JIHAP: A Virtual Serious Game for Neurological Haptic Rehabilitation

Abstract
This paper presents a new rehabilitation platform developed for enhanced physical therapy exercising. It consists of a virtual serious game, haptic feedback for physical interaction with the environment, and an intelligent controller that adapts the virtual game to the patients’ performance and therapy needs. The serious game virtually emulates real jigsaw puzzle games where the user has a picture broken into a certain amount of pieces and has to interconnect all of them. The proposed platform allows tailoring the virtual environment to each patient’s needs by using a set of performance indices that correlate specific game parameters and robotic measures with the evolution of the patient.

1. Introduction
According to the World Health Organization, stroke is currently the third most frequent cause of death worldwide and the leading cause of permanent disability in the US and Europe [1]. Neurological impairment after stroke frequently leads to hemiparesis or partial paralysis of one side of the body that affects the patient’s ability to perform Activities of Daily Living (ADL) such as walking and eating. Physical therapy, involving rehabilitation, can help hemiparetic patients to learn new ways of recovering lost functions. The goal of rehabilitation exercises is to perform specific movements that provoke motor plasticity in the patient, and thereby improve motor recovery and minimize functional deficits.

The use of robotic technology for rehabilitation treatment is an emerging field which is expected to grow as a solution by automating training. Robotic rehabilitation can: (i) replace the physical training effort of a therapist, allowing more intensive repetitive motions and delivering therapy at a reasonable cost, and (ii) assess quantitatively the level of motor recovery by measuring force and movement patterns.

Together with robotic devices, serious games are a key technological development to be pushed forward on enhanced rehabilitation therapies. A serious game is a game designed for a primary purpose other than pure entertainment (e.g. training, health care, defense, etc.).

Taking advantage of the above mentioned technologies, this paper presents a new rehabilitation platform and a virtual serious game called JIHAP (Jigsaw Haptic Puzzle), designed for enhanced physical robotic therapy. The main objective of the platform is the development of a working environment able to highly motivate the patient to perform physical therapies while adapting its behavior to the patient’s needs and performance.

2. Related work
Recent findings in medical science have demonstrated how physical exercises based on voluntary movements are able to produce significant clinical results in post-stroke motor recovery [2]. These results have pushed forward the development of several rehabilitation robots over the last decade. The capacity of robots to deliver training with high intensity and repeatability make them very valuable assistant tools to provide high quality treatment at a lower cost and effort. Researchers have widely demonstrated the effectiveness of robot-assisted therapy [3], although robots are not yet consistently found to be superior to manual therapy. These systems do not intend to replace the physiotherapists in the recovery program, but to support and assist them with new technology. Additionally, the usage of robotic systems allows precise measurements of movement kinematics and dynamics which can be used for assessing patient recovery ability and progress.

Regarding the use of Virtual Reality in the field of motor rehabilitation, most current robotic rehabilitation platforms use game based virtual scenarios to motivate and exercise the patient. While some of them are based on popular arcade games such as mazes or pac-man, others represent “real” virtual scenarios where the patient must fulfill many ADLs such as shopping in a supermarket or writing (Figure 1).

Figure 1. Examples of virtual games for neurological rehabilitation: a labyrinth game and a writing ADL game

3. Description of the virtual rehabilitation platform
The virtual rehabilitation platform developed consists mainly of three components: (i) A virtual serious jigsaw puzzle game with adaptive environment, (ii) haptic interaction with the virtual environment allowing physical exercise, and (iii) an intelligent controller able to measure user motion patterns and performance, and adapt both (i) and (ii) components to personalize the platform as required by each patient and each therapy session.
3.1. Serious virtual jigsaw puzzle game

The JIHAP environment consists of a computer jigsaw puzzle, a popular game which involves connecting various irregularly cut (‘jig sawed’) and interlocking pieces to recreate a complete picture. It has been selected for many reasons: (i) it is a very well-known game that anybody knows how to play without any type of instructions; (ii) it is challenging and motivating as this game has proven to be excellent for killing time and challenging for people of all ages.

Figure 2 shows the main environment of the serious game: on the top-left side the target puzzle picture is always displayed to the patient; at the bottom the puzzle slices are initially presented in random order; and on the top-right side the final worksheet is located where the patient must interconnect the slices in the correct order.

