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The development of a home-based virtual reality therapy system to promote upper extremity movement for children with hemiplegic cerebral palsy

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Abstract. Children with hemiplegic cerebral palsy (hemiplegia) have difficulty performing motor tasks with their hemiplegic upper extremity (UE). A virtual reality therapy home-based system (VRT-Home) using a Sony PlayStation 2 equipped with an "EyeToy" video camera was adapted for children to practise hemiplegic hand and arm movements and the system's preliminary usability was evaluated. To use the VRT-Home, participants sit in a chair, hold down a button that occupies their non-hemiplegic side and keeps the system on, and perform movements with their hemiplegic UE to play fun, immersive, games in virtual environments. Supervised test sessions with five child participants found that the system successfully elicited targeted hand/arm movements of the hemiplegic UE, particularly reaching activities that involve the shoulder and elbow. A further home usability study with five participants showed, through usage logging and caregiver and child satisfaction surveys, that the intervention with the VRT-Home was an enjoyable way to practise hemiplegic arm movements at home.

Keywords: Cerebral palsy, hemiplegia, upper extremity, virtual systems, occupational therapy, rehabilitation

1. Introduction

Cerebral palsy (CP) describes a group of disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that have occurred in the developing fetal or infant brain [12,13]. Children with hemiplegic cerebral palsy (CP), or hemiplegia, have a brain injury or anomaly of the motor cortex that creates a sensorimotor impairment of the opposite upper extremity (UE). The impairments are multifactorial and consist of a combination of muscle hypertonia, weakness, impaired selective motor control, decreased sensation, and neglect of the involved UE. Movements that are typically difficult for children with hemiplegia include shoulder abduction, elbow extension, forearm supination, wrist and finger extension, and thumb extension. Consequently, through learned non-use, they generally favour the use of their non-involved UE in everyday activities [5].

Currently, therapy programs emphasize repetition and practise of motor activities with the hemiplegic UE [4,16]. Home-based practise, therefore, is essential. One means of encouraging such practise is constraint-induced movement therapy (CIMT), in which the child's non-involved UE is constrained in a sling, mitt or cast, thereby forcing the use of the hemiplegic UE in activities and exercises [17,15]. While effective, CIMT

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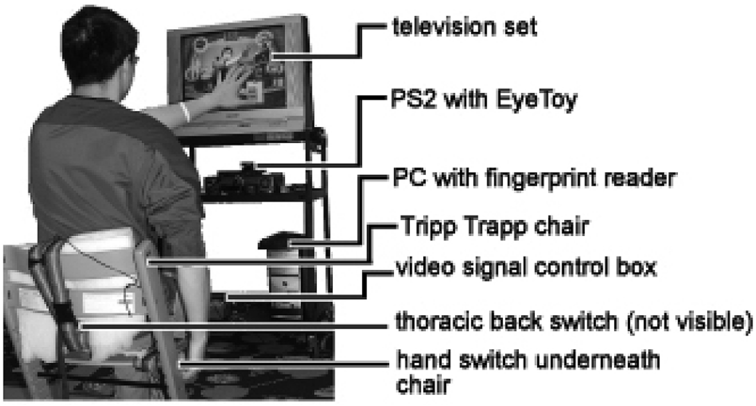

Fig. 1. System setup. The participant sits approximately 2 meters away from the screen and "reaches" for virtual objects visible on the TV.

can cause a higher risk of falls, reduced independence, and increased frustration for the child while wearing the constraint [5]. As a less-invasive alternative, therapists often recommend exercises for families to practise hand/arm movements with their child. However, given the numerous competing pressures on caregivers' time, adherence to such home programs may be difficult, making their effectiveness questionable [9].

Virtual reality (VR) therapy can provide an immersive and interactive computer experience that promotes practise of specific hand/arm movements for rehabilitation purposes [11]. Pilot studies with one institution-based VR therapy system that involves a video camera, video game software, and a visual display have suggested that VR play-based activities for children with cerebral palsy may increase their seated postural control [11] and sense of self-efficacy [10]. Another study with patients recovering from stroke found that using this system induced cortical reorganization and motor recovery [8]. While promising, the need for supervision, specialized training, or expensive equipment make existing systems unsuitable for *home-based* therapy for children with hemiplegia.

