Skyfarer: Design Case Study of a Mixed Reality Rehabilitation Video Game

Marientina Gotsis[1], Vangelis Lympouridis[1], Phil Requejo[2], Lisa L. Haubert[2], Irina C. Poulos[1], Fotos Frangoudes[1], David Turpin[1], and Maryalice Jordan-Marsh[1]

[1] University of Southern California, Los Angeles, CA, USA
{gotsis,frangoud,jordanma}@usc.edu, vangelis@lympouridis.gr, irinacpoulos@me.com, dhturpin@gmail.com

[2] Rancho Los Amigos National Rehabilitation Center, Downey, CA, USA
requejo@usc.edu, lisalhaubert@gmail.com

Abstract. This paper outlines a design case study for *Skyfarer*, a mixed reality rehabilitation application developed for upper body exercise of individuals aging with disability. We describe how experience, experiential and participatory design methodologies were combined to develop a game, which was publicly exhibited at IEEE VR and ACM SIGGRAPH, and formally evaluated in a biomechanical study at Rancho Los Amigos National Rehabilitation Center RLANRC.

Keywords: Mixed reality, virtual reality, rehabilitation, games, experience design, experiential design, participatory design, spinal cord injury.

1 Background

Chronic shoulder pain is a common secondary condition in manual wheelchair users with spinal cord injury (SCI) and it affects up to 70% of the population [1]. This high prevalence of shoulder pain is related to the weight bearing demands on the arms from manual wheelchair propulsion, transfers, and pressure relief raises. Pain further limits mobility and participation, which negatively impacts quality of life [2]. The efficacy of a non-surgical approach has been documented in the first randomized clinical trial (STOMPS) for treating existing shoulder pain in persons with SCI [3]. STOMPS included stretching and resistance-based exercises with small periods of resting. This protocol was found effective in treating and preventing pain when participants exercised regularly. The study demonstrated marked reduction (71% decrease) in shoulder pain and improvements in health-related and overall subjective quality of life after a 12-week home-based shoulder exercise program combined with instruction. Barriers to sustainability of this program include lack of time, resources, lack of accessibility of facilities [4, 5] and tedium, therefore integrating the exercises into a game could improve long-term adherence. This paper documents development activities enabled through our aging center leading to the creation of our first generation mixed reality (MR) game for shoulder strengthening and endurance exercise [6].

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2 Design Methodology

Camera-based virtual reality has been used for over a decade in clinical settings, with low cost systems recently available in rehabilitation of stroke [7], traumatic brain injury [8], and cerebral palsy [9]. MR experiences have been designed for patients with stroke [10] using phenomenological approaches to action representation and computing [11] through feedback that is provided on performance of activity level parameters and categories, in addition to body function level parameters and categories [12]. MR has been recently used for rehabilitation in individuals with spinal cord injury [13, 14]. Many challenges exist in the design of compelling and effective user experiences with MR because evidence for correlating user experience outcomes, with design principles of multimodal feedback and clinical outcomes is sparse and heterogeneous [9, 13, 15–17].

Additional challenges for our team included a) managing needs for a dual role "user" because the system must satisfy the needs of both the "patient/client" user and "clinician/health professional/caregiver" user; b) managing rapid technology change; c) cost-balancing of software programming and art asset creation prior to establishing clinical efficacy or effectiveness. To address these challenges, we combined multiple methodologies and convened a diverse team of designers, computer scientists, physical therapists, artists, engineers, a nurse psychologist, a choreographer, an occupational therapist, biomechanists, an industrial designer, and a physiologist. We integrated paradigms of *Experience*, *Experiential* and *Participatory* design in order to address the key aspects involved in the development of interactive body-based applications: design of the experience itself, usability, and integrity testing of the experience by the final recipients, and reflection of the designers on the overall process during various stages of the design (Table 1).

Table 1. Cross-tabulation of evaluation processes with design methodologies. *Experience Design* concerns the perception of an experience from a theoretical design and philosophical perspectives [18, 19]. *Experiential Design* addresses the reflection of the design process itself from the designer's perspective [20, 21]. *Participatory Design* focuses on the involvement of the final recipients of an intervention into the design process [22, 23].

