Haptic Trajectories for Assisting Patients during Rehabilitation of Upper Extremities

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ABSTRACT

In this paper, we present a pilot study of a haptic system that leads the patients' limb to follow trajectories performed on a plane or in space (2D or 3D haptic trajectories). This function is implemented by the Multimodal Guidance System (MGS) whose aim is to provide robotic assistance during the rehabilitation of upper extremities when patients perform 2D and 3D tasks during manual activities such as drawing, coloring and gaming. The MGS consists of a virtual environment including several technologies as haptic, sound and video gaming. The patients are able to feel virtual objects and haptic trajectories, which act as virtual guides taking advantages of its force feedback capabilities. A virtual environment is used forming a haptic interface between the patient and the game. The haptic device is driven under the user's movements and assisted through the Magnetic Geometry Effect (MGE). Several 2D and 3D haptic trajectories have been tested in order to analyze the use interaction with the MGS. Preliminary evaluation has been performed in order to obtain more information related to the accuracy of the haptic trajectories. The haptic device has been used as an input means for tracking the hand trajectory made by the patient according to the feedback received from 2D and 3D tasks. The performance has been evaluated by comparing the analysis of the tracking results.

Keywords: desktop haptic system, rehabilitation system, multimodal guidance, haptic guidance.

1. INTRODUCTION

Patients with motor function disorders due to brain disease are increasing recently in aging societies. The rehabilitation of patients' impairment would help them in performing typical activities of daily living and their quality of life [12]. If a patient's upper extremity is paralyzed, the quality of life dramatically decreases because it becomes quite tough to live by oneself and with no assistance [14].

The upper extremities motor functions are often compromised, with consequent problems to the control of arm movements [8]. The arm trajectories present increased curvatures and the movements are systematically misdirected due to abnormal muscle activation patterns and disruption in inter-joint coordination [1],[7],[13]. In addition, muscle weakness and spasticity limit the elbow and shoulder range of motion [11]. In order to realize the most performing therapy, the assistance from the physical therapist is absolutely necessary. However, it is difficult to provide an every day therapy program due to the medical expenses and because a rehabilitation therapy, which is based on motion-oriented tasks, requires consistency and time by the physical therapist [10].

In the last decade, robotic and haptic devices for upper motor rehabilitation have been increasingly studied, becoming a promising complement to traditional therapy as they can provide high-intensity, repetitive and interactive treatment of the impaired upper extremities. In addition, these systems can provide quantitative measurement of patients' progress [2]. Following this trend, we have developed several devices and systems in order to provide robotic assistance in the execution of tasks performed on a plane (2D tasks). A first prototype of a guidance haptic concept has been described in [3], and a multimodal assistive system has been described in [5] and [6] which consists in a combination of visual, haptic and sound interaction modalities. In these works, pilot studies have been conducted with persons with disabilities (PWD). These prototypes have been tested

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by people with specific disorders affecting coordination, such as Down syndrome and developmental disabilities, under the supervision of their teachers and care assistants inside their learning environment. Results of these preliminary studies [4] provide conclusive evidence that the effect of using these kinds of assistive systems increases the accuracy in the tasks operations.

In this paper we present an application of the MGS described in [3] and [5] where the usability of the full CAD system has been used to create the virtual trajectories and to store a data base for precisely comparing and analyzing test data. Additionally, we present a pilot study of a haptic system that leads the patients' limb to follow trajectories performed on a plane or in space (2D or 3D haptic trajectories). This function is implemented by the Multimodal Guidance System (MGS) whose aim is to provide robotic assistance during the rehabilitation of upper extremities when patients perform 2D and 3D haptic trajectories during manual activities such as drawing, coloring and gaming. The MGS consists of a virtual environment including several technologies as haptic, sound and video gaming.

2. MULTIMODAL GUIDANCE SYSTEM (MGS) ARCHITECTURE

The system consists of the Multimodal Guidance System (MGS) used by patients for performing rehabilitation tasks, and a Graphical User Interface (GUI) used either by patients during training or by therapists for setting up the exercises to perform. Fig. 1 provides a schematic view of the system architecture.

