Low-cost virtual rehabilitation games: House of Quality to meet patient expectations

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***Abstract*—Patients' willingness to play is essential for rehabilitation games. This study (1) identified patients' general expectations for rehabilitation games; and (2) evaluated two newly developed low-cost rehabilitation games through surveys. Patients were found to expect low-cost systems (< $100), ease of use, interesting game contents, proven clinical efficiency, and access to rehabilitation games without prescription although welcoming therapists to follow their progress. House of quality analysis performed for the two developed rehabilitation games based on the patient expectations identified the need to improve reliability and precision of the low-cost hardware as well as to demonstrate clinical benefits.**

Keywords—virtual rehabilitation; games; Kinect; P5 Glove; usability; house of quality

I. INTRODUCTION

There has been accumulating evidence that stroke patients can recover with rehabilitation even more than one year after the incident [1]. Unfortunately, primarily due to the high cost of therapies, patients are not typically treated at the chronic stage. The emergence of virtual rehabilitation systems such as rehabilitation games that patients could use at home has the potential to prolong the treatment duration and thus enhance patients' recovery if at a reasonable cost [2][3]. Holden and Dyar described that motivation, repetition, and feedback constitute the three essential key elements of virtual rehabilitation systems [4]. They can be seen as directly derived from the three key principles of an effective neuro-rehabilitation process: patient motivation, therapy intensity, and patient engagement in the movements [5][6][7].

Among the three elements, the patient motivation is of particular interest since it can directly induce the other two elements (repetition/intensity and feedback): the more a patient is motivated to play a rehabilitation game, the more he/she will play to increase his/her practice time as well as feedback. In order to maximize patient motivation and interest in playing rehabilitation games, it is very important to know patients' expectations regarding virtual rehabilitation games. Games must meet these patient expectations to ensure that patients will extensively use them and be able to obtain functional recovery from them.

Toward this end, the first objective of this study was to identify stroke survivors' expectations regarding virtual reality games for rehabilitation. The second objective was to evaluate two newly developed low-cost rehabilitation games according to the patient expectations to identify critical improvements needed using a technique called House Of Quality (HOQ) [8]. For the first objective, patients' general expectations about rehabilitation games and their expected usage of such games were obtained through a questionnaire. For the second objective, we have developed two upper-limb rehabilitation games using commercially available low-cost motion capture systems. Patients evaluated the games through a second questionnaire after experiencing the games. In addition, a focus group discussion was performed to get more informal feedback and extend the discussion on the possible evolutions of the games.

In order to clearly define the development priorities of virtual rehabilitation systems, we built a HOQ based on the patients' expectations obtained in the first objective. The HOQ is part of the User-Centered Design technique and is commonly used in industry to identify product needs or improvement needs based on customer expectations. This technique has been used in similar fields such as design of a robotic device for upper-limb rehabilitation [9] at the research and development stage.

II. METHOD

A. Patients

Three patients who had a stroke more than two years ago participated. The patients had different functional levels. One patient had completely recovered her movement capacity whereas another had almost recovered her functionality with only minor limitations in the shoulder and elbow movements. The last patient had poor voluntary movement capability with little movement of the shoulder. The patients' characteristics are described in Table I. Two patients had already experienced video games for rehabilitation (Wii games). All three patients were currently using computer at least 30 minutes a week. This study protocol has been approved by the local ethics committee.

TABLE I. PATIENT DESCRIPTION

Age	Sex	Time after stroke (years)	Type	Upper Limb Fugl-Meyer (/66)
75	F	2.5	Ischemic	66
41	F	10	Hemorrhagic	65
71	M	5.5	Ischemic	19

B. Procedure

A single session study has been conducted with three stroke survivors. In the first part, patients were asked to identify their expectations for virtual rehabilitation games by filling out a questionnaire as described in section II.B.1. In the second part, two games that we have developed as described in section II.B.2 were evaluated by the patients as described in II.B.3. Patients played the two developed games for 30 minutes while the ease or difficulty of setting up the hardware and starting/playing the games was assessed by observing patients in attempting to use the games. After experiencing the two games, they were asked to evaluate the games through a second questionnaire. Lastly, a focus group has been held with all patients as described in II.B.4. In order to clearly define the development priorities for the two developed games, an HOQ was built as described in section II.B.5.