Our long-term aim, therefore, was to develop a low-cost, VR therapy home-based system (called the VRT-Home) that promotes movements of the hemiplegic UE that the child finds difficult. Guided by fun, goal-oriented games, children may willingly spend more time practising these targeted hand/arm movements independently. Such a system should accommodate a wide range of abilities, be enjoyable and usable in a home setting without professional assistance or extensive monitoring by caregivers, and provide a simple way for clinicians to track usage. In this article, we focus on the first steps of the development and implementation of such a device, constructed largely from off-the-shelf hardware, by presenting the results of early supervised and home-based studies of the system's usability with children with hemiplegia.

2. Virtual reality therapy home-based system (VRT-home)

The VRT-Home, shown photographically in Fig. 1 and schematically in Fig. 2, has 3 main components: a video game device, a chair and video signal control subsystem, and a personal computer (PC) equipped with a fingerprint recognition device. The system's total cost is less than US$700. The software and hardware designs are freely available from the authors of this paper.

2.1. Video game subsystem

The system uses a Sony PlayStation 2 (PS2), a commercially available home video game system, and an EyeToy, a PS2 video camera accessory. When used together, players see a video image of themselves on the screen and can manipulate overlaid virtual graphics with physical movements (a type of augmented environment) [1]. Two games from the "Play 2" disc were used. In "Secret Agent," players reach to "touch" toys while avoiding movement in "spotlight" areas that appear throughout the screen; in "Mr. Chef," the player performs such tasks as "shaking" milkshakes by making circular arm motions or "chopping" pickles with slicing motions. Other accessories were an 8 megabyte memory card for storing game data and an Intec 7089 rechargeable wireless controller (which avoids tripping hazards). Within the "Play 2" software, the sensitivity was set to "high" and the difficulty level was set to "easy."

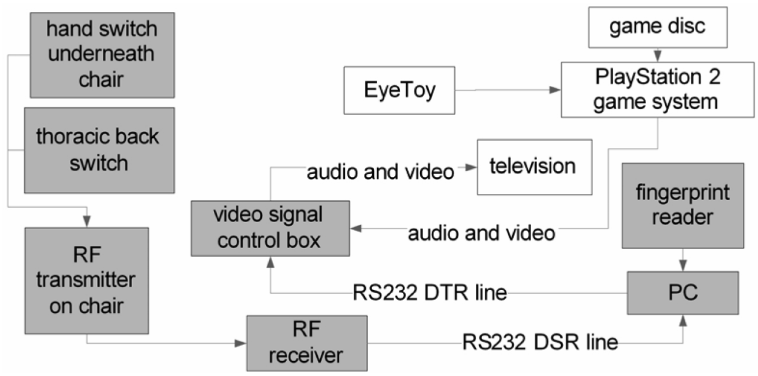

Fig. 2. Schematic of VR therapy system. Shaded boxes denote components added to the unmodified PlayStation 2 with EyeToy system.

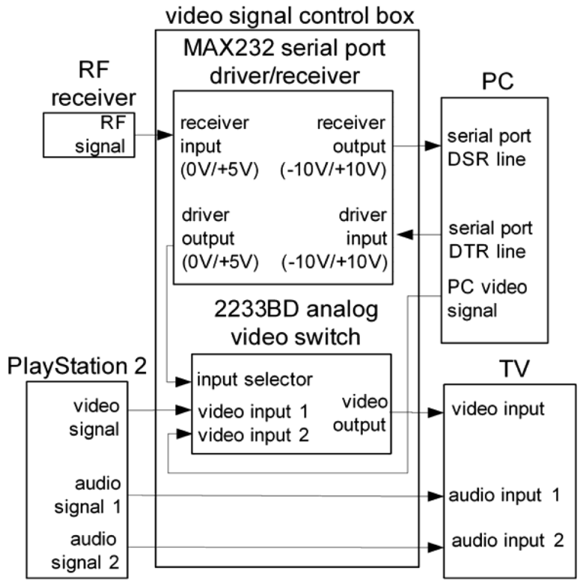

Fig. 3. Block diagram of circuit that determines whether the computer or PlayStation 2 (PS2) video output should be seen on the television screen. Here, RF = radio frequency, DSR = data send ready, DTR = data transmit ready.

