ORIGINAL RESEARCH

Development and Usability Test of an Innovative Low-cost Rehabilitation Game for the Upper Extremities of Neurological Patients

Bernhard Riess; Veronika David; Matthias Scherer; Stefan Kotzian; Mathias Forjan

Abstract

In recent years, virtual reality (VR) became more and more important in rehabilitation of upper extremities after stroke or other neurological diseases. Commercial gaming consoles, like the Microsoft Kinect, have been rapidly adopted in clinical settings. This paper presents the development of a rehabilitation game for the upper extremities with the Microsoft Kinect v2 sensor by simulating everyday situations. By using the Microsoft Kinect v2 sensor, the positions of the patients' hands are tracked, which are further processed to emulate the movement of virtual hands in a virtual environment. A modified System Usability Scale (mSUS) was used to evaluate the usability of the rehabilitation game developed. Eleven stroke patients took part in a preliminary usability study where they had to complete the exercises of the presented rehabilitation game twice. The mSUS were filled by each patient and the standardized System Usability Scale by the supervising therapists. The rehabilitation game is implemented with two different exercises, where one is a pure training of the motoric functions where the task is to catch books falling out of a bookshelf. In contrast, the second exercise additionally trains the cognitive function of the patient as objects in a kitchen need to be moved and categorized by their names. The mean values of the mSUS filled out by the patients and SUS filled out by the therapists were 78.4 and 91.0, respectively. The results of the usability test show satisfying outcomes, as a SUS-score >68 indicates a good usability. These findings are confirmed by the patients' feedback as they were very enthusiastic about this virtual rehabilitation scenario. To further evaluate the system developed, a usability study with 30 participants will be conducted.

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Keywords: virtual reality, rehabilitation of upper extremities, neurological diseases, Microsoft Kinect, System Usability Scale, Low-cost.

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Introduction

Nowadays, Virtual Reality (VR) is a very popular and well-known term in connection with video games. In recent years, this technology has found its way to the medical and therapeutical field. Motion-based gaming devices such as Sony's PlayStation Move, Nintendo's Wiimote or Microsoft's Xbox Kinect have revolutionized game-player-interaction[1] and blur the boundaries between reality and game. All these devices give users the opportunity to control games by using their body movement instead of pressing the buttons of a handheld game controller.[1] This motion-based way of interaction has opened new doors to introduce serious games with virtual realities in clinical settings.

For approximately ten years researchers aim for user-friendly and playful exercises and physiotherapy games in order to increase the patient's therapy achievements.[1] VR systems allow users to interact with a three-dimensional computer-generated scenario, which can engage the mirror-neuron system.[2] Gaming systems and the related software, necessary for using the devices, are easily accessible and affordable. Further on, game developing software such as the Unity Game Engine, or Unreal Engine are mostly open source.

Stroke is a major cause of disability among all ages. The main aspect for recovering after stroke is neuronal plasticity, which gives other areas of the brain the opportunity to take over functions of the ischemic zone.[3] Here the severity of the functional and anatomical lesion determines how complex the reorganization must be.[3] Therefore, the maximization of the effect of functional reorganization and plasticity should be the main target for the rehabilitation after stroke.[3] Promotion of functional changes within surviving motoric networks is the aim of several therapy concepts and methods.[4–9] VR technologies form the basis for relatively novel tools in neurorehabilitation, enabling a flexible deployment of scenarios directing towards specific needs. Several VR systems with emphasis on hand and upper limb rehabilitation have been proposed for the therapy of motor deficits (see Lucca[10] and Holden[11] for reviews).[3]

However, the effectiveness of virtual environments in the therapy and rehabilitation of patients after stroke or other illnesses is already proven.[2,12] The possibility to create different systems fitting perfectly to the special requirements of a patient without limitations due to motoric or cognitive shortcomings increases the task-oriented attention and learning.[13] Other positive effects are an increase of the locomotive efficiency and effectiveness due to the external focus during an exercise.[14] The various systems[4–9,15,16] also give the therapists the opportunity to focus completely on the patient and the correct performance of movements with no need to lower the exercise's level of difficulty. By taking full account of these effects, the system always provides enough stimuli to the brain to achieve the patient's personal therapy goal within their stay at the rehabilitation centre.