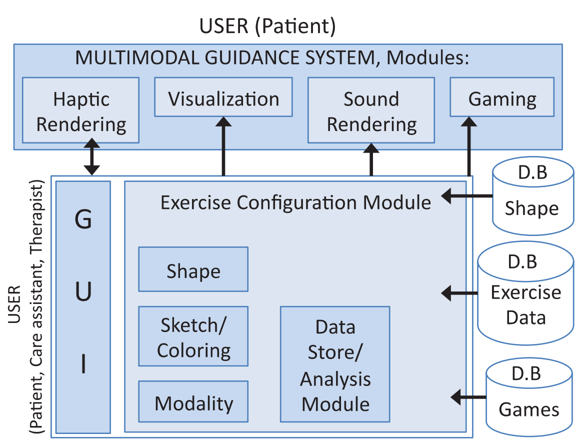

Fig. 1: Multimodal Guidance System (MGS) Architecture.

The Multimodal Guidance System (MGS) consists of a virtual environment including haptic and sound. Specifically, it consists of four main modules: the haptic rendering module, the visualization module, the sound rendering module and the gaming module. The haptic rendering module haptically renders virtual 2D shapes that are perceived by the user through a point-based haptic device; the visualization module renders the digital shape on the display, which corresponds to the one rendered haptically; the sound module provides audio feedback related to the user's hand velocity while performing the task, and finally, with the gaming module, the user is able to select the game and the difficulty of the task. The GUI allows the user to select several activities (sketching, coloring and gaming), and also to select the shape to use for the exercise, and the modality to use for the tasks, e.g. 1) with no haptic assistance, 2) with haptic assistance, and 3) with haptic assistance and sound.

The Phantom haptic device is used to provide feedback between the virtual environment and the user through the game interface, which has been developed using H3D [9]. The Phantom haptic device is a point-based device that consists of a stylus pen exerting forces according to the interaction with virtual objects.

The system allows us to track and record the patient's data for analysis and evaluation. These data are used to compute quantitative measurements of patient's progress.

3. GENERATION OF 2D HAPTIC TRAJECTORIES FOR SKETCHING AND COLORING

The Multimodal Guidance System can assist patients to follow trajectories performed on a plane (2D trajectories). Fig. 2 shows an example of generation of 2D shapes, which are then transformed into haptic guidance trajectories. Fig. 2a shows an isometric view of a 3D object **(2)**, which is intersected by a plane **(1)**. At the intersection is created the 2D haptic trajectory **(4)**, which is used by the MGS to provide the haptic guidance to the patient. The 3D model is necessary in order to assign the Magnetic Surface constraint, which is a technique used to render force on the haptic device based on a given distance from a virtual surface **(3)**. From the sketching initial point **(5)** up to the haptic trajectory **(4)** the Magnetic Surface constraint is disabled, allowing free-motion to the patient's hand. Fig. 2b represents the geometry from the patients' point of view, and Fig. 2c shows several geometries that have been used in the tests performed by the patients. Fig. 2d shows an isometric view of the coloring approach concept with a 3D shape **(2)**, the internal surface which acts as a rigid wall **(1)** and the lower surface **(3)** that is used by the MGS as a magnetic surface constraint. In this way, the user is able to perform the coloring task starting from the initial point **(4)**, which is located inside the 3D shape. The trajectory **(5)** required to coloring is linked to the lower surface **(3)** and limited by the internal surface **(1)**. Fig. 2e represents the geometry from the