2.2. Chair and video signal control subsystem

To play the games, the child sits on an instrumented straight-back chair. Because children with hemiplegia favour their non-hemiplegic UE, the chair's purpose is to permit gaming with the hemiplegic UE only. A Tash #58750 pillow switch (typically used for one-switch access devices) is attached underneath the chair and is held with the non-involved hand, constraining it from being used in the games, while a thoracic back switch (a Tash #58200 soft switch) is mounted on the chair's back to promote an upright seated posture and encourage elbow extension of the hemiplegic UE by discouraging the participant from leaning forward. The child must comply with the pushbutton switches because the video game is visible on the TV screen only if both switches are pressed. Specifically, the switches activate a radiofrequency (RF) transmitter mounted on the chair, which instructs a "video signal control box" connected to a personal computer (PC) to block or pass the video signal from the PS2 to the television.

2.3. Fingerprint recognition and user logging subsystem

The VRT-Home's PC has three functions: video signal control, fingerprint recognition to track whether the child is using the system, and simple logging to record usage frequency and duration. First, the child scans his or her fingerprint using an attached Microsoft USB Fingerprint Reader. Once the fingerprint is recognized, the child can press the chair button switches to see the PlayStation 2 video signal on the TV screen. Fingerprint-related events and switch activation and release events are time-stamped and logged in a Microsoft Access database for later analysis.

2.4. Usability evaluation

This study evaluated the VRT-Home's preliminary usability as defined by International Organization of Standardization (ISO) document 9241-11: we examined whether the VRT-Home could elicit targeted hand/arm movements (listed in Fig. 4) with effectiveness (the extent to which the task is achieved), efficiency (the rate at which the targeted movements were achieved), and satisfaction (the attitudes toward the use of the system) [7]. Usability studies use an iterative process, with changes made to the product design during repeated rounds of testing to address usability issues that arise. These methods are well-established in

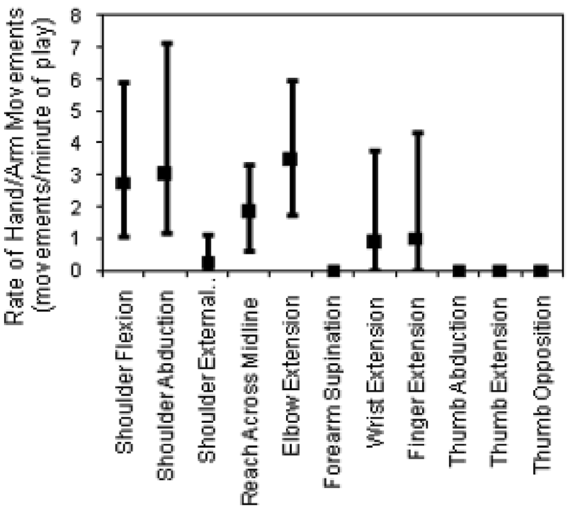

Fig. 4. The average rate and type of hand/arm movements observed over the ten sessions. Error bars represent the maximum and minimum observed rate of movements among the five participants.

the evaluation of new technologies in healthcare settings [14,2]. Given the sample sizes used, descriptive statistics were used to assess the VRT-Home's usability. All participants freely consented to the study. The protocol was approved by the institutional research ethics board.

2.5. *Supervised usability study*

Two rounds of supervised test sessions at a rehabilitation hospital were conducted with 5 children with hemiplegic cerebral palsy (4 boys, 1 girl; age, 8.1 $\pm$ 1.4 years). The participants had varying fine motor skills as indicated by their baseline scores in the House hand function classification system [6] (1 participant at level 2, 1 at level 4, and 3 at level 5) and the Quality of Upper Extremity Skills Test (QUEST) [3] (52.3 $\pm$ 18.2). In both videotaped 30-minute sessions, participants played "Secret Agent" and "Mr. Chef," the system logged usage, and one occupational therapist reviewed the video footage to record the number of times that the child performed each of the following hand/arm movements: shoulder flexion, abduction, external rotation, or reach across midline; elbow extension; forearm supination; wrist extension; finger extension; and thumb abduction, extension, or opposition. Each observed movement was qualitatively classified as "less than half" or "greater than half" range of movement, with "full range" defined as movement of the arm/hand through an established available range and "half range" as movement through half of the available range. Child and caregiver questionnaires administered at the end of each session were used to evaluate user satisfaction. These surveys included statements about the usability of the VRT-Home with 5-point Likert scales ("strongly disagree" to "strongly agree") along with open-ended questions asking participants to qualitatively describe their experience with the system. The usability issues identified in the first round of testing contributed to design changes prior to the second round.

