A Paediatric Interactive Therapy System for Arm and Hand Rehabilitation

Pawel Pyk, *Member, IEEE*, David Wille, Edith Chevrier, Yves Hauser, Lisa Holper, Ismael Fatton, Roger Greipl, Sonja Schlegel, Luzia Ottiger, Bärbel Rückriem, Aniña Pescatore, Andreas Meyer-Heim, Daniel Kiper, and Kynan Eng, *Member, IEEE*

Abstract— **Paediatric rehabilitation using virtual reality systems pose unique usability challenges distinct from those in adult rehabilitation. These challenges relate to the different epidemiology and aetiology of children's disorders requiring rehabilitation and the physical design of interactive virtual reality hardware for children of varying sizes. Just as importantly, children need highly entertaining interactive scenarios that suit their differing levels of cognitive development and thus their differing abilities to comprehend gaming scenarios. In this paper we present our virtual reality-based Paediatric Interactive Therapy System (PITS) designed specifically for upper arm rehabilitation in children aged from five years of age upwards. It incorporates a range of interchangeable position sensing devices (compass, bend sensor, pressure sensor and camera tracking) that can be adjusted to a large range of different hand sizes, and interactive gaming scenarios specifically designed for maximum entertainment value for children. We describe the neuroscientific principles behind our system, the technical details of the hardware components and the design of the interactive scenarios. An initial usability and patient acceptance pilot study has been conducted at the Rehabilitation Centre Affoltern of the University Children's Hospital Zurich. To date all patients have accepted the system, and trained in reaching and grasping tasks at a far higher rate than in conventional occupational therapy. The system thus promises to be a valuable complement to conventional therapeutic programs offered in rehabilitation clinics.**

I. INTRODUCTION

In recent years, virtual reality (VR) technology has been applied in neurorehabilitation interventions aimed at enhancing motor performance. It typically works by creating motivating exercise environments with systematic manipulation of intensity of practice and positive feedback. Attractive enriched environments, such as those that can be provided using VR technologies, may ameliorate some consequences of brain damage by stimulating motor learning and neuronal plasticity [1], [2]. It has been postulated that training and treatment of motor functions using VR can improve brain structure and function [3]. Additionally, the enjoyment experienced while working with VR may also increase the level of participation. The provision of immediate and positive feedback through VR has been found in adults to increase self esteem, empowerment and training compliance [4], [5].

Although several VR therapy studies have been undertaken in adults, few systems are designed for children and few trials and case reports have evaluated the effects of VR rehabilitation in children. The available results include treatment of upper limbs in children with cerebral palsy [6], [7] and brain injury [2], [8], [9], training of cognitive skills and attention [10] and investigation of neuropsychological disorders [11]. The motor therapy results found improvements in reaching quality, force and muscle activation and understanding of compensation strategies [12]. A comparison of VR with conventional exercise showed more completed repetitions in conventional exercises, but greater range of motion during VR [13]. One functional magnetic resonance imaging (fMRI) study has found evidence of training-related cortical reorganization in children [14], and a motivation study found improvements in perceived abilities, satisfaction in performance, pleasure and opportunity for engagement [15].

Several areas in VR-based paediatric therapy require further research. From a technological perspective, little work has been done on designing customizable VR hardware for children of different sizes or on developing games specifically for children. On the clinical side, there is so far no large-scale study of VR therapy covering different child pathologies. Further, although there are good outcomes in fun and enjoyment, the functional outcome of paediatric VR rehabilitation compared to conventional treatment is

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P. Pyk is with the Institute of Neuroinformatics, University of Zurich and ETH Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland (phone: +41-44-6353041; fax: +41-44-6353053; e-mail: ppyk@ini.phys.ethz.ch).

E. Chevrier, Y. Hauser, L. Holper, I. Fatton, R. Greipl, A. Pescatore, D. Kiper and K. Eng are with the Institute of Neuroinformatics, University of Zurich and ETH Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland (e-mail: edith@ini.phys.ethz.ch; yves.hauser@gmail.com; holper@ini.phys.ethz.ch; ismael@geckodrop.com; rogrei@b-f.ch; aninap@student.ethz.ch; kiper@ini.phys.ethz.ch; kynan@ini.phys.ethz.ch).