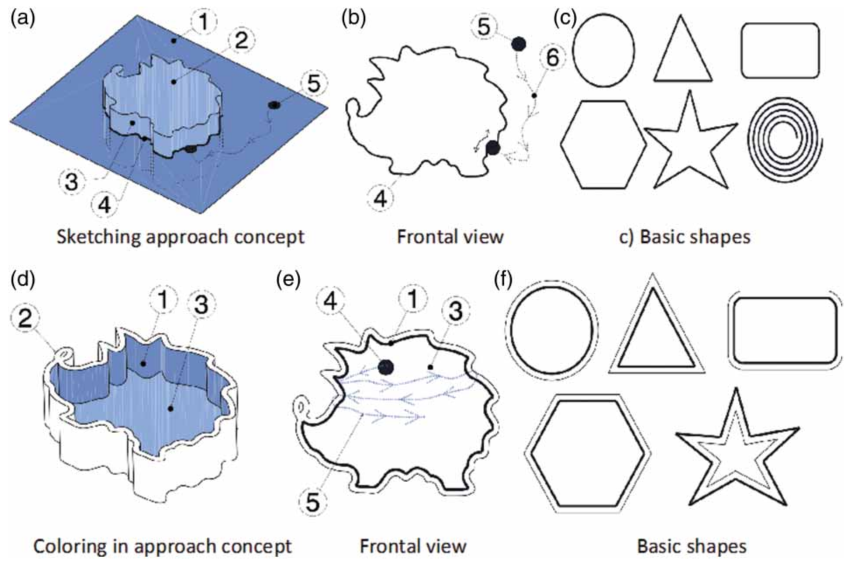

Fig. 2: Generation of 2D haptic trajectories for sketching and coloring internal surfaces.

patients' point of view, and Fig. 2f shows several basic shapes.

4. GENERATION OF 3D HAPTIC TRAJECTORIES FOR GAMING APPLICATIONS

The Multimodal Guidance System can assist patients to follow also trajectories performed in space (3D trajectories). In this case we have developed an application that combines a video game with 3D haptic trajectories. The game consists of a tower made of bricks that a patient must throw down. Through the GUI, the user (patient or therapist) can select the complexity level of the game. For example, the user can select the shape of the tower (quadrangular, pentagonal, hexagonal etc.), and the number of bricks as can be seen in Fig. 3. The interacting game and the haptic system concept have been developed through a series of virtual prototypes to enable the evaluation of its potential for improving the game results by the patients while performing the rehabilitation therapy.

The task of throwing down the bricks presents visual-motor integration. The shape of the tower and the number of bricks can be fully adjusted by the therapist to suit the needs of the patient. The game provides visual feedback to indicate which brick needs to be moved. Usually, the sequence is provided as can be seen in Fig. 3, starting from the brick-1, then the brick-2 and so on, in counter-clockwise. A first case of 3D haptic guidance trajectories consists of a single 3D trajectory that is used to assist the patient in the task of throwing down the tower bricks (Fig. 4a). A second case is a simplification of the task, and introduces three circular planes that are used to restrict the patients' motion along the vertical axis (Fig. 4b).

5. SOUND INTERACTION

The sound feedback gives the possibility to play metaphoric sounds while the user interacts with the system. These metaphoric sounds provide information to the patients according to the type of task performed. In fact, once the sound feedback is enabled, it gives the following information:

– Metaphoric sound A, if the stylus pen of the haptic device is not located directly on the haptic trajectories. This sound is a kind of warning alarm, meaning that the user's pen is located quite far from the haptic trajectories.

– Metaphoric sound B, is continuous played and is turned off when the velocity of the stylus pen is higher than a specific value. Also in this case, the sound is rendered as a warning alarm, which is deactivated when the user's pen moves too fast when following the haptic trajectories.

6. PATIENTS' DATA ACQUISITION

As mentioned before, the MGS is able to track the patient's hand movements while performing manual activities. In addition, the system can provide quantitative measurement of patients progresses by tracking and recording the force required to perform the tasks. These data can be used by the therapist to evaluate the patient progress, e.g. (a) how the muscle strength increases; (b) how the ability to control the movement during the 2D task is improved; (c) how the coordination between the arm, forearm and hand is improved.

The tracking and recording operations have been implemented by recoding the data provided by the stylus of the Phantom device using the DeviceLog command of the H3D API tool. The trajectories

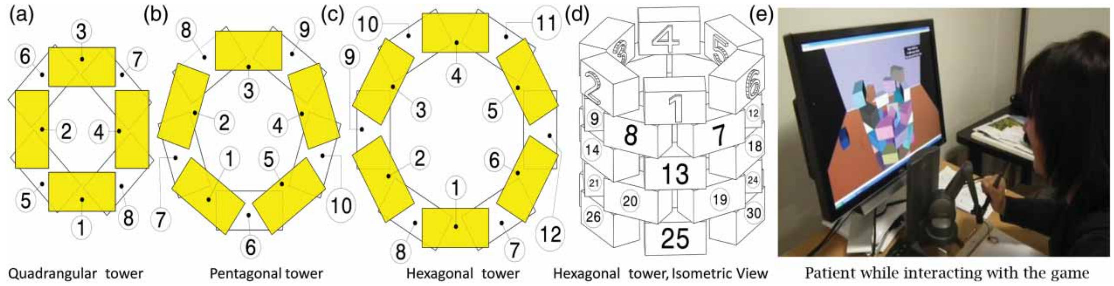

Fig. 3: The user (patient or therapist) selects the shape and number of bricks.