1) Patients' General Expectations on Rehabilitation Game Systems

For the first objective, the patients' expectations concerning rehabilitation games have been collected in the first questionnaire. Specifically, the patients were asked how much involvement of therapists they would like to have in their possible use of rehabilitation games through a series of four questions. Their preferences on the type of games (e.g., sport, puzzle, car racing, archery, activity of daily living) and movement focus (unilateral or bilateral, hand only or whole upper limb involvement) as they think suitable and motivating for a rehabilitation system were obtained through four more questions. The patients also answered whether they would use a virtual rehabilitation system at all if they had one at home. In addition, the expected frequency and time duration for playing games were obtained through four multi-choice questions. Finally, the amount of money the patients were willing to spend on a rehabilitation game system was assessed.

To enable quantitative analysis of HOQ, patients were asked to rate the importance of nine criteria on a Likert scale [10] from 1 (not important) to 5 (very important) as part of the first questionnaire. These ratings help identify the important criteria to increase patients' motivation in their use of rehabilitation games in the HOQ analysis. The nine criteria were: the system is easy to install; the system is easy to use; the game is interesting to play; the game is challenging; the game has fancy graphics; the game provides a score to keep me informed of my progress; the game provides a variety of scenes and activities; the game includes a clinical assessment; and the game has a proven clinical effect. Patients were also asked to add any additional criterion they think important.

2) Development of Low-Cost Upper-Limb Rehabilitation Games

The second objective of this study was to develop low-cost upper-limb rehabilitation games and assess them through patients' feedback. Two games were developed using two low-cost devices: a P5 Glove from Essential Reality, LLC (New York, USA; $59.99) able to track the hand position and orientation and each finger's bending, and a Kinect from Microsoft (Redmond, USA; $249.99) providing the posture of the upper limb.

a) Puzzle Game

The game presented in Fig. 1A is a puzzle game developed in C++ using Glut and OpenGl. The P5 Glove is used to get the hand position and orientation as well as the finger bending.

The player's goal is to complete the puzzle by moving each piece to the right location on the puzzle base. A direct mapping between the hand position and the grey circular cursor location allows the player to reach for different pieces or move a piece to different locations by moving his/her hand up/down and left/right. When the cursor is over a puzzle piece, the piece changes its color indicating to the player that the piece can be grabbed. Then the player can grab the piece by closing the fingers. After moving the piece to the right location and adjusting the piece orientation by rotating the forearm, the player can release the piece by opening the fingers. The game accepts that the piece has been correctly placed as long as it is within a certain tolerance for the position and orientation that is adjustable. A score reflecting the number of pieces correctly completed is provided to the player in the top left corner.

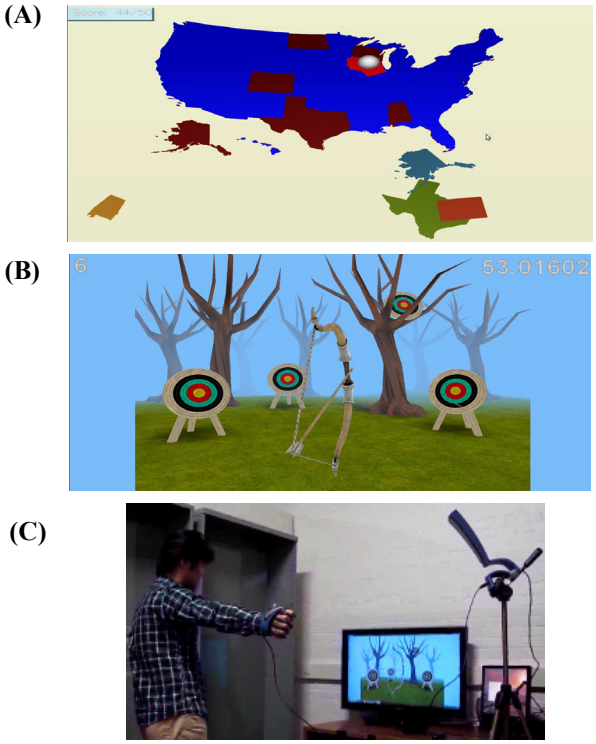

Figure 1. Screenshot of the puzzle game (A) and of the archery game (B) and a player using the P5 Glove and the Kinect (C).