D. Wille, S. Schlegel, L. Ottiger, B. Rückriem, and A. Meyer-Heim are with the University Children's Hospital Zurich Rehabilitation Center Affoltern, Mühlebergstrasse 104, CH-8910 Affoltern am Albis, Switzerland (e-mail: david.wille@kispi.uzh.ch; affoltern.ergotherapie@kispi.uzh.ch; affoltern.ergotherapie@kispi.uzh.ch; baerbel.rueckriem@kispi.uzh.ch; andreas.meyer@kispi.uzh.ch).

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unknown. Most importantly, investigations are needed of how children with disabilities transfer skills learned in VR from a virtual environment to the real world. We are trying to address these issues simultaneously in our multidisciplinary research. The main focus of this paper is on describing our efforts to develop customized VR rehabilitation technology and content for paediatric applications.

II. ACTION OBSERVATION AND IMITATION IN CHILDREN

Over the last decade, the hypotheses surrounding the mirror neuron system (MNS) have been very influential in shaping our understanding of motor learning through action observation and imitation. The mirror system hypothesis postulates that “mirror neurons” exist that are not only active when individuals execute motor actions, but also when they observe, imagine or listen to the same actions [16]. Mirror neurons were initially described in monkeys [17] and later suggested in humans [18]. The mirror system is thought to be a multi-sensory cortical network of areas that enables individuals to understand the meaning of actions performed by others through the activation of internal abstract representations of the observed actions. It is said to be located in the ventral premotor and the inferior parietal cortex, composing a tri-modal system of motor, visual and auditory functions [19].

There is currently considerable debate about the existence and development of the mirror neuron system in children [20]. It has been suggested that mirror system supports motor learning and social functioning in everyday life during typical human development in children [21]. Neuroimaging data support the hypothesis of an observation and imitation system in children’s brains [22] and its potential clinical value for understanding neurodevelopmental disorders associated with a faulty mirror system, such as autism spectrum disorder [23].

Inspired by the features of the mirror system, several clinical cortical repair applications have been developed in recent years. Promising results have been achieved in neurorehabilitation by integrating knowledge of the mirror system in clinical treatment, e.g. following cerebral stroke [24]. In this paper we describe our paediatric interactive therapy system (PITS) for children that, like our adult system [25], is designed to activate action observation and imitation systems. The key differences between PITS and our adult system are its emphasis on multiple entertainment scenarios rather than training as understood by adults, and support for hand sizes from child (5 years old) to adult. The system combines training of action execution with observation of virtual arms under the patient’s control (Fig. 1), which can be systematically altered depending on the patient’s needs.

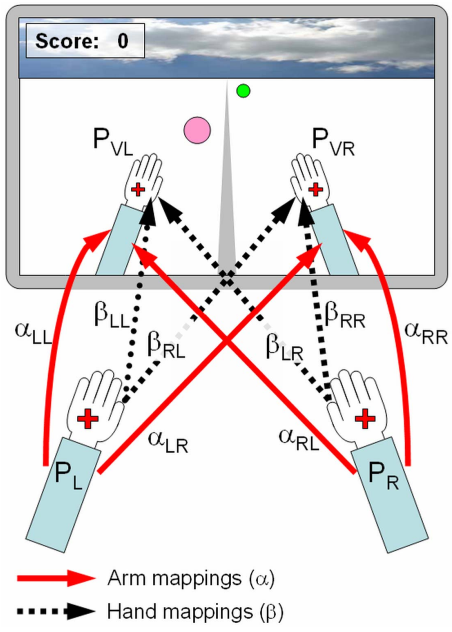

Fig. 1. From [25]. Schematic of mapping real left/right limb poses (P_L, P_R) to virtual limb poses (P_{VL}, P_{VR}). The mapping of P on to P_V is determined using a mapping function *f* using mapping parameters for the arm (α) and the hand/fingers (β):

$$P = \begin{bmatrix} P_L \\ P_R \end{bmatrix}$$

$$\mathrm{A} = \begin{bmatrix} \alpha_{LL} & \alpha_{RL} & \beta_{LL} & \beta_{RL} \\ \alpha_{LR} & \alpha_{RR} & \beta_{LR} & \beta_{RR} \end{bmatrix}$$

$$P_V = f\left(P, \begin{bmatrix} A_{1,*} \\ A_{2,*} \end{bmatrix}\right) = \begin{bmatrix} f(P_L, \alpha_{LL}, \alpha_{RL}, \beta_{LL}, \beta_{RL}) \\ f(P_R, \alpha_{LR}, \alpha_{RR}, \beta_{LR}, \beta_{RR}) \end{bmatrix}$$

The mapping function enables a variety of control scenarios to be supported, e.g. a patient with a paretic right limb may benefit if the real left limb assists with moving the virtual right limb to enable easier task success and thus more positive reinforcement.