3.2. Haptic interaction

Haptic devices currently used by JIHAP are two Sensable Inc. PHANToMs (PHANToM Omni and PHANToM Premium 1.5) and the LHIfAM [4]. The main differences among the devices are their workspace and their force and torque feedback capabilities. These devices allow measuring the translation and rotation of their end-effectors as the user holds them. In the virtual puzzle game, position and orientation of the end-effector are mapped to the position and orientation of a little blue circle on the screen (Figure 2). Real physical workspace of the devices is correlated to the screen size.

The virtual world is 2D (defined by x-y axes), but the devices can be moved in 3D (x-y-z axes). For an enhanced experience translation along z-axis (inside or outside of the screen) is restricted by continuously applying a spring-like force to the initial position:

\[ F_z = K(z_{\text{init}} - z), \]

where \( K \) is the stiffness coefficient and \( z_{\text{init}} \) the initial z position of the haptic device in the game.

When the user wants to select a puzzle piece he/she must place the little blue circle controlled by the haptic device near the center of the target puzzle piece, and exert a certain amount of force \( F_z \) against the screen. If both conditions are satisfied, then the position and rotation of the puzzle piece are stacked with those of the blue circle and the end-effector of the haptic device. Similarly, to leave the puzzle piece at a certain location the user must exert again a certain force \( F_z \).

3.3. Intelligent controller

The last component of the platform is the intelligent controller, a software module that adapts the virtual environment to each patient’s needs, governs the haptic device, processes data and outputs reports of the exercises (Figure 3). In some way it is responsible for the “serious” part of the game.

Optimal therapies are those that tailor the exercises to each patient’s needs and abilities. There is no standard treatment that fits all. Therefore, it is necessary that the game can be adapted to each patient in order to be efficient and valuable. The intelligent controller acquires patient information extracted from the haptic device (position, orientation and velocity) and the virtual game (total game duration, score, movement patterns, failures) and performs an evaluation of the patients’ needs and deficits after each game. Depending on the results of the evaluation it changes the environment (complexity, force feedback model, rotations, etc.) to a more challenging configuration to push patient recovery. Additionally, it keeps an historical record of user performance during therapy sessions and creates periodical reports.

The way the intelligent controller evaluates the patient status and performs the environment adaptation is by using a set of performance indices extracted from the input data. These indices are used to implement an estimator of user state and correspondingly change the JIHAP configuration.

4. Adaptive environment and performance indices

The virtual jigsaw puzzle has the ability to adapt its environment to fit the best therapeutic needs for each patient and each therapy session. An adaptive environment must fulfill two premises: (i) components have to be adaptable in some way, and (ii) the adaptation mode has to be governed by a well-defined performance parameter or indicator that serves for the desired target objectives.
4.1. Adaptive environment

JIHAP can vary or adapt its working mode in the following ways:

Target jigsaw puzzle: It can be any picture that the patient feels motivating (e.g. family, places, etc).

Number of puzzle slices: The target puzzle can be divided into a squared number of slices ranging from 4 up to 100. Puzzle slices are always randomly ordered.

Haptic device: Although it’s not part of the virtual environment itself, changing the haptic device can adapt the game’s requirements to different ranges of motion and force feedback capabilities.

Rotation of slices: Puzzle slices can be presented rotated in order to force the patient to make wrist motions to complete the exercises correctly. The rotation axis is perpendicular to the screen and centered in the middle of each puzzle slice. Initial rotation values range from -45° to 45°, randomly presented.

Resistive wrist torque ($T_r$): for the particular case of the PHANToM Premium 1.5, torque feedback is also possible at the end-effector. Therefore additional resistance torque feedback can be displayed for the roll motion as opposite to the natural rotation of the user:

$$T_r = K_t (w_0 - w), \quad (2)$$

where $K_t$ is the stiffness coefficient for torque feedback, $w$ the angular roll-rotation of the end-effector at any moment and $w_0$ the initial rotation angle of the haptic device.

