Design Principles for Hapto-Virtual Rehabilitation Environments: Effects on Effectiveness of Fine Motor Hand Therapy

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Abstract. We propose a set of principles to facilitate the design of haptic feedback virtual environments, which is expected to contribute to the effectiveness of the fine motor hand therapy. Firstly, we conducted a contextual study in a rehabilitation center to identify preliminary design elements using grounded theory. Based on these results, we defined a set of principles aiming to aid in the design of haptic feedback virtual environments to favour therapy effectiveness and patient's safety. Secondly, in order to evaluate the proposed design principles, we developed a haptic feedback virtual environment based on them and conducted a formative evaluation with five patients and three therapists. Preliminary results provided promising evidence, indicating a high perception of usefulness, ease of use and intention of use of the proposed environment and principles. Finally, to validate the impact of the design principles in therapy effectiveness, we carried out a second study with thirty participants, from which fifteen elderly had hand motor impairments. We found no significant differences in task execution time between healthy adults and elders with hand motor impairments. We found significant differences in precision or accuracy of the exercise. We confirmed the importance of key principles to facility the design of hapto-virtual environments that contribute to the effectiveness of the fine motor hand therapy. Further evaluations are needed to validate our results from a clinical viewpoint. We confirmed the importance of key principles to contribute to the effectiveness of the fine motor hand therapy. Further evaluations are needed to validate our results from a clinical viewpoint.

Keywords: Virtual rehabilitation · Haptics · User-centered design · Design principles · Neurorehabilitation

This work was partially funded by the Mexican Council for Science and Technology (CONACYT) under grant 218709 and CONACYT scholarship number 97753 for the first author.

H.M. Fardoun et al. (Eds.): REHAB 2014, CCIS 515, pp. 270–284, 2015.
DOI: 10.1007/978-3-662-48645-0_23

1 Introduction

In the recent years, several innovative strategies have been developed for improving post-stroke upper extremities motor recovery such as constraint induced movement therapy, electromyographic biofeedback, electromechanical assisted training, electrostimulation, high intensity therapy, robotics, repetitive task training, splinting and physical fitness training, among others [14,36,39]. The incorporation of emerging technologies such as virtual reality and haptic feedback in the rehabilitation therapy has attracted the attention of researchers and therapists because of its potential benefits, namely its capability to comply with neurorehabilitation principles [15,21] such as repetition, feedback, motivation, early intervention, and task oriented training—see for instance [36] and references therein.

As pointed out by [34,37], virtual reality allows for the design, creation and control of multi-dimensional simulated and interactive valid stimulus environments within which behavioral responding can be measured and recorded, providing in this way clinical assessments and rehabilitation tools that are usually not available in traditional therapy methods. Furthermore, when haptic feedback is also incorporated into the virtual environment, additional benefits such as force-feedback and tactile or kinesthetic input/output that are essential in many rehabilitation tasks are also provided [20].

Although there have been several proposals concerning the implementation of different kinds of hapto-virtual rehabilitation systems i.e., haptic-enhanced virtual reality environments, e.g., [20,23–25,28,40], there is still a gap between the design phase of those systems and their usage with real patients due to the lack of design principles that take into account both the needs of patients and therapists [30]. Most research works rely on the patient point-of-view to identify criteria (mainly for visual-based virtual environments) either focusing on the patient motivation, entertainment and engagement [4–8,13,16,18,19,22,33,36] or on the therapy usefulness [11,27,29,35,38]. However, ensuring therapy effectiveness and patient safety while providing the therapist with the adequate parameters to track patients performance and progress in hapto-visual rehabilitation environments are among the questions that remain yet to be answered [17]. To this end, we present in this work the preliminary results that allows us to identify designing principles for hapto-visual rehabilitation environments in fine motor hand therapy. We also present the evaluation results that allowed us to iterate these design principles, as well as to explore their effects on therapy effectiveness.

The remainder of the paper is organized as follows: Sect. 2 describes the contextual case study performed at the regional rehabilitation center. Section 3 explains the preliminary design principles that were identified during the study. We describe in Sect. 4 the methodology carried out to obtain feedback regarding the design principles with patients and therapists. Section 5 presents the evaluation results of the design principles, with emphasis on therapy effectiveness. In Sect. 6 we discuss the identified key design principles. We conclude with final remarks and future work in Sect. 7.