This puzzle game requires four different upper limb movements. To move the pieces, the player has to move his/her hand left and right and up and down which recruits both shoulder and elbow movements. In order to rotate the pieces, the player has to pronate or supinate the forearm. Finally, the shoulder, elbow, and forearm movements have to be coordinated with the flexion/extension of the fingers.

In order to allow players with different movement capabilities to play the game while minimizing frustration, the puzzle game is adapted to each player's range of motion. Upon start of the game, the player's range of motion is assessed while the player is asked to move the hand as far as possible in four directions (up, down, right, and left). The real world hand positions obtained are mapped to the computer screen size. In addition, the player's range of motion for the finger extension/flexion is obtained to ensure that the player will be able to grab and release puzzle pieces within his/her finger movement capability.

b) Archery Game

The second proposed game, presented in Fig. 1B, is an archery game developed in Blender for 3D graphics and C# and Python for network programming and hardware interface. The 3D models were adapted from the Blender tutorial website. Additionally, a Kinect and the P5 Glove are interfaced with Blender to update the player's arm posture and fingers flexion/extension, respectively.

In this game, the player plays archery. The player controls the bow orientation – left/right and up/down – by controlling the hand position with respect to the shoulder position. The player flexes the fingers to draw the bow and opens the fingers to release it. Four targets exist in different locations, requiring the player to move the arm in a large workspace to orient the bow toward each target. A score regarding the number of arrows that hit the targets is displayed in the top left corner of the screen and the time elapsed since the beginning of the game is displayed in the top right corner of the screen.

This archery game requires the coordination of three movements. Shoulder and elbow movements are needed to orient the bow and aim at the target. The action of closing/opening the fingers is needed to draw the bow and shoot.

3) Game Testing and Evaluation

For the second objective aiming at evaluating the two developed games, the patients were asked to play the games and give their feedback. To evaluate usability of these rehabilitation games at home, the patients' ability to set up the hardware (the P5 Glove and the Kinect) and start the games by themselves without assistance by just following an instruction sheet was examined. Assistance to accomplish this task was provided if needed after five minutes to complete the set up and to ensure that the patients were able to play the games. Assistance was also provided to explain the rules of the games and help the patients understand the working of the P5 Glove and Kinect if needed. The patients played each of the two games for 10-15 minutes for a total of 30 minutes.

After experiencing the two games, the patients evaluated the two games by filling out the second questionnaire. For each game, the patients rated how much the game satisfied each of the nine criteria used in the first questionnaire on a Likert scale from 1 to 5. Since the three of the nine criteria (variety of scenes and activities, clinical assessment, and clinical efficiency) have not been taken into account in the development of the two games, the three criteria were not included in the questionnaire and automatically received 1 rating for the purpose of the HOQ analysis.

In addition, the patients' perception on the level of difficulty was obtained through a series of three questions. They addressed the game's general difficulty and the difficulty of the shoulder and elbow movements as well as the finger movements required to play. Finally, the patients' general appreciation and suggestions about the games were obtained through open-ended questions.

4) Focus Group

The second questionnaire was immediately followed by a focus group discussion that lasted approximately 45 minutes. All patients were asked to comment interactively on their game playing session regarding what they enjoyed, what they disliked, and what seemed to be the priority in the next developments. In addition, they revisited their general expectations on virtual rehabilitation game systems by making a link with their experience and needs through focus group discussion.

5) HOQ Construction to Prioritize Games' Technical Needs

The goal of the HOQ was to define improvement priorities among technical characteristics of the two developed games in order to effectively respond to the patients' expectations – generally called "customers requirements". To build the HOQ, first, the technical characteristics related to virtual rehabilitation game systems were identified from an engineering point-of-view. They are listed in Fig. 2 top row, "Technical characteristics": existence and quality of an installation manual; existence and quality of game instructions; device reliability; device precision in measuring the player's movements; gameplay, i.e., game rules, player interactions, and type of challenges; game adaptation to individual patients' functional level and possible use of Artificial Intelligence; multiple levels in the game; game realism in terms of graphics, sounds, and physics simulation when applied; presence and quality of 3D display; existence of a clinical assessment in the game; and existence of clinical studies.