In respect of the advantages of these virtual environments, this paper presents the development and usability test of a low-cost rehabilitation game for the upper extremities for neurological patients with the Microsoft Kinect v2 sensor by simulating real-life situations in the living area.

Methods

For the development of the virtual rehabilitation game the requirements were defined with the therapists from the Neurological Rehabilitation Centre Rosenhügel (NRZ Rosenhügel). The therapists' experiences with existing VR rehabilitation games show, that these games or exercises are often not adaptable to the individual needs and abilities of the patients, which can change from day to day. Thus, the difficulty of existing rehabilitation exercises is too high, and the patient gets frustrated or demotivated. Therefore, it is important that the virtual reality game is individualizable to the abilities of the patient. Some patients are e.g. not allowed to bow down due to their type of restriction or cannot interact with the system bilaterally, as the motoric functions of one half of the body are limited after stroke. The requirements, which arose out of these needs are:

- A selectable and restrictable area of interaction, e.g. choosing between the left or right half of the monitor
- Different interaction modes (interaction possible with one or both hands)
- Individual calibration for each patient
- Different levels of difficulty

With these individual settings, the exercises should be adjustable to the daily condition and the rehabilitation progress of the patients. The game itself was implemented in C# and UnityScript and as user interface the Microsoft Kinect v2 sensor was chosen.

Kinect v2 Sensor Specifications

The Microsoft Kinect v2 sensor, originally developed for video game interaction, is a motion capturing device based on a RGB camera, an infrared emitter and an infrared depth sensor supporting time-of-flight ranging. Thus, it enables building a high-resolution depth image of 512 × 424 pixels with 30 frames per second. The price of approximately 100 EUR makes it attractive for low-budget applications in different fields ranging from robotics to the medical field. In contrast, state-of-the-art time-of-flight cameras and other devices having these functions are much more expensive.[17]

Development of the Virtual Reality rehabilitation system

The design of the rehabilitation game was realised with the Unity Game Engine 5.3.5f1, while the code was written in C#. The 3D objects within the exercises were made by using Autodesk Inventor Professional 2016 Build 138 and Autodesk 3ds Max 2016. With the Kinect sensor and the Software Development Kit provided by Microsoft (Kinect for Windows SDK 2.0), it is possible to detect every object with human proportions in front of the Kinect sensor and to create 3D coordinates of each of the 25 predefined determinable joints automatically. For this system, only the coordinates of the left and right hand joints are used. Within the exercises implemented, two 3D hands are the

Table 1. Standardized questions of the System Usability Scale (SUS), developed by J. Brooke[18]

1	I think that I would like to use this system frequently.
2	I found the system unnecessarily complex.
3	I thought the system was easy to use.
4	I think that I would need the support of a technical person to be able to use this system.
5	I found the various functions in this system were well integrated.
6	I thought there was too much inconsistency in this system.
7	I would imagine that most people would learn to use this system very quickly.
8	I found the system very cumbersome to use.
9	I felt very confident using the system.
10	I needed to learn a lot of things before I could get going with this system.

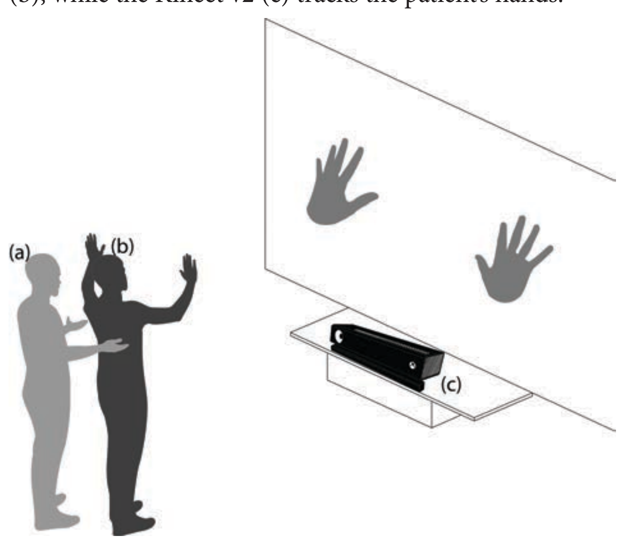
Table 2. Questions of the modified System Usability Scale (mSUS), based on Cameirão et al.[3]

1	I think that I would like to use this system frequently.
2	I think that I would need the support of a technical person to be able to use this system.
3	I would imagine that most people would learn to use this system very quickly.
4	I felt very confident using the system.
5	I needed to learn a lot of things before I could get going with this system.
6	The task was entertaining.
7	The task was too long.
8	The task was easy to understand.
9	It was difficult to control the virtual hands.
10	I would like to continue this treatment.