2 Contextual Case Study

A qualitative study was carried out during three months at the regional rehabilitation center located in Ensenada, Baja California, México, to gain an initial understanding regarding traditional fine motor hand therapy. Twelve specialists (e.g. rehabilitation medical specialist, occupational therapists, psychologists, among others.) took care of approximately 80 patients with motor and cognitive impairments in this center. We performed structured and unstructured interviews with 5 of the 12 specialists, from which 1 rehabilitation medical specialist, 1 occupational therapist, 2 physical therapists and 1 psychologist. All of them answered a 5-point Likert scale questionnaire of 40 items. Additionally, 8 non-participative direct observation sessions (30 min each, 4 h total) involving 5 patients with different conditions such as carpal tunnel surgery, cerebrovascular accidents, and brain lesions were performed (Fig. 1).

Interviews and observation sessions were recorded, transcribed and analyzed using grounded theory [9]. As a result, we have identified the different stages of a traditional occupational therapy session (Fig. 2). On average, an occupational therapy session lasts 30 min. During the first session, occupational therapists create an individual treatment program based on the initial patient assessment. In

Fig. 1. Non-participative direct observation of a traditional occupational therapy session.

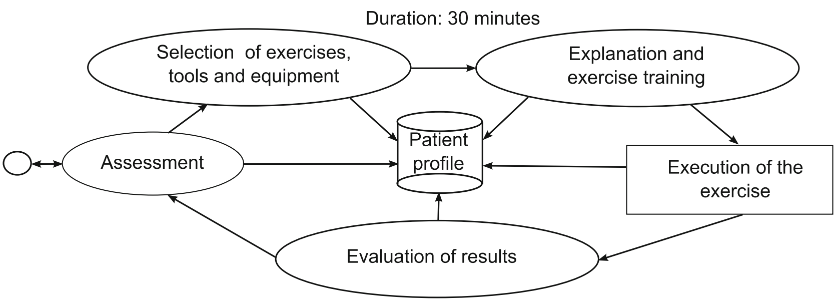

Fig. 2. The different stages of a traditional occupational therapy session.

subsequent sessions, occupational therapists select the tools and equipment that will be used by patients in each therapy session. Then, therapists explain and show the patient how to perform the exercises, review the treatments periodically, evaluate patient's progress and make changes to the treatment as needed. The whole therapy session is carried out under therapists supervision and assistance. Finally, occupational therapists analyze patient's performance and write it down on his medical record.

We have further identified the main characteristics of the occupational therapy for improving fine motor hand skills (Table 1). For instance, ludic activities are among the strategies used by occupational therapists to motivate the patients. Depending on the function to be enhanced, the exercises are selected as: exercises to improve muscle strength (e.g., pulling or moving objects of different weight and size, or pressing dough), exercises to improve eye-hand coordination (e.g., solving puzzles, mazes and dot-to-dot pictures), exercises to increase range of motion (e.g., stretching rubber) and exercises to increase sensitivity (e.g., touching objects with different textures).

3 Preliminary Design Principles

A design principle is used by interaction designers to guide them when designing user-centered applications [11,31]. From the contextual study described in Sect. 2, we have identified a preliminary set of designing principles that incorporates the therapists viewpoint. These design principles are classified in two categories: principles that aim (a) to guarantee therapy effectiveness, and (b) to ensure patient's safety when designing the interaction with hapto-visual environments.

With respect to *therapy effectiveness* we distinguish the following design principles:

– Adaptability. According to occupational therapists, this principle is important to assess the range of motion and strength of the patient, to thereby adapt therapy.
– Therapy tasks tailored according to the patient's motor impairment.
– Motivation based on recreational activities to engage and entertain the patient during the therapy.
– Suitable selection of the haptic interface.

Concerning *patient's safety*, the design principle involves the careful selection of the range of motion and strength of the therapy tasks according to the patient's physical ability.

4 Evaluation of the Design Principles

In this section we describe the virtual environment we developed taking into account the design principles explained in Sect. 3. We also present a formative evaluation conducted with 5 patients, as well as a refined version of the design principles.