Second, these technical characteristics are matched to the patients' expectations (Fig. 2 left column, "Patient expectations") through an interrelationship matrix. One patient expectation may depend on several technical characteristics and one technical characteristic may impact several patient expectations. The interrelationship matrix (**I**) is filled with a weight ($\mathbf{I}_{i,j}$) describing the relationship between a patient expectation (i) and a technical characteristic (j). The weights represent a strong, moderate, weak, or no relationship, as symbolized with ⍰, ○, ▲, and empty cell, with corresponding numerical values of *9, 3, 1*, and *0*, respectively. This interrelationship matrix constitutes the center of the HOQ presented in Fig. 2, and allows linking the technical characteristics (top row) to the patients' expectations (left

column). The patients' evaluation of each game per patient expectation is listed in Fig. 2 right column. The HOQ produces the output (Fig. 2 bottom rows), providing useful guidance for further game development priorities.

The total weight for each technical characteristic, T_j, independent of the game evaluation, is computed as follows:

$$T_j = \sum_{i=1}^{NbCriteria} W_i \times I_{i,j} \quad (1)$$

while W_i is the weight of the i^{th} criterion of the patient expectations and $I_{i,j}$ is the corresponding interrelationship value.

The development priority score, P_j, is then computed for each game as follows:

$$P_j = \sum_{i=1}^{NbCriteria} W_i \times I_{i,j} \times (5 - R_i) \quad (2)$$

with R_j as the patients' rating of the given criterion for each game (provided in Fig. 2 right column). The development priority scores for each technical characteristic and each game are listed at the bottom of the HOQ.

III. Results

A. Patients' General Expectations on Rehabilitation Game Systems

1) Patients' Expectations from the Questionnaire

Concerning the therapist involvement in rehabilitation games, none of the patients thought that a therapist should prescribe the rehabilitation games, but two of the three patients said they would welcome a therapist to track their usage and progress and give encouragement. As for the types of games, the patients ranked sport games the most motivating followed by racing and archery games, whereas puzzle games were ranked as the least motivating. Nevertheless the patients ranked puzzle games and activities of daily living such as kitchen and grocery simulations as the most suitable for rehabilitation games, and the sport and archery games as less suitable. Two patients expressed that games should focus on only the impaired hand and arm, whereas the other wanted use of hands and arms bilaterally.

All patients stated that they would use a virtual rehabilitation game system if they had one at home. Two patients said they would be willing to play rehabilitation games 3-5 times a week, 45-60 minutes at a time, while one patient said she would play 1-2 times a week, 20-30 minutes at a time. Two patients affirmed that they would likely buy a rehabilitation game system for a price ranging from $20 to $100, while the third patient was not interested in buying such a system.

The results of the patients' ratings for the importance of the nine criteria are presented in a descending order in Table II.

TABLE II. Patients' Expectations: Criteria Rating on a 1 to 5 Scale.

Criterion	Mean
Easy to install	5.00
Interesting	5.00
Challenging	5.00
Easy to use	4.67
Clinical assessment	4.67
Adaptation	4.33
Proven clinical effect	4.00
Progression score	3.67
Graphics quality	3.33
Variety	3.33

The patients expressed that the chosen criteria described their expectations well and they did not have any other criterion to add.

2) Patients' Expectations from the Focus Group

During the focus group discussion, the presence of progress measurement in rehabilitation games was cited as important. Considering the game contents, all patients mentioned that some games should be more directly related to activities of daily living, giving the example of the Wii cooking game. Finally, all patients appreciated the idea of possibly playing games with their relatives, and stated that it could be a really motivating aspect.

B. Evaluation of the Developed Games

1) System Set Up

All patients were able to accomplish most of the set up the system and run the games by themselves, following the provided instruction sheet. However, all patients needed some assistance, mostly to adjust the placement of the P5 and Kinect sensors to be in the capture range.

2) Criteria Rates

The patients' evaluation of the games indicates a good overall rating for the archery game (*3.7*) and an average overall rating for the puzzle game (*2.9*) as shown in Table III. Since one of the patients was not able to play the games at all due to his low movement capabilities, only two patients' evaluations were analyzed. The two low scores below three for the puzzle game were concerned with the progression score and adaptation. It was revealed from the second questionnaire and the focus group discussion that the technical imperfection of the calibration process for the puzzle game led to difficulty in playing the game. When the patient's hand wearing the P5 Glove moved out of the P5 Glove's capture range during the calibration, it generated too large a number for the hand position as error. Consequently, the game required too large movements for the patients to move the cursor across the screen and the patients were thus unable to move the pieces to the right locations. As a result, the patients reported big frustration for not being able to complete the puzzle game.