Formula 1. Formula for the SUS-score resulting in a value between 0 and 100.

$$SUS = 2.5 \times \sum_{i=1}^{10} \left((\text{Points } Q_{(2\times i-1)} - 1) + (5 - \text{Points } Q_{(2\times i)}) \right)$$

Figure 1. Basic set-up of the therapeutic unit. The therapist (a) can supervise the movement of the patient (b), while the Kinect v2 (c) tracks the patient's hands.



main control elements. The position of these hands changes with the coordinates of the hand joints. The virtual hands are used to interact with the virtual objects like books in a virtual bookshelf or different food in a virtual kitchen.

Usability Test Procedure

Over one week eleven stroke patients (9 male, 2 female) performed the exercises of the rehabilitation game at least twice. The subjects' average age was 58 years, including one 15-year-old male. Without the 15-year-old subject the average age was 62 years. After the second trial, they gave feedback by filling out a modified system usability scale (mSUS) questionnaire. The questionnaire for the patients had to be modified, based on Cameirão et al[3] due to the feedback of the therapists, which determines that some questions are not answerable by the patients because of the therapy procedure, where only the therapists operate the program on the computer.

Five questions had to be changed. The questions "I found the system unnecessarily complex.", "I thought the system was easy to use.", "I found the various functions in this system were well integrated.", "I thought there was too much inconsistency in this system." and "I found the system very cumbersome to use." were replaced by "The task was entertaining.", "The task was too long.", "The task was easy to understand.", "It was difficult to control the virtual hands." and "I would like to continue this treatment." (Table 2). The five supervising therapists filled out a standardized system usability scale (SUS) questionnaire, listed in Table 1.[18]

The SUS score is calculated by means of a specific formula (Formula 1). The value of each odd question (positive formulated) is subtracted by one, while the values of the even questions (negative formulated) are subtracted from 5. Finally, these new values are summarized and then multiplied by 2.5 to obtain a value between 0 and 100. Zero represents low, while 100 represents high usability. This formula is modified for the patient questionnaires to enable the calculation of the mSUS, due to the imbalance between positively and negatively formulated questions. Therefore, the part of the formula for one even question is replaced by the part for an odd question.[18]

Results

The virtual rehabilitation game is implemented with two different exercises with 10 levels of difficulty as well as with two different mode of use – a training and a comparison mode. One exercise is a pure training of the motoric functions, whereas the second exercise additionally trains the cognitive function of the patient. In a preliminary usability study eleven patients and five therapists filled out the mSUS or SUS questionnaire, respectively.

Figure 2. Home screen to enable the change of the exercise properties. Here the area (a), where the objects get activated, and which hand (b) is active during the exercise can be changed. The level of difficulty (c) has a value between one (easy) and ten (hard). The Button (d) closes the program. In field (e) the name of the patient and in field (f) the time for the exercise in seconds has to be entered. Via clicking the button (f) the selection of the two exercises appears below it. In the section (h) it is possible to switch between the compare and the training mode. Checkbox (i) activates the manual calibration. Button (j) creates the documentation file only for the name entered, while button (k) starts the exercise.

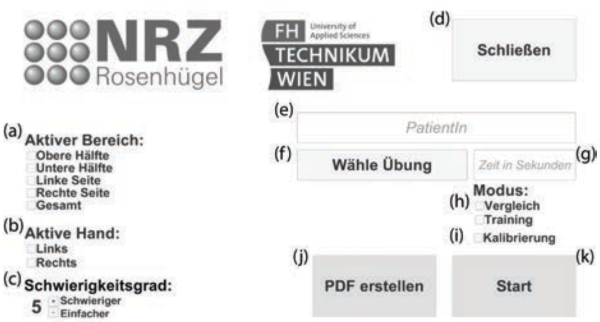


Figure 3. Calibration for the optimal usability of the exercises for each patient. Buttons (a-d) to capture the patient's maxima in each direction. The Button (e) enables the return to the home screen.