Table 1. Characteristics of traditional occupational therapy.

Category	Property	Dimension
Fine motor skills hand therapy	Feature	Based on formal or ludic activities
		Goal-based movements
		Exercises for specific movements
	Tools	Everyday toys, textures, mirror
	Equipment	Mechanotherapy
		Electromyography
	Exercise	Move and press divers artifacts
	Movement	Fingers, palm and wrist flexion or extension
		Fingers and wrist abduction or adduction
		Tip, palmar, lateral
		Wrist supination or pronation
		Cylindrical, spherical or hook grasp
	Function to be enhanced	Strength
		Sensation
		Range of motion
		Precision (eye-hand coordination)
	Etiology	Birth defect
		Injury or accident
		Degenerative disease
	Problem	Patient's absenteeism
		Lack of motivation
		Subjective assessment
		Lack of technology that motivates to exercise
	Strategy	Ludic or formal activities according to patient's skills

4.1 Hapto-Virtual Environment

As a proof-of-concept of the preliminary design principles, we have developed a haptic maze environment. Haptic feedback is provided with the Novint Falcon haptic device [2]. The Novint Falcon is a 3 degrees-of-freedom (dog) parallel robot that provides users with haptic feedback. It has a workspace of approximately 10.6 cm^3. Open-source three-dimensional (3D) computer graphics software Blender [1] as well as the cross-platform game creation system Unity [3] were used to develop the virtual environment. The user in the virtual environment is represented by a proxy (or avatar) that moves in a 3D space. The

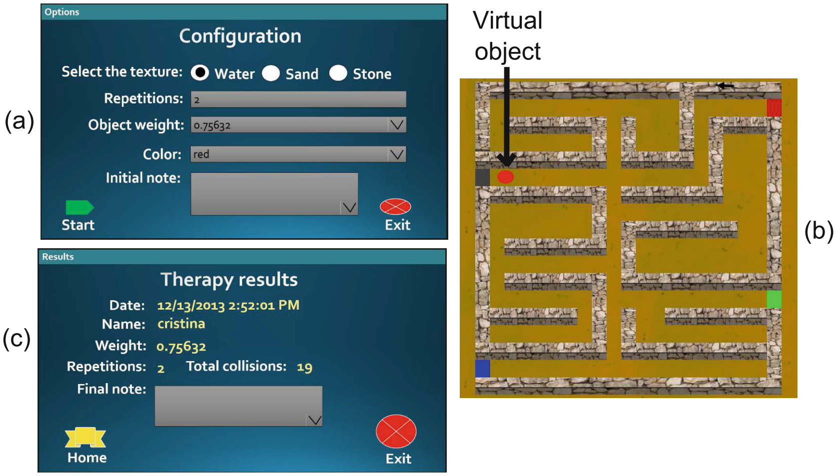

Fig. 3. Haptic-enhanced virtual environment: (a) therapy configuration; (b) exercise in the haptic maze for wrist therapy; (c) therapy results.

collision detection algorithm is carried out with Unity libraries as well as with penalty-based methods [26,32].

Our main objective in developing the haptic maze was to enhance the strength and wrist-movement accuracy of the patient. In the virtual environment (Fig. 3) we distinguish three main components: (a) a configuration screen where the occupational therapist selects not only the visual features of the virtual environment, but also the number of task repetitions and the simulated weight of the haptic proxy; (b) the haptic maze; and (c) the results screen where patient performance is displayed.

4.2 Formative Evaluation

In order to evaluate the design principles that were used for the development of the virtual environment, we conducted two therapy sessions with 5 patients (Fig. 4). These sessions were supervised by two occupational therapists and one physical therapist. After each therapy session a Technology Acceptance Model (TAM) [10] Likert scale 5 questionnaire regarding perception of usefulness, ease of use and intention of use of the haptic virtual environment was answered by patients and therapists. Evaluation results are shown on Table 2. These results provide evidence about patients and therapists having a high perception about the proposed environment's usefulness, although the latter perceived a higher usefulness (i.e. completely agree) than the former (i.e. agree). Also, therapists perceived the environment as having a high ease of use (agree), although it was not the case for patients which were neutral. Finally, intention of use was projected as high (i.e. completely agree) by both kinds of users.