2.6. *In-home usability study*

Following the two rounds of supervised testing, we conducted a home-based usability study with 5 additional children with hemiplegic cerebral palsy (4 boys, 1 girl; age, 8.0 $\pm$ 0.7 years), each of whom showed an ability to play the VRT-Home games in individual supervised trial sessions. A research assistant installed the system in each participant's home. The participants were instructed to use the VRT-Home for 30 minutes per day for 10 days. The main outcomes were caregiver and child questionnaires administered by a research assistant at the end of the study, along with usage-logging by the VRT-Home's computer.

3. Results

3.1. *Usability issues*

In the first round of supervised testing, the chair's size and 20-degree back angle (recline) made it difficult for some of the participants to sit upright and press the switches while playing the games. A median score of 3 ("neither agree nor disagree") was seen for the survey statement, "Holding down the buttons was easy." As well, some participants slid out of the chair as the session progressed. To resolve these issues, the chair's back was made upright and a non-slip Dycem mat on the seat of the chair helped the participants to stop slipping. Other usability issues, such as the fingerprint reader's sensitivity, were also identified and resolved. In the questionnaire administered after the in-home usability study, all 5 participants gave a score of 5 ("strongly agree") to the statement, "Once I started playing the games, I could keep the system going."

3.2. *System usage*

Figure 4 displays the average observed rates of each targeted movement over all 10 supervised test sessions. Participants performed an average of 13 $\pm$ 4 movements per minute over a mean playing time of 19 $\pm$ 3 minutes per session. The count of movements per

Table 1
Summary statistics for supervised usability test sessions

Measurements	Round 1 ($n = 5$)	Round 2 ($n = 5$)
Total neuromotor movements/minute of play	10 ± 1	16 ± 8
Quality of movements (Percentage of movements greater than 50% range)	72% $\pm$ 17%	70% $\pm$ 13%
Percentage of play time when switches were successfully pressed by user	92% $\pm$ 9%	94% $\pm$ 7%
Number of times that switches were released/minute of play	3.0 ± 2.7	1.9 ± 1.6

NOTE. Values indicate mean $\pm$ standard deviation.

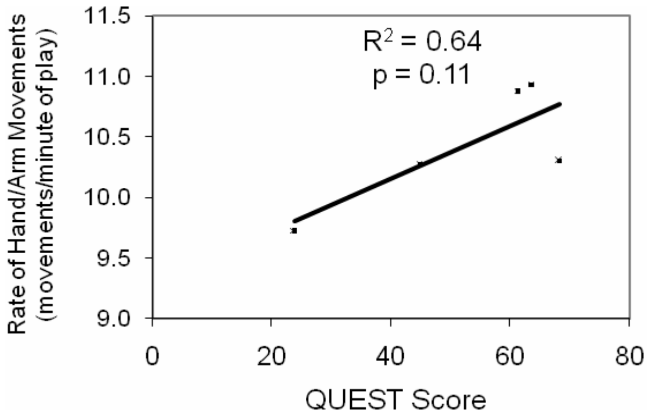

Fig. 5. Relationship between average rate of targeted movements and level of UE function (QUEST score) for the five participants in the first round.

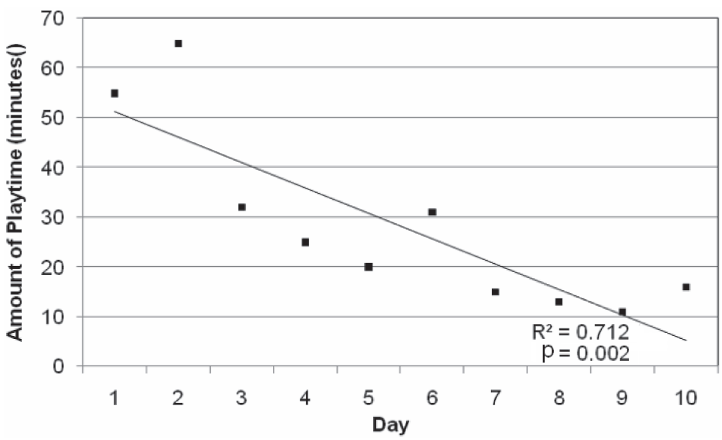

Fig. 6. Average playtimes in home-based usability trials. Error bars represent the maximum playtime on each day.