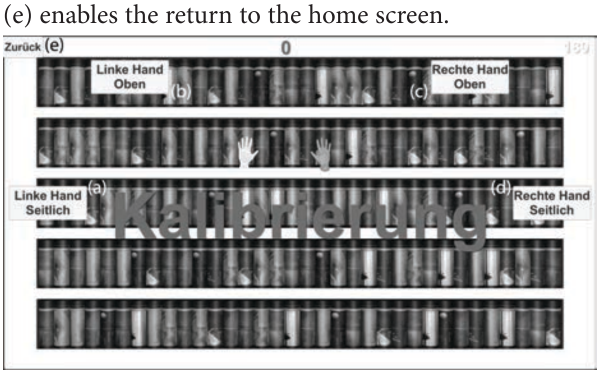
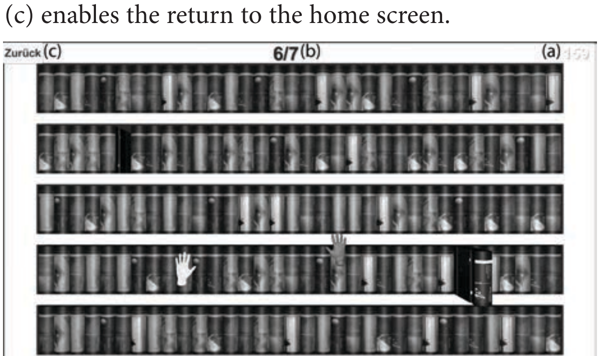


Figure 4. Exercise one ('BookShelf') for training the patient's upper extremities. In the upper right corner the remaining time in seconds (a), while in the upper center the number of books caught related to the total number of books activated (b) is displayed. The Button (c) enables the return to the home screen.



The Virtual Reality System

The realization of an easy to use and low cost rehabilitation system was done by using the Microsoft Kinect v2 to track the hands of the patient, which enabled the interaction with the system (Figure 1).

With the start of the program the home screen (Figure 2) is the first screen of the system, where the different properties of the exercises can be defined by the therapist before the exercise starts. Two different exercises were designed. Both exercises have a time limit and the area, where objects get activated, can be changed. It is also possible to choose which hand should be available within the exercise and how difficult the exercise should be. A level of difficulty of one represents easy, while ten represents hard. Two modes, the compare and the training mode, are implemented. Within the training mode the objects for interaction are chosen at random, while in the compare mode the objects are chosen randomly the first time and afterwards saved on the hard disk. When the patient enters the compare mode again, the objects saved are loaded to check if now more points can be achieved than previously. Each patient has a documentation file where each single exercise performed is logged with date, number of objects caught and activated, available time, name of the exercise, calibration factors, level of difficulty, active areas and hands used.

When the patient uses the system for the first time, a calibration (Figure 3) is performed. Therefore, the patient moves his left and right hand as far as possible to the edges of the screen. The calculation of the calibration factors is done by dividing the patient's personal maximum by the real width/height of the screen. This factor is used to adapt the actual coordinates of the patient's hands during the exercise. In the case of a bad calibration it is possible to repeat it anytime by selecting the checkbox on the home screen.

Exercise one enables the training of the upper extremities, while exercise two additionally provides the training of the patients' cognitive system. In exercise one (Figure 4) the task is to catch books falling out of a bookshelf. Books caught move back to their original position, while books dropped disappear. The second exercise (Figure 5) represents a kitchen environment, divided in different sections and filled with appropriate objects. On the bottom of the screen the system displays the name of an object, which has to be grabbed and moved to a specific area before a defined time has elapsed. The number of objects correctly handled is displayed on the top center of the screen within both exercises and saved after finishing to show the progress of the patient's rehabilitation. In exercise one, a higher level of difficulty makes the books move faster, while in exercise two the timeframe for grabbing an object gets shorter.

Usability test

The results of the modified patient questionnaires are shown in Table 3, while the results of the standardized therapist questionnaires can be seen in Table 4. The mean value of the calculated mSUS of the patient questionnaires is 78.4 with a standard deviation of 11.1. The calculated SUS of the therapist questionnaires is 91.0 on average with a standard deviation of 4.9.