Fig. 4. Patients conducting therapy sessions during the formative evaluation of the design principles.

Table 2. Perceived usefulness, ease of use and intention of use.

Aspect analyzed	Patients	Therapists	Total
Perceived usefulness	4.0/5	4.5/5	4.2/5
Perceived ease of use	3.0/5	4.2/5	3.6/5
Intention of use	4.5/5	4.6/5	4.5/5

Based on the lessons learned during the development and evaluation of the haptic virtual environment, the preliminary design principles described in Sect. 3 were modified (others were added) as follows.

Therapy Effectiveness

- *Patient's data accessibility:* Store the patient's data according to the clinical record requirements; allow for data access according to the specialist's role; display a performance record of the patient.
- *Therapy adaptability:* Execute a task that allows to determine objectively the level of difficulty of the exercise for the patient (for instance, number of repetitions, weight of the virtual object); automatically suggest the difficulty level according to the patient's performance record; learning level of the exercise that does not add excessive difficulty to the patient's motor rehabilitation.
- *Ludic activity based motivation:* Gain the patient's attention by including game-based visual and auditory elements combined with strength feedback.
- *Goal-oriented movements for skill generalization:* Repetitive and intense basic movements (such as finger and wrist flexion and extension, finger adduction and abduction, fine pincer grasp) for motor re-learning.
- *Suitable selection of the haptic interface for movement execution:* Careful selection of the haptic interface according to the movement to be enhanced (e.g., exoskeleton or haptic device with end effector).
- *Mechanisms for determining success of the therapy:* Establish mechanisms that allow to identify patients' improvements based on quantifiable results (for example speed, position, weight of the virtual objects).

Table 3. Biomechanical properties of the hand [12].

Movement	Value
Hand opening maximum range	15 cm
Wrist rotation maximum range	180 deg
Thumb mean orientation	45 deg
Maximum grasping force, measured for one finger	40 N
Maximum wrist torque	0.5 Nm

– *Continuous interactions:* Guarantee the synchronization between the visual, auditory and haptic feedback according to the virtual objects' characteristics.

Patient's Safety

– *Regarding the range of movement and hand's maximum strength:* Limit the range of movement of the exercise and the maximum weight of the virtual objects according to the biomechanical properties of the patient's hands (see Table 3.
– *In case of failure, stop communication with the device at an appropriate time:* Provide simple mechanisms that allow for stopping the activity in case of failure of the haptic device.

5 Evaluating Therapy Effectiveness

In order to further evaluate the proposed design principles, as well as to gather additional evidence regarding their influence in therapy effectiveness based on patient's performance, we conducted a second study that is briefly described next. A second version of the haptic maze was also developed, which integrates the design principles (for instance: data accessibility, ludic elements and auditory feedback) described in previous sections.

5.1 Participants

2 groups of 15 participants each were recruited. In the control group, 15 healthy adults (8 women and 7 men, average age 55.73 ± 7.56 years) who live an independent life and have no apparent motor impairment problems served as participants. In the intervention group, 15 elders (8 women and 7 men, average age 78.80 ± 11.30 years) with hand motor impairments, e.g., rheumatoid arthritis, were recruited from the home for elderly "Casa Hogar del Anciano" and "Casa del Abuelo", both located in Ensenada, Baja California, Mexico.

5.2 Experiment Design and Procedure

The experiment followed was a within subjects paradigm, i.e., both groups performed the task under the same following condition:

C1. Virtual environment with auditory, visual and haptic feedback using the Novint Falcon haptic interface (Fig. 5).

Participants of both groups performed one task consisting of moving an object through the maze to virtually "touch" three doors of different colors in the indicated order—red, green and blue—(Fig. 6) with a simulated proxy weight of 100 gr. While moving the object through the labyrinth, if the participant collides the avatar with any wall, he gets auditory, visual and haptic feedback. We formulated the following hypotheses:

H1. The task execution time of healthy adults is shorter than the task execution time of elderly with motor impairments.
H2. The number of collisions detected for healthy adults is smaller than the number of detected collisions for elderly with motor impairments.