minute of play in the first round of testing and the participants' total QUEST scores, depicted in Figure 5, were positively correlated ($R^2 = 0.64$, $p = 0.11$). Table 1 provides summary statistics collected from the two rounds of supervised test sessions; Table 2 provides the average playing time for each of the 5 participants in the in-home usability study. On average, participants used the system at home for 29 ± 32 minutes per day. A decline in the average daily play time ($p = 0.002$) is evident in Fig. 6.

The questionnaires provide insight into experiences with the VRT-Home. In the supervised tests, the child participants stated that they "strongly agreed" that they "had lots of fun today," "would like to take the video

Table 2
Average daily VRT-Home usage by participant in home study

Participant	Daily usage of VRT-Home (minutes)
1	19 ± 18
2	53 ± 55
3	26 ± 10
4	22 ± 16
5	22 ± 24

games home to play," and "would like to come back another day to play the video games." As well, all 5 caregivers responded "strongly agree" to the statement, "My child would enjoy using this virtual reality therapy system at home," and responded either "agree" or 'strongly agree" to, "I think that my child would practise therapy activities every day with this system at home" and "I would like to have this system at home." Later, in the in-home usability study's questionnaire, all 5 child participants strongly agreed with the statement, "I enjoyed playing the games." Caregivers, meanwhile, responded with a median score of "strongly agree" to the statement, "My child enjoyed using the virtual reality therapy system at home" and a median score of 4 ("agree") for the statement, "It was easy to get my child to play on the virtual reality therapy system." In both cases, the scores ranged from 2 ("disagree") to 5 ("strongly agree"). These responses are representative of the results from the entire questionnaire.

4. Discussion

The VRT-Home's usability is discussed below in terms of effectiveness, efficiency, and user satisfaction.

4.1. Effectiveness

As shown in Fig. 4, the VRT-Home effectively elicited movements of the proximal hemiplegic UE, including shoulder flexion and abduction, reach across midline, and elbow extension. Fewer targeted movements of the wrist, fingers, and thumb were observed. This may be because VRT-Home games are typically played with reaching-type movements. Meanwhile, the hand and thoracic back switches appeared to be effective at occupying the non-hemiplegic UE. The number of button releases decreased from 3.0 ± 2.7 switch releases/minute in the first round to 1.9 ± 1.6 releases/minute in the second round of supervised testing, likely due to successful design adjustments or increased familiarity with the system.

4.2. Efficiency

A home-based VR therapy system needs to elicit targeted hand/arm movements at substantial rates. Figure 4 illustrates that this occurred with shoulder and elbow reaching activities – participants performed shoulder abduction, for example, an average of 3 times per minute. In the child survey, the statement "I don't feel tired" had a median response of "neither agree nor disagree," which suggests that the physical demands of playing the games were challenging but reasonable.

During the in-home study, the average playtime of 4 of the 5 participants was less than 30 minutes per day, as specified in the instructions for the study. Further, as the days passed, the number of minutes played per day decreased, which likely meant that fewer UE movements were performed. Introducing a wider variety of games or permitting greater scheduling flexibility with the VRT-Home may mitigate this issue.

4.3. User satisfaction

The questionnaire results suggest that the participants appeared to enjoy performing the movements elicited by the VRT-Home. This is generally a positive finding that indicates that the VRT-Home could be a fun way to promote therapy activities. However, it may also suggest a gradual loss of novelty of the system, a possibility supported by the declining amount of playing time observed in the in-home study. This may be an important consideration for game selection and the design of longer future in-home study with clinical efficacy measurements. This could be addressed by the periodic addition of new games.

4.4. User characteristics that affect usability

Figure 5 illustrates that every participant in the supervised testing were able to use the VRT-Home and perform targeted hand/arm movements, but children with higher baseline function as measured on the QUEST generally had greater rates of targeted movements in the first round of testing. A larger sample size is needed to determine whether age, experience with playing video games, or other user characteristics are important determinants of the VRT-Home's usability.