TABLE III. THE PATIENTS' EVALUATION OF THE GAMES FOR EACH CRITERION.

Criterion	Puzzle game	Archery game
Easy to install	3	3
Easy to understand	4	4
Graphics quality	3	4
Progression score	2	4
Interesting	3	4
Challenging	3	4
Adaptation	2	3
Average	**2.9**	**3.7**

3) HOQ Outcomes

The complete HOQ identified development priorities for each game as shown in the bottom rows of in Fig. 2, based on the patient expectations (Table II), patients' evaluation of each criterion for each game (Table III), and the interrelationship matrix. The technical characteristics with percent scores in red correspond to the highest priority (above 10%), followed by the orange (between 5% and 10%) and green (less than 5%). The top three development priorities for both games were: device precision, device reliability and clinical studies. Thus, these three technical characteristics appear to be of the greatest importance of all. The four following development priorities were: gameplay, game adaptation, the number of levels, and integration of clinical assessment. In summary, these technical characteristics were identified as essential to patients' motivation to play the games which is a key point in the use of virtual rehabilitation games.

4) Focus Group Highlights on the Developed Games

During the focus group discussion, one patient expressed frustration concerning the game testing session since he was not able to put on the P5 Glove and play the games due to his low movement capacities. He thus insisted on the importance of the adaptation of these systems to patients with different levels of recovery. The two other patients also expressed some frustration that the puzzle game was too hard to play due to the technical issues related to the calibration process. One patient enjoyed the archery game very much, because it was an activity he used to practice before stroke. Generally, all patients agreed that games requiring tasks that they were able to accomplish before their stroke are particularly attractive.

Technical characteristics / Patient expectations	Weight	Installation manual	Game instructions	Device reliability	Device precision	Gameplay	Game adaptation/AI	Number of levels	Game realism	3D display	Clinical assessment	Clinical studies	Puzzle game	Archery game
Criteria													Rating	
Easy to install	5,0	⊙											3	3
Easy to use	4,7		⊙			O							4	4
Adaptation	4,3			O	O								2	3
Interesting	5,0				▲	⊙		O	▲	O			3	4
Challenging	5,0			▲		⊙	⊙			O			3	4
Graphics quality	3,3								▲	O			3	4
Progression score	3,7						▲						2	4
Variety	3,3					O	O	⊙					1	1
Clinical assessment	4,7			⊙	⊙						⊙	⊙	1	1
Proven clinical effect	4,0			⊙	▲							⊙	1	1
	Total weight	45	42	96	64	114	59	45	8,3	40	42	78		
	Percentage	7,1	6,6	15	10	18	9,3	7,1	1,3	6,3	6,6	12		
Puzzle game	Priority weight	90	42	374	246	231	138	140	17	80	181	325		
	Percentage	4,8	2,3	20	13	12	7,4	7,5	0,9	4,3	9,7	17		
Archery game	Priority weight	90	42	343	215	144	88	134	8,3	40	168	312		
	Percentage	5,7	2,7	22	14	9,1	5,6	8,4	0,5	2,5	11	20		

⊙ Strong relationship
O Moderate relationsh
▲ Weak relationship

Figure 2. The complete House Of Quality for the two low-cost games provided development priorities (outcomes) at the bottom rows, based on the patient expectation ratings on the left column, games' technical characteristics on the top row, the interrelationship matrix in the center, and the patients' evaluations of the two games on the right column. Red, orange, and green numbers indicate the highest (>10%), intermediate (between 5% and 10%) and the lowest (<5%) development priorities for each game.