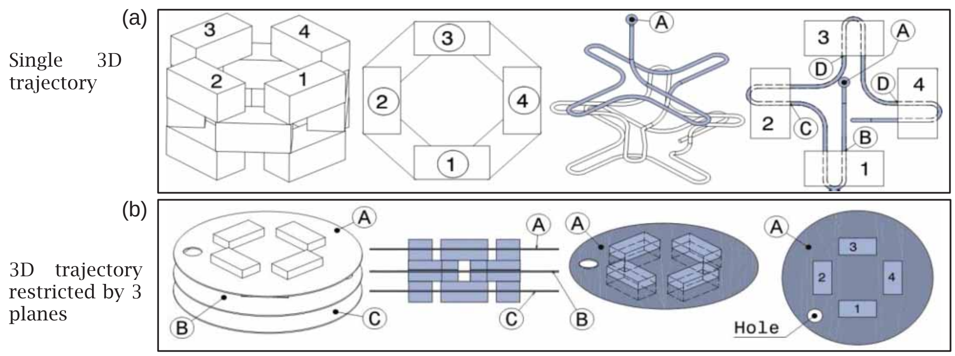

Fig. 4: Generation of 3D haptic guidance trajectories. a) Single 3D trajectory approach; b) 3D trajectory restricted by three circular planes.

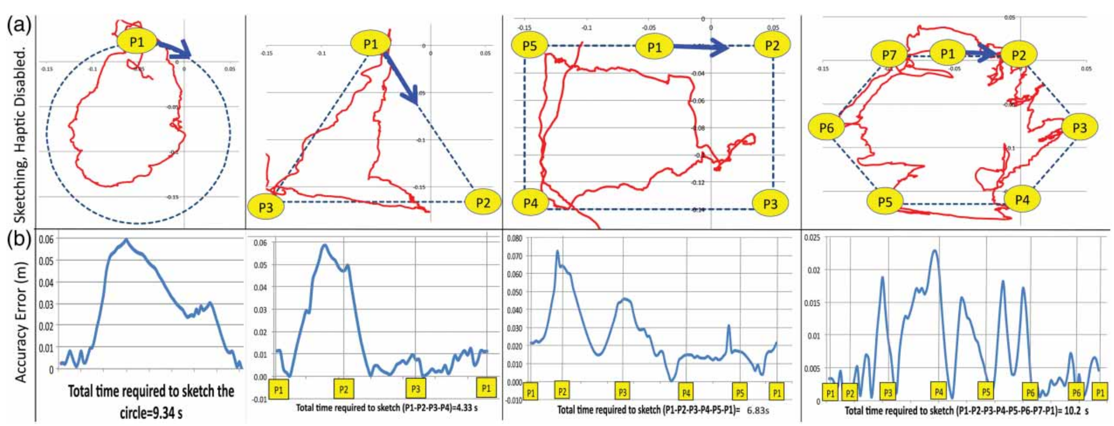

Fig. 5: Procedure for sketching several basic geometries, and accuracy results with the haptic force feedback disabled.

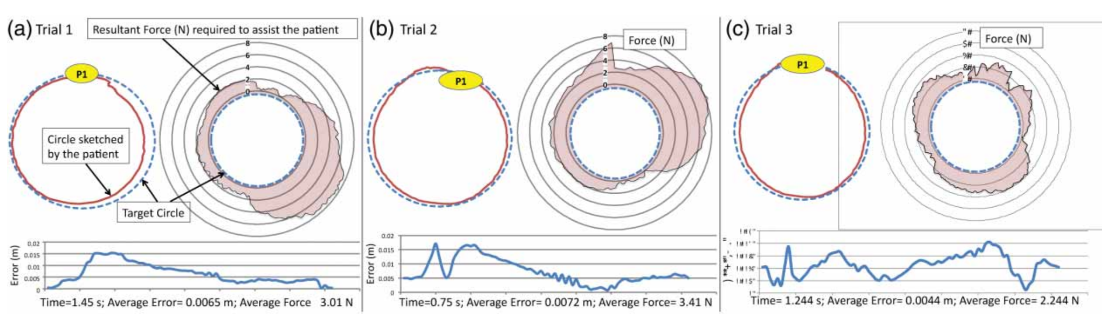

Fig. 6: Results with haptic and sound feedback enabled while sketching a circle.