Virtual damping force ($F_b$): A resistive force contrary to the movements of the user while performing the exercises can be projected continuously:

$$F_b = -B_v \cdot v, \quad (3)$$

where $B$ is a constant value representing a damping term, and $v$ is the velocity vector of the user on the screen plane. This force can vary from 0 to the maximum force capabilities of the haptic device used. The value of $B$ has to be inside certain limits to avoid system instabilities [5].

Both $T_r$ and $F_b$ allow applying resistive forces against the user’s movements, that is, challenging the strengthening of the muscles as a complement to rehabilitation exercises that are more focused on gaining accuracy and velocity.

4.2. Performance indices

JIHAP distinguishes between two groups of patients: beginners and advanced users. Beginners are those patients that still don’t have much range of motion in their affected limbs and need a certain amount of physical assistance to perform movements. Advanced users are those that are able to move without assistance through the workspace of the game although they lack accuracy or muscle strength.

For beginners, the serious game works on the basis that a certain amount of robotic assistance is needed to perform movements. Therefore, the primary goal of the exercises is to challenge the patient to reduce the amount of robotic assistance provided and improve their range of motion. At this level, the game will visually highlight the piece to be held by the user and its place at the target puzzle. That is, the user does not really have to think what piece goes where; he/she must only care about reaching the highlighted puzzle piece as fast as possible, hold it, and place it at the highlighted target place. During the game, robotic assistance is only provided if the patient does not move at a certain speed, and is computed by following the control approach presented in [6]:

$$F_n = -Kp$$

$$F_a = -K(q - q_m) \quad \text{if} \quad (q < q_m) \quad (4)$$

where the final robotic actuation is computed as the sum of an assistance force $F_a$ along the target axis (e.g. the axis from the initial position of a puzzle piece and its final position) and a normal force $F_n$ that avoids normal deviations $p$ from the target axis. $K$ is the controller stiffness, $l_m$ is the length of the target movement, $t_m$ is the predefined duration of the movement and $t$ is the current duration time. According to equation (4) the robot only provides assistance $F_a$ if the user does not move a certain distance $q$ along the target axis higher than the controller’s minimum jerk movement $q_m$.

The therapeutic challenge resides in motivating the patient to perform movements without robotic assistance and faster each time. Therefore, a performance index used to measure user recovery is the robotic assistance quantity $P_{RA}$ along the target axis [7]:

$$P_{RA} = \frac{RA}{RT}, \quad (5)$$

where $RA$ is the total distance covered with robotic assistance, and $RT$ the total distance needed to complete the game. As the patient is able to reduce the $P_{RA}$ the game challenges him/her by shortening the predefined duration time $t_m$ of the movement, thus forcing the patient to move faster.

Additionally, for beginners, when the user reaches the center of a puzzle piece or the target position for the puzzle piece, a blocking force $F_{block}$ is displayed that sticks the position of the haptic device to the middle of the piece ($x_{pos}$, $y_{pos}$), thus helping users perform the selecting force $F_s$:

$$F_{block} = K(x_{pos} - x) + K(y_{pos} - y), \quad (3)$$

Table 1 shows an example of the adaptation of the serious game among six levels of difficulty. The performance index condition states that the maximum robotic assistance allowed in the game is 10%, except for the last level where the user should be able to perform the game without robotic assistance. From level to level $t_m$ is lowered so that the user must perform movements faster to avoid active robotic assistance. In this example, $t_m$ is tailored for average speed that ranges from 10 mm/s to 32 mm/s. Numeric values presented in Table 1 are only an example of many progressive algorithms and levels that can be defined as combinations of force aid requirements.
For advanced users, the serious game assumes that robotic assistance forces $F_a$, $F_b$ and $F_{\text{block}}$ are not necessary for the movement. The patient is free to move anywhere and catch or leave any puzzle piece, thus visual aids are also no longer available. In this mode, JIHAP adaptation to the users performance is achieved by changing four parameters: (i) the number of puzzle pieces, (ii) the initial rotation of the puzzle pieces, (iii) by providing a movement resistive damping force $F_a$, and (iv) by providing a resistive roll torque $T_r$ (for haptic devices with wrist torque feedback capabilities). These parameters are configured by defining two performance indices used to measure user recovery in the advanced users group, total time to complete the puzzle $TT$, and the number of puzzle pieces wrongly placed at the target puzzle during the game $nf$.