4.5. Limitations

In this study, our goal was to develop and begin to evaluate the usability of the VRT-Home as a new tech- nology. While the movements elicited and the participants' survey responses to the VRT-Home are positive findings, with 5 patients per round, the sample size is not sufficiently large for detailed statistical analyses. The next important step will be larger studies that assess the impact of playing the VRT-Home on the child's hand function and a potential decrease in disregard/neglect using standardized outcome measures within a randomized controlled study design.

5. Conclusion

We have described the implementation and preliminary usability of a virtual reality therapy system designed for home use for training upper extremity function of children with hemiplegic cerebral palsy. The VRT-Home has been demonstrated to elicit certain proximal movements of the hemiplegic hand/arm with a high degree of enjoyment and satisfaction in children with hemiplegia. Further study is planned to investigate the potential for enhancement of upper extremity function via a VRT-Home-based therapy program.

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References

[1] T. Chau, C. Eaton, A. Lamont, H. Schwellnus and C. Tam, Augmented environments for pediatric rehabilitation, *Technology and Disability* **4** (2006), 167–171.

[2] M. Conyer, User and usability testing – how it should be undertaken? *Aust J Educ Technol* **11** (1995), 38–51.

[3] C. DeMatteo, M. Law, D. Russell, N. Pollock, P. Rosenbaum and S. Walter, The reliability and validity of Quality of Upper Extremity Skills Test, *Phys Occup Therp Pedi atr* **13** (1993), 1–18.

[4] S.V. Duff and A.M. Gordon, Learning of grasp control in children with hemiplegic cerebral palsy, *Dev Med Child Neurol* **45** (2003), 746–757.

[5] A.M. Gordon, J. Charles and S.L. Wolf, Methods of constraint induced movement therapy for children with hemiplegic cerebral palsy: development of a child-friendly intervention for improving upper-extremity function, *Arch Phys Med Rehabil* **86** (2005), 837–844.

[6] J. House, F. Gwathney and M. Fidler, A dynamic approach to the thumb-in-palm deformity of cerebral palsy, *Bone Joint Surg Am* **63** (1981), 216–225.

[7] ISO 9241-11:1998(E), Ergonomic requirements for office work with visual display terminals (VDTs) – Part 11: Guidance on usability. Geneva: International Organization for Standardization, 1998.

[8] S.H. Jang, S.H. You, T.H. Kim, M. Hallett, S.H. Ahn, Y.H. Kwon, J.H. Kim and M.Y. Lee, Virtual reality-induced cortical reorganization and associated locomotor recovery in chronic stroke: an experimenter-blind randomized study, *Stroke* **36** (2005), 1166–1171.

[9] M. Law and G. King, Caregiver compliance with therapeutic interventions for children with cerebral palsy, *Dev Medicine Child Neurol* **35** (1993), 983–990.

[10] D.T. Reid, Benefits of a virtual play rehabilitation environment for children with cerebral palsy: a pilot study, *Pediatr Rehabil* **5** (2002), 141–148.

[11] D.T. Reid, Changes in seated postural control in children with cerebral palsy following a virtual play environment intervention: a pilot study, *Isr J Occup Ther* **11** (2002), E75–E95.

[12] P. Rosenbaum, B. Dan, R. Fabiola, A. Leviton, N. Paneth and B. Jacobsson, Proposed definition and classification of cerebral palsy, April 2005, *Dev Med Child Neurol* **47** (2005), 571–576.

[13] T.D. Sanger, M.R. Delgado, D. Gaebler-Spira, M. Hallett and J.W. Mink, Classification and definition of disorders causing hypertonia in childhood, *Pediatrics* **11** (2003), 89–97.

[14] S.G.S. Shah and I. Robinson, User involvement in healthcare technology development and assessment: Structured literature review, *Int J Health Care Qual Assur* **19** 2006, 500–515.

[15] J.E. Taub, S.L. Ramey, S. DeLuca and K. Echols, Efficacy of constraint-induced movement therapy for children with cerebral palsy with asymmetric motor impairment, *Pediatrics* **113** (2004), 305–312.

[16] J. Valvano, Activity-focused motor interventions for children with neurological conditions, *Phys Occup Ther Pediatr* **1/2** (2004), 79–107.

[17] J.K. Willis, A. Morrelo, A. Davie, J.C. Rice and J.T. Bennett, Forced treatment of childhood hemiparesis, *Pediatrics* **110** (2002), 94–96.

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