Discussion

With the use of the Microsoft Kinect and open source software platforms, a low-cost and mobile rehabilitation system for the upper extremities has been developed. The requirements defined for the rehabilitation exercises are all met. With the possibility to restrict the area of interaction, the therapists could define the type of movement the patient had to perform. By the selection of the interaction mode with one hand, the training of the weaker body side could be intensified. The ten levels of difficulty enable an adjustment of the exercises to the progress of the patient's health status. Furthermore, the individual calibration enables the adaption of the virtual hands' positioning to ensure that each edge of the screen is reachable for the user. Thus, the exercises are highly adaptable to the individual needs and abilities of one patient.

The results of the therapists' usability test confirm an easy and intuitive use of the system developed. The possibility to stand behind the patient without causing detection errors made it possible to secure the patient during the exercise. In doing so, they could focus on the patient and the correct movement too. However, for further improvement of the system, the use of supporting equipment, such as a framework with weights for reducing the force needed to lift an arm, could be implemented.

In regard of the results of the patients' usability test, the system shows a good acceptability. The patients were pleased about the variety in their therapy schedule and often surprised how quickly the time passed during the therapy. As real-life situations were chosen for the implementation, the patients knew after the first description what they had to do within the exercises. Especially in exercise two they were able to identify the desired object intuitively.

The lower mean value of the mSUS and higher standard deviation compared to the SUS of the therapists stem from some uncertainty about the meaning of the questions. The therapists often had to explain what is meant with the question. The age difference between patients and therapists and the accompanying technical understanding could also have had a negative influence on the results. There were more than twice as many patients than therapists who filled out the questionnaire which additionally changed the result. Nevertheless, the SUS of the system presented had a value of 91.0 in average, while the mean value of the mSUS was 78.4. A SUS greater than 68 signifies good usability while a score under 68 signifies

Figure 5. Exercise two ('Kitchen') for training the patient's upper extremities and cognitive skills. In the bottom center the name of the target object (a) is shown. In the upper right corner the remaining time in seconds (b), while in the upper center the number of correct objects moved related to the total number of objects activated (c) is displayed. The Button (d) enables the return to the home screen.

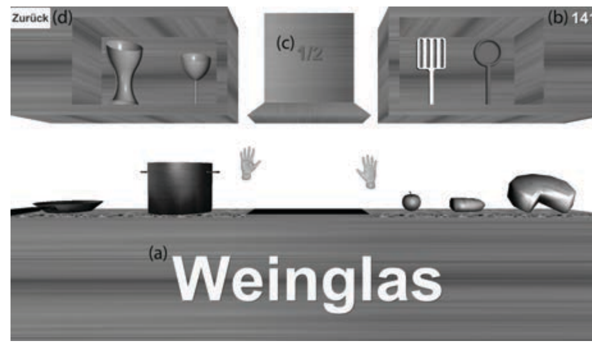


Table 3. Results of the modified SUS questionnaire, filled out by the eleven patients

	mSUS-Questions										
Patients-ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**mSUS Score**
1	5	3	4	5	4	5	4	5	4	5	**70.0**
2	4	3	4	5	3	4	2	5	2	4	**75.0**
3	4	2	4	5	2	4	1	5	1	5	**87.5**
4	5	5	5	5	5	5	1	5	5	5	**70.0**
5	5	3	2	1	2	5	1	5	3	5	**70.0**
6	5	5	4	5	1	5	1	5	1	5	**87.5**
7	5	1	5	5	3	5	1	5	1	5	**95.0**
8	4	1	2	4	4	5	1	1	4	5	**62.5**
9	3	1	5	5	1	3	1	5	1	5	**90.0**
10	5	5	5	5	1	5	1	5	1	5	**90.0**
11	2	1	5	4	1	2	4	5	1	1	**65.0**
											78.4 ± 11.1

Table 4. Results of the standardized SUS questionnaire, filled out by the therapists

	SUS-Questions										
Therapist-ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**SUS Score**
1	4	1	4	1	4	2	4	1	5	1	**87.5**
2	5	1	4	2	4	1	5	1	4	2	**87.5**
3	5	1	4	1	4	2	5	1	4	2	**87.5**
4	5	1	5	2	5	1	5	2	5	2	**92.5**
5	5	1	5	1	5	1	5	1	5	1	**100.0**
											91.0± 4.9

various problems of a system.[18] Both values obtained in the study show that the system has a usability from nearly perfect to good. These results are also attributable to the input of the expertise of the therapists at the NRZ Rosenhügel. They already worked with other Virtual Reality systems and contributed their experiences to the design process of this rehabilitation system.