III. VIRTUAL REALITY DEVICES FOR PAEDIATRIC REHABILITATION

A. The PITS Station

The PITS system consists of a custom work table on wheels (optionally height-adjustable), two data gloves, a monitor with speakers and a PC (Fig. 2). The work surface area is free from ferromagnetic materials to prevent interference with the digital compasses used in the data gloves. The flat LCD TV monitor (Sony Bravia KDL-32S2530, 81 cm diagonal, 1366 x 768 pixels) is connected to a PC (Dell OptiPlex 745, Intel Core 2 Duo E6300, 1 GB RAM) with accelerated graphics (BFG Technology nVidia 7900GS, 256 MB RAM).

The data glove hardware uses one main module and up to 16 nodes, although the current PITS system uses two sensory nodes. The USB-powered, electrically safety isolated main module powers the nodes and supports a serial bus running the Two Wire Interface (TWI, Atmel). Several interchangeable, configurable sensory nodes have been developed (magnetometer/accelerometer, bend sensor, pressure sensor). Nodes exchange data with the main module at 28 Hz for a single node and 23 Hz for two nodes on the TWI bus.

Fig. 2. The PITS system in use with a child. Shown are the monitor, table (100 x 60 cm) with adjustable lighting and wrap-around data gloves.

B. Data Glove Design for Children

The modular data glove design supports easy fitting of swollen or paretic hands of all sizes (Fig. 3). The angular position of each hand is measured with a 3D compass implemented as a combination of a 3D magnetometer (MicroMag3, PNI Corp.) and 3D accelerometer (MMA7260Q, Freescale Semiconductor). Each module has its own microcontroller (ATmega32, Atmel). The software on the microcontroller calculates the 3D angular hand pose by remapping the magnetometer readings using the accelerometer readings to find the most likely horizontal plane (assuming a vertical gravity vector), and then using a compass tilt compensation algorithm [26]

The thumb, index, and middle finger on each hand are measured using bend sensitive resistors connected via a half-bridge to the analog-to-digital microcontroller inputs (Fig. 3). Depending on the glove size either 4-inch sensors (FLX-01, Gentile Abrams Entertainment) or 3-inch sensors (3000-3001, Flexpoint) are used. The microcontroller also controls a tactile feedback vibration motor (Compact Pager Motor SHICOM M4H, G16153, The Electronic Goldmine) mounted between the index and middle fingers.

The 3D compasses (N=6) were tested under static conditions (Fig. 4). The maximum measured error was about 7 degrees for yaw angle and less than one degree for the tilt (pitch/roll) angles. When combined with in-game calibration of arm "home" positions, these results are more than good enough for use in therapy when large ferromagnetic objects are kept away.

C. Glove-Free Grasping: Squeeze Bottle

Since data gloves are difficult for some patients to wear, a glove-free grasping method was implemented (Fig. 5). It consists of a sealed bottle containing an electronic barometer module (MS5534A, Intersema Sensoric SA) and microcontroller (Atmega32) on a small module (20.3 x 47.0

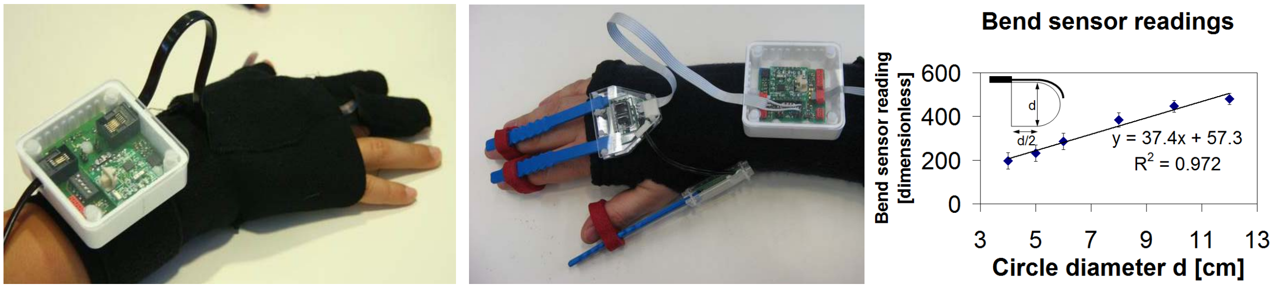

Fig. 3. Data glove variants and performance. (Right) Wrap-around, easy-fit neoprene glove designed for patients with arm and hand paresis. Available in 5 sizes from XS (child) to XL (adult) with 3-inch or 4-inch bend sensors. The bend sensors, encased in plastic housing to allow for free gliding, fit into pockets on the top of the hand and fingers. (Middle) Fabric glove based on an elastic textile tube with thumb hole, available in 3 different sizes. The node and bend sensors are attached to the glove using Velcro and to the fingers with 12mm thick foam rings (available in 5 sizes). (Left) Variation in bend sensor readings for six different sensors stretched over forms of varying size. Error bars indicate ±1 standard deviation.