5.3 Evaluation Results

The exercises were evaluated using objective performance data from the virtual environment, namely, the task execution time (efficiency) and the number of collisions detected with the virtual walls (precision of movement or accuracy). Table 4 presents a summary of the scores obtained by each participant.

We analyzed the results of the therapy effectiveness in terms of performance of both groups (see Table 5). As can be seen in Table 5, we found no significant difference in task execution time between healthy adults and elders with hand motor impairments (H1), we found significant difference in precision of the exercise (H2). These results confirms the importance of provide adaptability in the exercise. The balance between exercise and challenge should be appropriate to

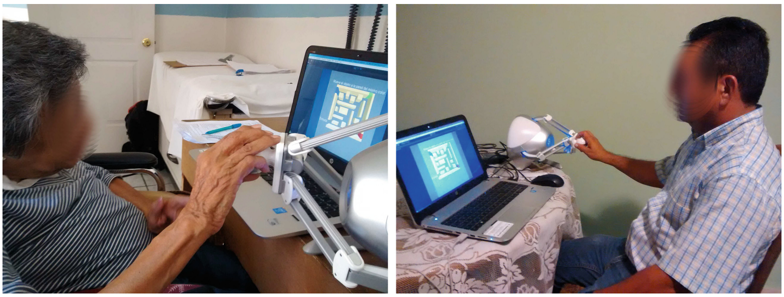

Fig. 5. Participants conducting the exercise with the Novint Falcon haptic interface during the therapy effectiveness evaluation of design principles: (a) elder with motor impairment, (b) adult with no motor impairment.

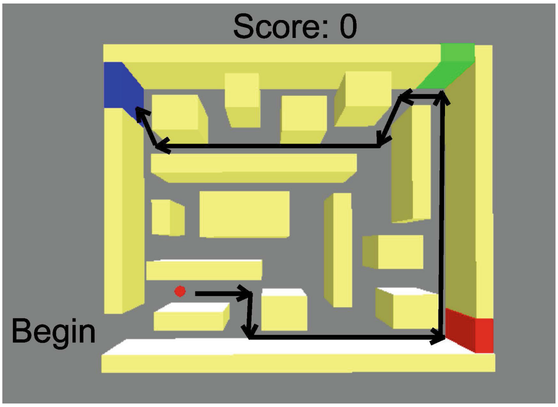

Fig. 6. Exercise in the haptic maze. The ideal trajectory motion is depicted in black. The proxy (red dot) changes its color to indicate the wall color that the user has to touch in the indicated order (red, green and blue) (Color figure online).

Table 4. Evaluation results of the exercise in terms of task execution time and number of collisions. G1: group of healthy adults, G2: group of elderly with hand motor impairments. SD: Standard Deviation.

Participant	Outcome			
	Time (sec)		Number of collisions	
	G1 (SD = 23.63)	G2 (SD = 28.93)	G1 (SD=15.63)	G2 (SD = 12.56)
1	46.13	74.74	14	51
2	51.35	109.74	15	21
3	31.12	57.68	13	21
4	43.87	84.48	19	36
5	44.03	58.39	13	34
6	94.37	79.57	19	17
7	64.41	47.37	22	30
8	26.94	27.26	18	13
9	33.88	46.33	8	14
10	69.34	89.51	18	33
11	110.24	130.48	76	55
12	35.32	52.13	8	25
13	26.47	44.74	16	21
14	46.32	84.56	13	26
15	38.30	21.25	16	11

Table 5. Summary of Kruskal-Wallis and Nemenyi test [41] on H1 and H2 hypotheses.

Critical value	Statistical value	Significance of difference
H1		
Kruskal-Wallis test (alpha = .1, 1 degree of freedom)		
2.706	3.561	Significant
Nemenyi test (alpha = .025)		
3.17	2.668	Not significant
H2		
Kruskal-Wallis test (alpha = .025, 1 degree of freedom)		
5.024	5.160	Significant
Nemenyi test (alpha = .025)		
3.17	3.387	Significant

ensure a successful and effective therapy. In addition, it is important that the selection of exercises and level of challenge be a simple task for both therapists and patients. Moreover, it is important to gradually modify the difficulty level of the exercise to out ongoing progress. This can be done either automatically by means of a decision algorithm or manually with the help of a therapist during the execution of the exercise [36]. For instance, the properties of the virtual objects within the hapto-virtual rehabilitation environment such as weight, size and quantity, among others, can be adjusted during the exercise to ensure an appropriate level of force and range of movements, while providing and adequate level of challenge and engagement to the patient.