performed by the patients and the forces required to perform them have been tracked at a sample rate of 25 Hz. The system starts tracking and recording data as soon as the stylus of the Phantom device gets in contact with the 3D shape near the starting point. The data captured throughout the tasks include the *x*, *y*, *z* coordinates of the user's trajectory [*Px*, *Py*, *Pz*], the total time necessary for the patient to perform the activities, the force vector [*Fx*, *Fy*, *Fz*] that is exerted to the user (only when the haptic modality is enabled), which means that the Magnetic Surface Constraint is also enabled, the velocity [*Vx*, *Vy*, *Vz*] with which the patient proceeds when performing the 2D and 3D tasks, and finally the total time *t* necessary to complete each trial. The data-recording phase stops as soon the patient returns to the starting point for the 2D task, and when all the bricks of the tower have been thrown down for the 3D task. Eventually, the data are preprocessed in order to compute the variance and the mean values for each component of the force vectors, per user and per trial.

6.1. Positional Error While Performing 2D Tasks without Haptic Assistance

In order to show how the system and the method work, we have performed several tasks with the help of a post-stroke patient. The first task consists of sketching basic geometries, e.g. circle, triangle, rectangle and hexagon, without haptic assistance. The patient is instructed to sketch the basic geometry counter-clock wise as best he can by following the virtual template on the screen, as can be seen from Fig. 5a. The red curves show the trajectory performed by one patient without the haptic support. These figures provide only qualitative information about the accuracy of the task; the patient and the physiotherapist can see both, the target ideal shape and the real trajectory. However, from Figs. 5b it is possible to get information related to both, the accuracy of the shape and the time required to sketch the shape. In this case, the patient requires 4 seconds to complete the circle, 4.33 sec. for the triangle, 3.83 sec. for the rectangle and 10.2 sec. for the hexagon. In order to estimate the deviation of each patient's trajectory with the ideal (target) trajectory, a vector has been calculated for each point of the ideal shape, which includes the minimal distance from the nearest point of the patient's trajectory.

6.2. Positional Error and Forces while Performing 2D Tasks with Haptic Assistance

The second task is related to sketching the same basic geometries performed in the previous task, but using the haptic and sound assistance. Fig. 6 shows the tracking results from the same patient while performing the task. During the first trial (Fig. 6a) the time required to sketch the circle was 1.45 sec. with a maximal force of about 7.8N (Average Force = 3.01N, Average Error = 6.5 mm). In the second trial (Fig. 6b), the time required was shorter but the maximal force was quite higher, 0.75 sec. and 8.64N respectively (Average Force 3.41N, Average Error 7.2 mm). Finally, in the third trial (Fig. 6c) the time required to complete the circle was 1.244 sec. with a maximal force of about 4N (Average Force = 2.244N, Average Error = 4.4 mm) with a more homogenous force distribution. Figures show the force values required to sketch the circles.

The time required to sketch the circle without haptic assistance was 9.34 s while in the trials by using the MGS with the haptic feedback enabled were: 1.45 sec., 0.75 sec. and 1.244 sec. respectively. The patient was able to perform the task considerably faster (85%, 90% and 86%), and with a considerable higher accuracy.

Fig. 7 shows the tracking results while sketching a triangle. The force data values have been developed along the circular trajectory (polar coordinate system). In the first trial (Fig. 7a) the time required to sketch the triangle was 2.84 sec. with a maximal force of about 7.2N (Average Force = 1.67N, Average Error = 4.5 mm). In the second trial (Fig. 7b), the time required was shorter but the force was quite higher, 1.46 sec. and 8N respectively (Average Force 2.61N, Average Error 3.8 mm). Finally, in the third trial (Fig. 7c) the time required to complete the triangle was 1.608 sec. with a maximal force of about 7N (Average Force = 1.734N, Average Error = 3.5 mm).