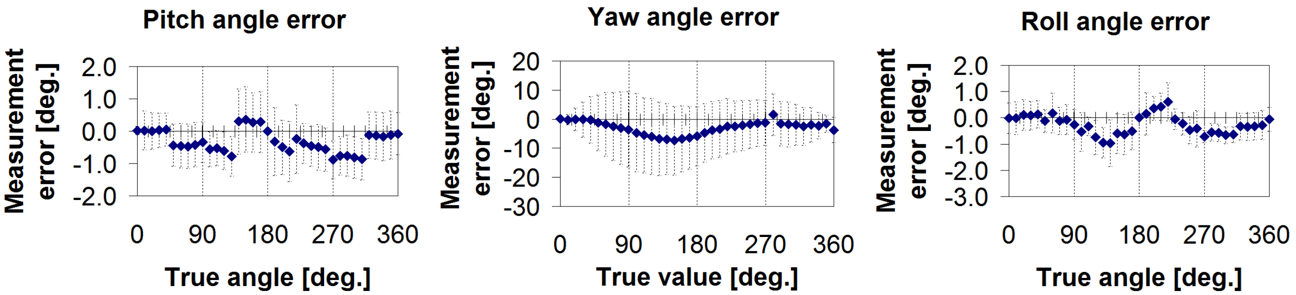

Fig. 4. Mean errors in yaw, pitch and roll angles for six different 3D compasses. Error bars indicate ±1 standard deviation.

mm) placed entirely inside the bottle. The pressure sensor communicates with the microcontroller via a 3-wire synchronous serial interface. The sensor module can be connected to the rest of the system either as a TWI module, or by generating analog signals equivalent to bend sensors (microcontroller PWM output low-pass filtered with a simple RC circuit). In addition to being easier to use than gloves, the bottle provides a resistance force which can be useful for improving hand strength, at the cost of only detecting the overall grasping force rather than individual finger movements.

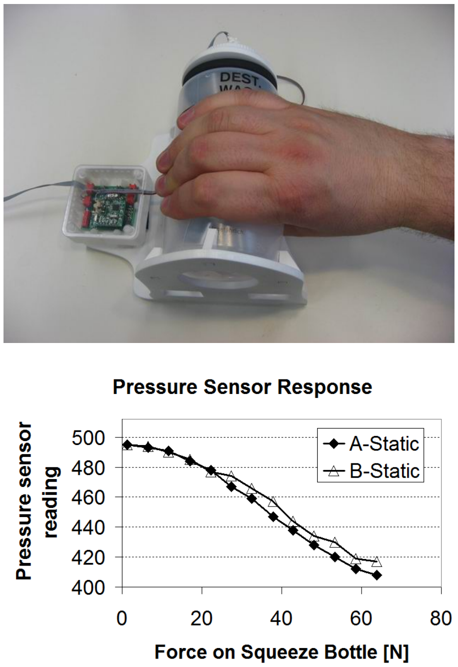

Fig. 5. (Top) Assembled squeeze bottle system showing compass module on an integrated base designed for table-top use. (Bottom) Variation in pressure sensor reading versus static force for two sample squeeze bottles (A and B). Both curves can be well approximated across their entire range by linear regression ($R^2 = 0.982$ for bottle A, $R^2 = 0.975$ for bottle B). The sensitivities of the bottles from the linear regressions are 1.56 N/unit for bottle A and 1.39 N/unit for bottle B.

D. *Optical Marker-Based Tracking*

Optical tracking (ARToolkit, artoolkit.sourceforge.net) was tested as an alternative implementation of hand position tracking. It uses a camera (QuickCam Pro 9000, Logitech) operating at 800 x 600 pixels with 20 Hz update. A dual-patch marker is worn on each hand (Fig. 6) and reference patch is placed on the table. Compared to the compass-based hand tracking, optical tracking has the advantages of lower cost and providing absolute position. However, it has a longer time lag (about 0.1 seconds), needs large patches (7 cm) for acceptable accuracy and is highly dependent on lighting conditions which are difficult to control in clinical use. Future development will focus on improving the lighting independence of the system and feature multi-modal optical/compass tracking.