IV. DISCUSSION

A. Patients' General Expectations on Rehabilitation Game Systems

The patient expectations identified in this study are expected to guide future rehabilitation game developments including the choice of hardware used to interact with patients, game design, and game setup. Stroke survivors wanted access to virtual rehabilitation games without the need for prescription by clinicians, possibly speaking to their desire for freedom and worry for medical costs. However, the patients were open to therapists' involvement as to following the patient progression, helping with the game adaption, and encouraging the patients. The types of games the patients considered as the most motivating (sport and archery games) were considered as less suitable for rehabilitation purposes by them. On the other hand, the types of games they considered less motivating (puzzle games and activities of daily living such as kitchen and grocery simulations) were considered as the most suitable for rehabilitation games by them. Patients desired games using both the hand and arm either bilaterally or unilaterally (paretic only), suggesting that games should take into account coordinated multi-joint or multi-limb movements requiring both hand and arm movements, as in the two developed games. All patients were willing to use a virtual rehabilitation game system 1-5 times a week, 20-60 minutes at a time. Their preferred price range was $20 to $100, confirming the need for very low-cost systems. Patients preferred to have the ease to install and use the system, interesting game contents of the games, and proven clinical effects in rehabilitation games, as opposed to fancy graphics or game varieties. Thus, fancy 3D graphics or game appearances should not take too much development resource as they are seen less of a concern for patients.

B. Evaluation of the Low-Cost Upper-Limb Rehabilitation Games

The choice of the lowest possible motion capture devices (P5 Glove and Kinect) for developing rehabilitation games appears to be in the right direction, given the patients' preferred purchase price of rehabilitation game systems. In addition, usability of these devices, especially with the fact that patients were able to set up and start the game with little assistance, demonstrates the feasibility of low-cost rehabilitation games for home use and encourages future development.

The HOQ analysis identified the device reliability, device precision, and clinical studies as the most important areas to improve in further development of the two low-cost upper-limb rehabilitation games developed in the laboratory. Especially, the calibration issues were brought up by the patients. The reliability and precision of the low-cost motion capture devices (P5 Glove and Kinect) may be further improved by better calibration procedures, remedy for movements that are out of a capture volume, additional filtering, and better movement detection algorithms. In addition, the instruction manuals may be improved to provide patients with good understanding of how the motion capture volume works for the two devices, to ensure correct working of these devices as well as to minimize patients' frustration. Future studies should address these technical issues and examine clinical efficiency which has not been demonstrated yet with full randomized, blinded comparative studies for low-cost virtual rehabilitation systems in general.

The intermediate development priorities identified were gameplay, game adaptation, the number of levels, and integration of clinical assessment. Especially, adaptation to each patient's movement capabilities has been raised as a crucial point during the focus group discussion regarding the sense of frustration. It is well appreciated that rehabilitation games should be able to accommodate patients with a wide range of movement capabilities in order to provide opportunities to a great number of patients. Minimizing patients' frustration is also an important concern since motivation and psychological involvement have a great role in the recovery process. One possible way is to use several movement inputs to control a game for low functioning patients, as proposed in [11]. However, this idea bears the risk of patients not utilizing the most impaired joint or movement by compensating the task by using other joints or movements.

C. Limitations

The major limitation of this study is the small number of patients recruited. They were at different recovery stages, which allowed identification of various issues related to the game evaluations. Since a key factor for rehabilitation success is the patient motivation, it is crucial to take into account patients' expectations in addition to therapists and engineers' point of views. Thus, a study with more patients is needed to provide a more complete overview of patients' expectations.

The HOQ did not include all of the patients' expectations identified in the first objective, such as the estimated usage or the purchase price. However, HOQ analysis appeared to be a useful tool to highlight development priorities based on the included patient expectations. This tool can be used in further development stages as well as for other developers to help meet the customer expectations and increase the likelihood of success of rehabilitation game developments.

V. CONCLUSIONS

The two objectives of this study were: to get patients' expectations regarding virtual rehabilitation game systems and to evaluate two low-cost puzzle and archery games developed in the laboratory in order to identify the optimal directions for game improvement. The patients' expectations on rehabilitation game systems included ease to install and use, interesting game contents, and proven clinical effects as opposed to fancy graphics or variety of game contents. Patients also expressed their interest for therapists following their progress but without the need to have these games prescribed by therapists. Patients preferred very low-cost systems (less than $100) that they could easily use at home between one and five times a week for minimum 20 minutes per session. In order to have the two developed games accepted by patients, improvement of the motion capture devices' reliability and precision as well as demonstration of the clinical benefits were identified as most needed.

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