6 Discussion

The results of the conducted formative evaluation allowed, on the one hand for gathering preliminary evidence towards the perception of participants about the usefulness, ease of use and intention of use of the developed environment, and on the other hand for obtaining a refined version of the principles for the design of haptic virtual environments for fine motor hand rehabilitation.

Regarding participants' perceptions, although this perception was high on usefulness and intention of use for both patients and therapists, this was not the case for ease of use. In the latter case, therapists perceived it high, but patients were neutral about it. This could be due to the challenge imposed to patients by the indirect manipulation required to interact with/through the haptic device. In this sense, it is necessary to further investigate principles to balance this challenge, to try to increase the patient's ease-of-use perception. Concerning the design principles, these aim at achieving *therapy effectiveness* and *patient's safety*. Although other research works have proposed similar principles for therapy effectiveness (e.g. [38] considers principles about goal-based movements, ludic activity based motivation, and patient's performance), our proposal includes principles regarding accessing patient's information according to the specialist's role for decision making, and the appropriate selection of the haptic interface according to the movement to be enhanced. To the best of our knowledge, none of these principles have been included in previous efforts. Additionally, and also to the best of our knowledge, no other proposal have considered the inclusion of design principles for patient's safety, such as the importance of having a simple mechanism for stopping the haptic device in case of failure.

Moreover, the results from the second study allowed us firstly, to further scrutinize therapy effectiveness based on performance, and secondly, to iterate the preliminary design principles. Although we found no significant difference in task execution time between healthy adults and elders with hand motor impairments, we found significant difference in precision of the exercise. These results suggests that the elderly, having visual and hand motor disabilities, find more motivating finishing the task rather than completing the exercise with accuracy. It is worth mention that only 2 of the 15 elders had experience on the use of the computer, compared to 7 from 15 of the healthy adults. In addition, the auditory feedback enhanced the user experience of participants with visual disabilities from both groups. We also found that 80 % of participants were interested in comparing their performance with that of the others. This suggest the inclusion of elements in the virtual environment that promote motivation and engagement such as different kinds and level of challenges, and incentives.

7 Conclusions and Future Work

We have reported the evaluation results of a preliminary set of principles for the design of hapto-virtual rehabilitation environments for fine motor hand therapy, with an emphasis on effectiveness of the therapy. With this we aim at supporting developers to facilitate their understanding of key principles to include in the design of hapto-virtual rehabilitation environments for upper limb rehabilitation. Our main findings suggest that although the elements introduced through the principles (e.g. the inclusion of haptic force feedback) are well appreciated by both the patients and the therapists regarding usefulness and intention of use, additional work should be conducted to overcome some of the challenges introduced by them regarding ease of use (e.g. the use of a haptic device to provide force feedback introduces indirect manipulation, which imposes an additional challenge to patients, whom need to "map" their movements in the physical to the actions on the objects in the virtual environment). In addition, the results from the evaluation of the effectiveness in terms of performance, suggest the importance of the design principles and the identification of new ones such as sharing information among participants to increase motivation. So far we have not evaluated the safety design principles. Nevertheless, it is important to take into account the maximum range of motion and strength of the hand, according to the participant assessment. We believe that the principles may reduce development times, and increase chances of therapeutic validity of hapto-virtual rehabilitation environments in terms of therapy effectiveness and patient's safety.

Further studies are needed not only to iterate and evaluate the safety design principles, but also to evaluate the design principles impact from the clinical point of view.

Acknowledgments. The authors would like to thank the specialists and patients from "Centro Integral de Rehabilitación", and the elderly from "Casa Hogar de Anciano" and "Casa del Abuelo" in Ensenada, Baja California, México, for their valuable support and participation in this research work. We are also grateful to undergraduate students who have participated in the development of the haptic maze application.

