accurate assessment test because it assesses the upper limb functioning through observation in contrast to other available outcome measures that tend to rely on questionnaires answered by patients. ARM test has excellent intrarater (ICC = 0.0989) and interrater (ICC = 0.0995) reliability [13, 14] and great evidence of criterion validity that is comparable to the upper limb test of Fugl-Meyer Assessment and Motor Assessment Scales, making it a recommended outcome measure by professional association groups, such as Stroke Taskforce (StrokEdge) for chronic stroke. In addition, it is suitable to detect the progress of the patients over time [15].

In this study, we have used the ARM to evaluate the motor functions of the affected and the unaffected hand. We wanted to make sure that the severity of the stroke had no impact on the unaffected hand. The results of the ARM for both the affected and unaffected hands are shown in Table 2.

2.7. Experiment. Patients had four rehabilitation sessions per week for six weeks. Three of these four sessions were conducted at home under the supervision of a certified physiotherapist. One session per week took place in the rehabilitation center. Patients were free to stand or sit while they were performing the exercises. The therapists helped the patients wearing the glove on their unaffected hand. After that, the therapists asked the patients to stand at 2.2 meters from the Kinect camera. The therapists did not count the first few trails of the exercise during each session; they wanted the patients to get ready before they perform the official counted task. The patients could ask to end the rehabilitation session whenever they felt tired or uncomfortable. The experiment lasted for thirty minutes at each session.

A moving cup experiment was designed to help patients restore function in their affected upper limbs. The game is divided into several levels that differ by the movement distance, as well as, the trajectory line. The participants were asked to follow the line connecting the ball with the virtual cup (Figure 3). Whenever a new level starts, the trajectory line

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**Table 2: Results of Action Research Arm test of affected and unaffected hands at the beginning of the study.**

| Patient   | Affected hand | Unaffected hand |
|-----------|---------------|-----------------|
| Patient one | Between 3 and 7* | Between 51 and 55 |
| Patient two | Between 3 and 6 | Between 53 and 55 |
| Patient three | Between 5 and 8 | Between 54 and 57 |

* Maximum score of this test is 57.

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**Figure 2: Rehabilitation system.**

**Figure 3: A subject is performing the exercise at home.**
The variations of the movement velocities of the patients at the end of the study were not random; they changed with the change of the exerted force. Whenever the patients depended more on their affected hand to perform the exercise, the force measured by the unaffected hand, which acted here as a natural robotic arm, decreased and hence the velocity of the hand decreased too. This can be clearly seen in Figures 4(a) and 4(b) for patient one, Figures 4(e) and 4(f) for patient two, and Figures 4(k) and 4(l) for patient three, where the velocities change in the same intervals the forces change.

Despite the smaller difference between the means of the forces applied on the glove at the beginning and the end of the study, the measurement values of the forces were statistically significant (Table 3). The same argument can be applied to the velocity and the mean difference is small, but the paired samples t-test succeeded to reveal a statistically reliable difference between the mean value of velocity of the patients at the beginning of the study and the mean value of the velocity at the end of the study. However, there is no statistically reliable difference between the acceleration and the jerkiness at the beginning and at the end of the study.

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The clinical assessment (ARM) score at the end of this study showed an improvement of both hands, the affected and the unaffected (Table 4). The results of the clinical test were correlated with the outcome measurements obtained from the glove and the camera. The level of progress of the upper limb motor function was inversely correlated with force exerted on the unaffected hand ($r = 0.79$) and inversely correlated with the speed of the hand's movement ($r = 0.75$). This indicates that the smaller the values of the force and the velocity, the less the arm motor impairment.

The overall evaluation of the system (glove + virtual environment) by the patients was satisfactory (Table 5). Patient one, the oldest one among the other patients, had no previous experience with 3D environment, and he found it enjoyable, but needed more time to get used with it. However, the three patients agreed that the system was comfortable to use, fun, and entertaining.

### 3. Discussion

In this paper, we designed and implemented a low-cost rehabilitation glove that meets the needs of stroke patients that could not, or barely could, move their affected upper limb. The bell-shaped trajectory of the hand movement during the first weeks indicated that the whole work is done by unaffected hand. This result confirms previous researches that have studied the trajectory of a normal hand of healthy subject moving from one point to another [17]. However, these trajectories look like a combination of the trajectories of health subjects and stroke patients together. It is obvious that when the patients fully depend on their unaffected hand, the curve looks like the curve of healthy subject, but when they put an effort and use their affected hand, the curve looks like the curve of stroke patient. Moreover, less variation of jerkiness at the beginning of the experiments indicates that the stroke had no impact on the unaffected hand of the patients.