As a next step, a usability study with 30 participants at the NRZ Rosenhügel will be conducted for further evaluation of the system. The participants are going to perform the exercises, which will be improved according to the experiences and feedback gained. The participants will fill out the standardized SUS questionnaire, which enables the calculation of the standardized Score and therefore a better comparability with literature.

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Author Disclosure Statement

The authors declare that they have no conflicts of interest in the research.

References

1. Sooklal S, Mohan P, Teelucksingh S. Using The Kinect For Detecting Tremors: Challenges And Opportunities. In: IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI). 2014, p. 768–71.
2. Saposnik G, Teasell R, Mamdani M, Hall J, McIlroy W, Cheung D, et al. Effectiveness of Virtual Reality Using Wii Gaming Technology in Stroke Rehabilitation. *Stroke J Cereb Circ*. 2010;41(7):1477–1484.
3. Cameirão MS, Badia SBI, Oller ED, Verschure PFMJ. Neurorehabilitation using the virtual reality based Rehabilitation Gaming System: methodology, design, psychometrics, usability and validation. *J Neuroengineering Rehabil*. 2010;7:48.
4. Kwakkel G, van Peppen R, Wagenaar RC, Wood Dauphinee S, Richards C, Ashburn A, et al. Effects of augmented exercise therapy time after stroke: a meta-analysis. *Stroke*. 2004;35(11):2529–2539.
5. Karni A, Meyer G, Jezzard P, Adams MM, Turner R, Ungerleider LG. Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature*. 1995;377(6545):155–158.
6. Ertelt D, Small S, Solodkin A, Dettmers C, McNamara A, Binkofski F, et al. Action observation has a positive impact on rehabilitation of motor deficits after stroke. *NeuroImage*. 2007;36(Suppl 2):T164-173.
7. Cirstea MC, Levin MF. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabil Neural Repair*. 2007;21(5):398–411.
8. Blanton S, Wilsey H, Wolf SL. Constraint-induced movement therapy in stroke rehabilitation: perspectives on future clinical applications. *NeuroRehabilitation*. 2008;23(1):15–28.
9. Bhatt E, Nagpal A, Greer KH, Grunewald TK, Steele JL, Wiemiller JW, et al. Effect of finger tracking combined with electrical stimulation on brain reorganization and hand function in subjects with stroke. *Exp Brain Res*. 2007;182(4):435–47.
10. Lucca LF. Virtual reality and motor rehabilitation of the upper limb after stroke: a generation of progress? *J Rehabil Med*. 2009;41(12):1003–1006.
11. Holden MK. Virtual environments for motor rehabilitation: review. *Cyberpsychology Behav Impact Internet Multimed Virtual Real Behav Soc*. 2005;8(3):187-211-219.
12. da Silva Cameirão M, Bermúdez I Badia S, Duarte E, Verschure PFMJ. Virtual reality based rehabilitation speeds up functional recovery of the upper extremities after stroke: a randomized controlled pilot study in the acute phase of stroke using the rehabilitation gaming system. *Restor Neurol Neurosci*. 2011;29(5):287–298.
13. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: a review of influential factors. *Med Educ*. 2010;44(1):75–84.
14. Wulf G, Landers M, Lewthwaite R, Töllner T. External focus instructions reduce postural instability in individuals with Parkinson disease. *Phys Ther*. 2009;89(2):162–168.
15. Paraskevopoulos I, Tsekleves E. Use of gaming sensors and customised exergames for parkinson's disease rehabilitation: A proposed virtual reality framework. 5th Int Conf On Games Virtual Worlds Serious Appl VS-GAMES 2013. 2013;1–5.
16. Lee JD, Hsieh CH, Lin TY. A Kinect-based Tai Chi exercises evaluation system for physical rehabilitation. In: 2014 IEEE International Conference on Consumer Electronics (ICCE). 2014. p. 177–8.
17. Butkiewicz T. Low-cost coastal mapping using Kinect v2 time-of-flight cameras. In: 2014 Oceans - St John's. 2014. p. 1–9.
18. Brooke J. SUS - *A quick and dirty usability scale*. Redhatch Consulting Ltd., 12 Beaconsfield Way, Earley; 1986 p. 1–7.