References

1. Blender. http://www.blender.org. Accessed 15 Aug 2014
2. Novint Falcon. http://www.novint.com. Accessed 15 Aug 2014
3. Unity game engine. http://unity3d.com. Accessed 15 Aug 2014
4. Alankus, G., Lazar, A., May, M., Kelleher, C.: Towards customizable games for stroke rehabilitation. In: Proceedings of the 28th International Conference on Human Factors in Computing Systems - CHI 2010, pp. 2113–2122, no. 2113 (2010)
5. Annema, J., Verstraete, M., Abeele, V., Desmet, S., Geerts, D., Leuven, I.: Videogames in therapy: a therapist's perspective. In: International Conference on Fun and Games, pp. 94–98 (2010)
6. Boulanger, C., Boulanger, A., de Greef, L., Kearney, A., Sobel, K., Transue, R., Sweedyk, Z., Dietz, P., Bathiche, S.: Stroke rehabilitation with a sensing surface. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems-CHI 2013, pp. 1243–1246. ACM Press (2013)
7. Burke, J., McNeill, M., Charles, D., Morrow, P., Crosbie, J., McDonough, S.: Optimising engagement for stroke rehabilitation using serious games. Vis. Comput. **25**(12), 1085–1099 (2009)
8. Chen, Y., Lehrer, N., Sundaram, H., Rikakis, T.: Adaptive mixed reality stroke rehabilitation: system architecture and evaluation metrics. In: Proceedings of the First Annual ACM SIGMM Conference on Multimedia Systems, pp. 293–304 (2010)
9. Corbin, J., Strauss, A.: Grounded theory research: procedures, canons, and evaluative criteria. Qual. Sociol. **13**(1), 3–21 (1990)
10. Davis, F.: Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Q. **13**(3), 319–340 (1989)
11. Dix, A., Finlay, J., Abowd, G., Beale, R.: Human-Computer Interaction, 3rd edn. Pearson/Prentice-Hall, Harlow (2004)
12. Dovat, L., Lambercy, O., Ruffieux, Y., Chapuis, D., Gassert, R., Bleuler, H., Teo, C., Burdet, E.: A haptic knob for rehabilitation of stroke patients. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 977–982, October 2006
13. Flores, E., Tobon, G., Cavallaro, E., Cavallaro, F., Perry, J., Keller, T.: Improving patient motivation in game development for motor deficit rehabilitation. In: International Conference on Advances in Computer, pp. 381–384 (2008)
14. Henderson, A., Korner-Bitensky, N., Levin, M.: Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. Top. Stroke Rehabil. **14**(2), 52–61 (2007)