The time required to sketch the triangle without haptic assistance was 4.33 sec. while in the trials by using the MGS with the haptic feedback enabled were: 2.84 sec., 1.46 sec., and 1.61 sec. respectively. The patient was able to perform the task considerably faster (34%, 66% and 62%), with a higher accuracy.

The same procedure has been used to track the position and forces while sketching a rectangle and the force data values have been developed along the circular trajectory (polar coordinate system).

In the first trial (Fig. 8a) the time required to sketch the rectangle was 3.544 sec. with a maximal force of about 8.2N (Average Force = 1.473N, Average Error = 2.7 mm). In the second trial (Fig. 8b), the time required was 3.59 sec. with a maximal force of about 8N (Average Force 1.61N, Average Error 3.2 mm). Finally, in the third trial (Fig. 8c) the time required to complete the rectangle was 2.25 sec. with a maximal force of about 7.5N (Average Force = 1.844N, Average Error = 4.3 mm).

The time required to sketch the rectangle without haptic assistance was 6.83 sec. while in the trials by using the MGS with the haptic feedback enabled were: 3.544 sec., 3.59 sec. and 2.25 sec. respectively. The patient was able to perform the task considerable faster (48%, 47% and 67%), with a higher accuracy.

By analyzing the previous results, the main outcome is that the post-stroke patient significantly

Tower	3D Trajectory	First Trial		Second Trial		Third Trial	
		Qty.of Bricks	Time(s)	Qty.of Bricks	Time(s)	Qty.of Bricks	Time(s)
hexagonal	Single	30	210	30	188	30	203
	Restricted by 3 planes	30	123	30	129	30	118

Tab. 1: Time results while performing the 3D task.

reduces the time required to draw the 2D shapes; it is also evident the higher accuracy while sketching. One explanation would be that the patient performed "straighter" curves while sketching and using the haptic trajectories. As the deviation of the trajectories with the ideal shapes decreases as can be seen comparing the positional errors on Figs. 5, 6, 7 and 8. This means that the final trajectory comes closer to the ideal shape.

6.3. Results while Performing 3D Tasks (Gaming)

We have carried out several preliminary trials in order to test the system usability and to verify the patients' improvements while performing the 3D task in which it is used the game for catching the patient's attention. Fig. 9a shows the hexagonal tower with the 30 bricks in their nominal position, and then the patient has moved the brick-1, as can be seen from Fig. 9b. Fig. 9c shows the instant in which the brick-2 is moved; Fig. 9d shows the instant in which the brick-3 is moved and so on, up to completely move the 30 bricks. Fig. 9e shows the patient while performing the 3D task. Tab. 1 shows the time results for each trial.

The authors are aware of the fact that the number of persons involved in the tests are not statistically significant, but the aim of the tests was to check the effectiveness of the approach and the necessity of improvements.

7. DISCUSSION

The data stored by the MGS can provide the rehabilitation therapist with an objective and quantitative view of the patient's progress and the effect of the therapy. The report of the patient's activity includes a qualitative picture of the 2D and 3D activities while using the haptic trajectories, a quantitative error and a force diagram. Basically, these are the graphics that show weather or not the patient is making progresses. Performances are computed after each trial is finished, and are stored in the personal patient's database. The authors are aware of the fact that the number of trials are not statistically significant, but the aim of the test

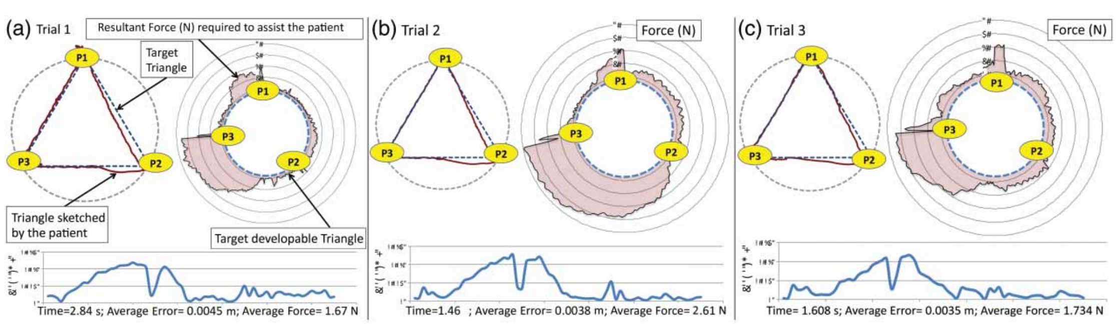

Fig. 7: Results with haptic and sound feedback enabled while sketching a triangle.