Table 2 shows an example of the adaptation of the serious game’s parameters described as the patient passes the levels defined by the corresponding performance indices.

Table 1. Game level configuration for the Beginners group

<table>
<thead>
<tr>
<th>Level</th>
<th>Pieces</th>
<th>Visual Aids</th>
<th>Force Aids</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 8$ s), $F_b$, $F_{\text{block}}$</td>
<td>$P_{\text{FA}} &lt; 10%$</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 7$ s), $F_b$, $F_{\text{block}}$</td>
<td>$P_{\text{FA}} &lt; 10%$</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 6$ s), $F_b$, $F_{\text{block}}$</td>
<td>$P_{\text{FA}} &lt; 10%$</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 5$ s), $F_b$, $F_{\text{block}}$</td>
<td>$P_{\text{FA}} &lt; 10%$</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 4$ s), $F_b$, $F_{\text{block}}$</td>
<td>$P_{\text{FA}} &lt; 10%$</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 3$ s), $F_b$, $F_{\text{block}}$</td>
<td>$P_{\text{FA}} &lt; 10%$</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>Yes</td>
<td>$F_a$ ($a_c = 2.5$ s), $F_b$</td>
<td>$P_{\text{FA}} = 0%$</td>
</tr>
</tbody>
</table>

Table 2. Game level configuration for the Advanced Users group

<table>
<thead>
<tr>
<th>Level</th>
<th>Pieces</th>
<th>Rotation</th>
<th>$F_a$</th>
<th>$T_r$</th>
<th>Performance Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>$TT &lt; 40$ s, $nf = 0$</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>$TT &lt; 50$ s, $nf = 0$</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>No</td>
<td>Low</td>
<td>No</td>
<td>$TT &lt; 50$ s, $nf = 0$</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Yes</td>
<td>Low</td>
<td>No</td>
<td>$TT &lt; 50$ s, $nf = 0$</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>$TT &lt; 160$ s, $nf &lt; 2$</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>$TT &lt; 200$ s, $nf &lt; 2$</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>No</td>
<td>Low</td>
<td>No</td>
<td>$TT &lt; 200$ s, $nf &lt; 2$</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>Yes</td>
<td>Low</td>
<td>No</td>
<td>$TT &lt; 220$ s, $nf &lt; 2$</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>$TT &lt; 400$ s, $nf &lt; 3$</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>Yes</td>
<td>High</td>
<td>No</td>
<td>$TT &lt; 500$ s, $nf &lt; 3$</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>Yes</td>
<td>Low</td>
<td>No</td>
<td>$TT &lt; 600$ s, $nf &lt; 3$</td>
</tr>
</tbody>
</table>

In advanced mode, where movement is unrestricted for the user, the puzzle environment developed allows multiple strategies to solve the game. The patient can take, leave or wrongly interconnect any puzzle slice. As a result, the game allows experiencing positive rehabilitative brain effects by triggering brain problem solving functions but also by complicating traditional robotic measures. Measures such as optimal path deviation or trajectory error [8] used in literature for evaluation in point-to-point exercises are not straightforward performance indices for this game. However, the total time to solve the puzzle gives a good indicator of the mean velocity followed by the user, and the number of failures shows the brain capacity of the patient. Additionally, movement resistive damping force $F_b$, and resistive roll torque $T_r$ applied are good measures of the strengthening of the muscles, since they can be progressively adapted as the patient’s force capacities improve. Many additional levels or inter-levels can be defined by adapting these two parameters progressively.

5. Conclusions

JIHAP v1.0 is the first approach of the authors to develop a complete haptic platform for neurological rehabilitation. It is based on a proper combination of robotic technology and virtual reality to deliver optimal and personalized therapy to patients. The first version described through this paper has accomplished the development of a virtual serious game able to adapt to different patients by re-configuring the environment as the user improves performance. This allows creating a very motivating and challenging scenario that continuously engages the patient with the activity.

The serious game presented emulates real puzzle games in an immersive environment. The user interacts with the environment by triggering brain problem-solving functions and acting physically through the haptic system, thus experiencing positive rehabilitative effects. It was developed to convey motion and force exercises with a high dose of motivation, through the integration of related work and results in the field.

References