15. Holden, M., Dyar, T.: Virtual environment training-a new tool for neurorehabilitation. Neurol. Rep. **26**(2), 62–71 (2002)
16. Ines, D., Abdelkader, G.: Mixed reality serious games: the therapist perspective. In: International Conference on Serious Games and Applications for Health, pp. 1–10, no. V (2011)
17. Jones, C.: Design Methods. Wiley, New York (1982)
18. Jung, Y., Yeh, S., Stewart, J.: Tailoring virtual reality technology for stroke rehabilitation: a human factors design. In: Computer Human Interaction, pp. 929–934 (2006)
19. Kaber, D., Zhang, T.: Human factors in virtual reality system design for mobility and haptic task performance. Rev. Hum. Factors Ergon. **7**(1), 323–366 (2011)
20. Kayyalil, R., Shirmohammadil, S., Saddik, A., Lemaire, E.: Daily-life exercises for haptic motor rehabilitation. In: IEEE International Workshop on Haptic Audio Visual Environments and their Applications, pp. 12–14, no. October (2007)
21. Kleim, J., Jones, T.: Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. J. Speech Lang. Hear. Res. JSLHR **51**(1), S225–S239 (2008)
22. Lewis, G., Woods, C., Rosie, J., McPherson, K.: Virtual reality games for rehabilitation: perspectives from the users and new directions. In: 2011 International Conference on Virtual Rehabilitation, pp. 1–2. IEEE, June 2011
23. Li, Y., Kaber, D., Tupler, L., Lee, Y.: Haptic-based virtual environment design and modeling of motor skill assessment for brain injury patients rehabilitation. Comput.-Aided Des. Appl. **8**(2), 149–162 (2011)
24. Mali, U., Goljar, N., Munih, M.: Application of haptic interface for finger exercise. IEEE Trans. Neural Syst. Rehabil. Eng. **14**(3), 352–360 (2006)
25. McLaughlin, M., Rizzo, A., Jung, Y., Peng, W., Yeh, S., Zhu, W., USC/UT Consortium for Interdisciplinary Research: Haptics-enhanced virtual environments for stroke rehabilitation. In: Proceeding of IPSI (2005)
26. Moore, M., Wilhelms, J.: Collision detection and response for computer animation. Comput. Graph. **22**(4), 289–298 (1988)
27. Morán, A.L., Orihuela-Espina, F., Meza-Kubo, V., Grimaldo, A.I., Ramírez-Fernández, C., García-Canseco, E., Oropeza-Salas, J.M., Sucar, L.E.: Borrowing a virtual rehabilitation tool for the physical activation and cognitive stimulation of elders. In: Collazos, C., Liborio, A., Rusu, C. (eds.) CLIHC 2013. LNCS, vol. 8278, pp. 95–102. Springer, Heidelberg (2013)
28. Mullins, J., Mawson, C., Nahavandi, S.: Haptic handwriting aid for training and rehabilitation. In: IEEE International Conference on Systems, Man and Cybernetics, vol. 3, pp. 2690–2694. IEEE (2005)
29. Nielsen, J.: Usability Enginnering. Academic Press, Inc., Boston (1994)
30. Ramírez-Fernández, C., García-Canseco, E., Morán, A.L.: Towards a set of design principles for hapto-virtual rehabilitation environments: preliminary results in fine motor therapy. In: Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth 2014). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Oldenburg, 20 May 2014. http://dx.doi.org/10.4108/icst.pervasivehealth.2014.255359
31. Rogers, Y., Sharp, H., Preece, J.: Interaction Design: Beyond Human-Computer Interaction. Wiley, New York (2011)
32. Saddik, A.E.: Computer haptics (Chap. 5). In: Saddik, A.E., Orozco, M., Eid, M., Cha, J. (eds.) Haptics Technologies. Springer Series on Touch and Haptic Systems, pp. 105–143. Springer, Heidelberg (2011)

33. Saini, S., Rohaya, D., Rambli, A., Sulaiman, S., Zakaria, M.N., Rohkmah, S., Shukri, M., Iskandar, B.S.: A low-cost game framework for home-based stroke rehabilitation system. In: 2012 International Conference on Computer & Information Science (ICCIS), pp. 55–60 (2012)
34. Schultheis, M., Rizzo, A.: The application of virtual reality technology in rehabilitation. Rehabil. Psychol. **46**(3), 296–311 (2001)
35. Seo, K., Kim, J., Lee, J., Jang, S., Ryu, H.: Serious games for stroke patients: attending to clinical staff's voices. In: The 5th International Congress of International Association of Societies of Design Research, pp. 1–11 (2013)
36. Sucar, L., Orihuela-Espina, F., Velazquez, R., Reinkensmeyer, D., Leder, R., Hernandez-Franco, J.: Gesture therapy: an upper limb virtual reality-based motor rehabilitation platform. IEEE Trans. Neural Syst. Rehabil. Eng. **22**(3), 634–643 (2014)
37. Sveistrup, H.: Motor rehabilitation using virtual reality. J. Neuroeng. Rehabil. **1**(1), 1–8 (2004)
38. Timmermans, A., Seelen, H., Willmann, R., Kingma, H.: Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. J. Neuroeng. Rehabil. **6**(1), 1–18 (2009)
39. Woldag, H., Hummelsheim, H.: Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: a review. J. Neurol. **249**(5), 518–528 (2002)
40. Xu, Z., Yu, H., Yan, S.: Motor rehabilitation training after stroke using haptic handwriting and games. In: Proceedings of the 4th International Convention on Rehabilitation Engineering & Assistive Technology (2010)
41. Zar, J.H.: Biostatistical Analysis. Prentice Hall, New Jersey (2010)