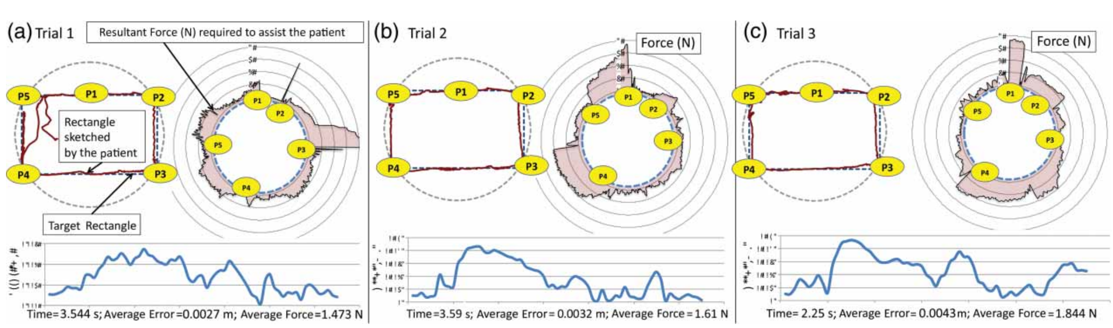

Fig. 8: Results with haptic and sound feedback enabled while sketching a rectangle.

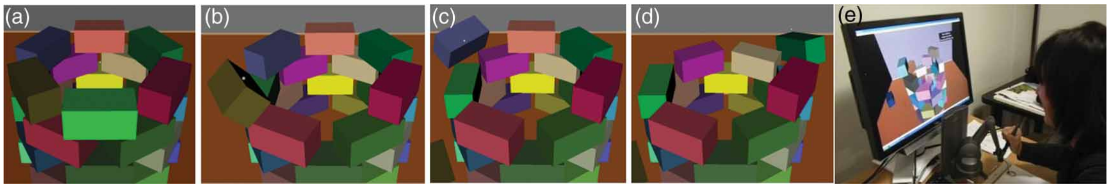

Fig. 9: Hexagonal tower, made with 30 bricks (one column and 5 rows pattern).

was to check the effectiveness of the approach and the necessity of improvements.

Although we obtained encouraging results after performing the trials, and it is evident that after the trials the patients showed an improvement, it is not clear if the improvements resulting from the training brought direct benefits in activities of daily living (ADL). Therefore, the improvements after training made by the patient in terms of time while sketching may indicate a better coordination during the movements.

8. CONCLUSION

The results of our study showed that the haptic trajectories help patients during manual tasks by means of using the MGS as a rehabilitation tool. The main outcome of this pilot study is that the patients significantly reduce the time required to draw the 2D shapes when the 2D haptic trajectories are enabled, which indicates that each patient learned to use the device and felt more comfortable with the exercise. In addition, we have compared the sketching data obtained by using the device with and without the haptic trajectories. The comparison shows considerable difference in the accuracy of the operation. Regarding the 3D haptic trajectories, results also reported that the patients reduce the time required to move and hit the tower bricks. It is planned to reference the data from patients to evaluate the effect of the MGS in a rehabilitation program.

Further research, however, is still needed to improve the performance of the Multimodal Guidance System by increasing the working volume of the device to meet more demanding rehabilitation applications. In addition, at the current development stage, the system is a prototype that requires engineering. This would improve the performance of some components, and also significantly reduce the cost of the overall system, toward making it a marketable product. Additionally, we will study the creation of 2D and 3D tasks in function of the group of muscles that need direct rehabilitation. The improvement of the system in these directions will constitute our future work.

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