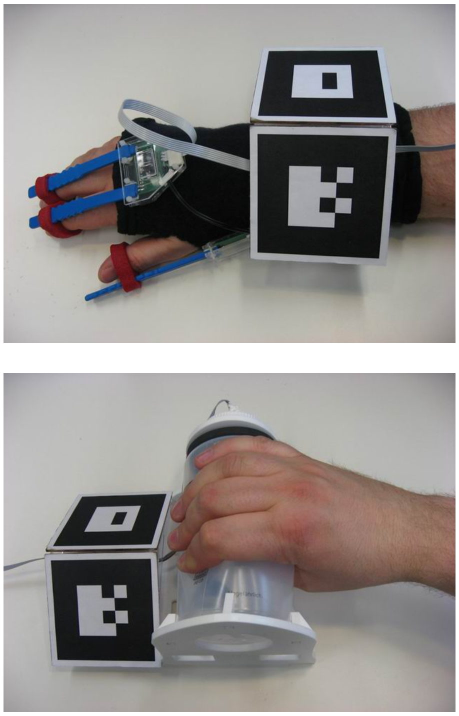

Fig. 6. Optical marker-based hand tracking in combination with (top) the data glove and (bottom) the squeeze bottle system for finger tracking. The patches shown are 7cm square and 120° apart.

IV. VIRTUAL REALITY SOFTWARE FOR PAEDIATRIC REHABILITATION

A. *Requirements*

The primary software requirement is to intensively exercise desired reaching and grasping motions for an hour each day over several weeks. While adult stroke patients were happy to play an earlier version of a ball interception game with very rudimentary graphics, no music and basic sound effects, children are much harder to keep focused and motivated. Our software had to be entertaining and varied enough in content and difficulty to keep children entertained, while also exercising different required arm actions as specified by therapists. We designed three different game scenarios (Fig. 7) to exercise different arm and hand motions: Toy Catching (reach and grasp), Catch the Carrot (reach, grasp, move, release) and Tomato Juggling (supinated interception and grasping). Each scenario can be played with the hands pronated, supinated or in between. However, Toy Catching is played most naturally with pronated hands, Catch the Carrot is suited to a vertical grasp (the carrots grow vertically) and Tomato Juggling lends itself to play with supinated hands. Each game includes full data logging capabilities at different levels of detail plus support for individual patient profiles.

B. *Toy Catching*

In this scenario, the player views and controls virtual representations of their arms in a first-person perspective view. Various toys appear, one at a time, from a large “mouth” at the other end of the room and move towards the player. The player’s task is to reach left or right to intercept each toy with an open hand (a “touch” event). Upon interception, the toy freezes for a short time period, during which the player must close his/her hand to “catch” the toy, which then disappears. Partial points are awarded for completing each part of the action. If the player’s hand is already closed at interception, a “punch” event is recorded with partial points. Adjustable parameters include the rate of toy appearance, toy movement speed, the lateral dispersion of toy trajectories, and the time window for catching the toy after touching it.

C. *Catch the Carrot*

This scenario also includes first-person perspective virtual arms. Carrots grow out of the ground in front of the player, which must be grasped, moved to baskets at the far left and right sides, and then released. Partial points are awarded for completing each movement. At the same time, a rabbit runs around trying to steal the carrots. The player can fend off the rabbit by hitting it, which also results in points being awarded. This game is more difficult than Toy Catching, as it involves the extra place and drop movements and simultaneous bimanual actions (hitting the rabbit while holding a carrot). It can also involve forwards reaching as well as sideways reaching, depending on where the carrot grows out of the ground.

D. *Tomato Juggling*

Tomato Juggling is more difficult again than Catch the Carrot, as it requires the player to track and intercept dynamically bouncing objects using both hands simultaneously. Tomatoes and eggs fall into the playing area, and the player must keep them in the air by controlling two cushions. Squeezing a cushion at impact causes the object to bounce higher. Points are scored when the player manages to juggle a tomato or egg into one of the boxes at the side of the screen. To make things even more difficult, the boxes are normally closed. They can be opened by bouncing an object to hit a suspended key, which causes the boxes to open for a limited time period. This game does not include an on-screen representation of the player’s arms, so it is not designed to stimulate the player’s action observation and imagery pathways.