Although the patients could not reach a zero force, which means the affected hands were not in fully control at any time, the significant variation of the forces between week one and week six shows clearly the progress of the patients. The clinical assessment confirms these results. Moreover, using the unaffected hand as a leading natural robotic arm of the affected hand made the unaffected hand stronger than before. The bigger the difference between the time needed to finish

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### Table 3: Paired $t$-test of the three patients.

| Patient | Fi-F2 | Sig. | V1-V2 | Sig. | A1-A2 | Sig. | J1-J2 | Sig. |
|---------|-------|------|-------|------|-------|------|-------|------|
| One     | −1.14 | 0.062| 0°    | 0.011| 0.002 | 0°   | 9.6E−6| 0.56 |
| Two     | 1.86  | −0.9 | 0°    | 0.026| 0.011 | 0°   | 4.6E−6| 0.81 |
| Three   | 1.14  | −0.062| 0°    | 0.014| 0.017 | 0°   | 7.7E−6| 0.89 |

* Means there is a statistical difference between the values.

### Table 4: Results of Action Research Arm test of affected and unaffected hands at the end of the study.

| Patient  | Affected hand | Unaffected hand |
|----------|---------------|-----------------|
| Patient one | Between 8 and II* | Between 52 and 56 |
| Patient two | Between 6 and 9 | Between 53 and 57 |
| Patient three | Between 8 and 12 | Between 55 and 57 |

* Maximum score of this test is 57.
Figure 4: Captured parameters at week one and week six. (a), (e), and (k) are the force exerted by the affected hand on the unaffected hand at weeks one and six of patients one, two, and three, respectively. (b), (f), and (l) are the velocity of the affected hand at weeks one and six of patients one, two, and three, respectively. (c), (g), and (m) are the acceleration of the affected hand at weeks one and six of patients one, two, and three, respectively. (d), (h), and (n) are the jerkiness of the affected hand at weeks one and six of patients one, two, and three, respectively.
the exercises at week one and week six, the more the patients, depending on their affected hand. For example, patients one and three, who have clinically progressed more than patient two, have registered bigger time difference than patient two.

Our results are compatible with previous researches that have been conducted by Cirstea and Levin [17], Turolla et al. [8], and Lambery et al. [18]. In [17], the time needed to complete a rehabilitation exercise by the stroke patients was significantly larger than that of healthy subjects. Moreover, the measurement values of the velocities of the stroke patients were characterized by a larger degree of variation than the healthy subjects. Furthermore, the clinical test has revealed a significant correlation between the severity of the stroke and the kinematics of the affected hand. In [8], stroke patients were allocated to two treatments groups. Virtual environment was used along with the conventional treatment in the first group, while the other group was receiving the conventional treatment only. By the end of the study, stroke patients that received virtual environment rehabilitation recovered more than those who had the conventional therapy only. The feasibility of robot-assisted therapy on the upper limb recovery after stroke was shown in [18]. Patients have shown a significant improvement of their upper limb motor function six weeks after the end of the therapy.

Finally, the affordable price of the overall system, along with the comfortability of use and effectiveness in the rehabilitation process of the stroke patients, supports the concept that such system can help stroke patients with severely damaged upper limb restore some aspects of motor performance.

4. Conclusion and Future Work

A new poststroke glove rehabilitation system has been designed and implemented in this paper. The system helped those patients whose upper limbs were severely affected by the stroke to the extent that they would not be able to move them. A low cost, comfortable glove mounted by eight sensors was worn on the unaffected hand and acted together as a natural robotic arm. The results were very encouraging. The clinical assessment indicated the feasibility of the proposed system with severely stroke patients. In our future work, we will add a strap to the system. The strap will be mounted with sensors that measure the forces of the muscles. We will put the strap around the affected forearm of the patients and ask them to extend and flex their fingers while they are moving their arm. We will use the captured values to determine the strength of both, the fingers and the forearm muscles. Also, our future work will be including a long-term study with ten patients to determine the effectiveness of the system.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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