V. PATIENT TESTING

We have conducted an initial usability and patient acceptance pilot study. Participants were recruited from an in-patient rehabilitation setting (Rehabilitation Center Affoltern am Albis, University Children’s Hospital Zurich) and followed up over a three-week period. PITS was integrated into the 3 times/weekly occupational therapy sessions (45 min.) using three different game scenarios. All therapy was carried out by occupational therapists without technical developer supervision or intervention. The outcome measures during the 3 week trial were the Melbourne Test (MT) [27] [28], Box and Block Test (BBT) [29] and the Nine Hole Peg Test (NHPT) [30] [31] measured in pre- and post-design. The Melbourne Test measures arm motor function and performance in daily-life activities, while the Box and Block Test and Nine Hole Peg Test provide objective measures of performance in reaching and grasping tasks. Additionally, to assess patient motivation, patients were asked about their enjoyment after each completed session (“How much fun was the session for you?”) measured on a scale from 0-10 (0 = lots of fun, 10 = no fun at all).

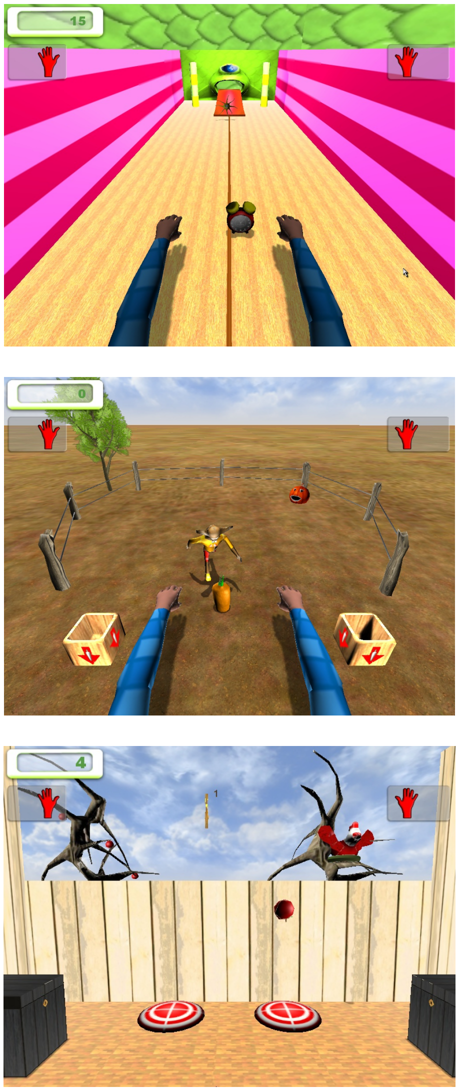

Fig. 7. PITS scenarios. (top) Toy Catching, (middle) Catch the Carrot, (bottom) Tomato Juggling.

PITS was tested on 4 children (mean age 13.5y, range 11-15y, 4 boys, 0 girls). Diagnoses were traumatic brain injury, Guillain-Barré-syndrome, plexusparesis and meningomyelocele. All patients accepted the system and trained reaching and grasping tasks at a far higher rate (approx. 300 grasps/session) than in conventional occupational therapy (<200 grasps/session). Pre- and post-assessments showed some improvements in hand function corresponding to improved test scores: MT +11.22% ($p = 0.109$), BBT +7,8 items ($p < 0.05$), NHPT –3.76 sec ($p = 0.279$) ('+' indicates improvement in MT and BBT, '–' indicates improvement in NHPT). Patient motivation was found to be high and was maintained over three weeks by using the three different game scenarios with variations in game difficulty (mean motivation score never dropped below 5).

VI. CONCLUSION

We have shown that PITS can be applied to real rehabilitation situations by therapists without technical expert intervention. PITS can be included in a rehabilitation program for children with congenital or acquired central motor dysfunctions. It addresses the need for child-specific upper arm rehabilitation by combining modular customizable hardware with multiple entertaining game-based training scenarios. It has been tested on four patients with varying neurological disorders, yielding promising results regarding patient acceptance and motivation. The potential benefits of PITS include reduced staff therapist costs when used in group therapy settings, increased patient motivation and objective evaluation of patient progress via game scenario scoring and monitoring of the evolution of game difficulty settings during therapy. Further clinical research is necessary to determine if the system improves significantly on conventional therapies, both in terms of motor function outcomes and patient/staff motivation. Future work will concentrate on clinical validation studies, group-based cooperative and competitive gaming and home-based rehabilitation and monitoring.

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