EVALUATION PROCESSES	DESIGN METHODOLOGIES		
	Experience	Experiential	Participatory
Movement protocol analysis	✔	✔	
Pattern discovery workshop		✔	✔
Focus group discussion			✔
Rapid prototyping	✔	✔	✔
Biomechanical study	✔		✔
Public playtesting		✔	✔

3 Case Study Presentation

3.1 Movement Protocol Analysis

The STOMPS handout with detailed exercise instructions and a graphical description of the protocol are given to patients with a set of Bodylastics® (Fig.1). The patients are encouraged to exercise three times a week in order to achieve reduction of their shoulder pain, but there is no evaluation of their performance other than clinical and psychosocial outcomes. The graphical material has not been evaluated for its pedagogical effectiveness and doing so formally was beyond the scope of our project. Internal team analysis confirmed that it was difficult to communicate the qualities of a gesture in two dimensions, even with the addition of drawings, since gesture is a four dimensional action. Rehabilitation movements, in particular, require fine motor-control adjustments and enhanced body awareness that is affected by the proprioceptive abilities of the individual. Moreover, every patient has a different level of disability and various degrees of upper-body control.

Methods. The first step toward design of a gesture-controlled interactive experience is to capture and analyze the expected movements within the context of the application. Both the quantity (e.g., number of repetitions) and the quality (e.g., trajectory, speed) of movements must be inventoried when working from an existing exercise protocol, such as STOMPS. The interaction designer (Lympouridis) and choreographer (Poulos) led this investigation with an extensive analysis of the movement rehabilitation protocol as it was provided to the patients/clients. This allowed the design team to gain insight and define a set of questions for the biomechanists and therapists, such as the range, velocity, and trajectory of each exercise, the position and alignment of the body, and the requirements for optimal performance. The next step was to visualize the expected motion data from optimally and sub-optimally performed *movement phrases* which were small, simple and complete motion units with a beginning, middle and end [24] (Fig.2).

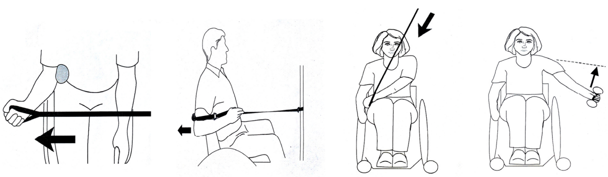

Fig. 1. STOMPS resistance-based exercises (excluding stretching): external rotation, rowing, diagonal pull, and diagonal lift (left to right)

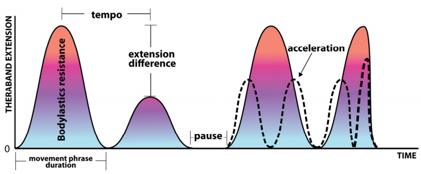

Fig. 2. Motion visualization of optimal (1st) and sub-optimal movement phrases (2nd, 3rd, 4th)

Finally, we assigned labels to describe the main characteristics of movement phrases, such as repetitive, palindromic, sinusoidal, or resistive and created a list of verbs that describe a characteristic action such as lifting, digging, walking, flying, reaching, and pulling. Overlap analysis revealed two categories of repetitive actions: a) movement phrases as increments of a longer action (e.g., pulling a bucket with a rope from the well, or reaching to a point in some steps), and b) movement phrases for short and complete actions (e.g., operating a switch, open and closing a door). We considered the exercise goal of the movements (strength vs. endurance). Poulos also helped the team explore how movement phrases could become *choreographic phrases* that convey feelings, images, ideas, or that present visual impressions, a story, a symbol, or design element [24].

3.2 Pattern Discovery Workshop and Focus Groups

Since the STOMPS home-based clinical trial did not evaluate quality or quantity of movements performed by the participants[1], the design team wanted to know how patients performed the movements. It was also important to identify compensatory actions, such as leaning and/or twisting of the back or joints. Moreover, in order to transition to a technology-enabled exercise system, the design team needed to observe how users performed the exercises to determine how much "teaching" and "guiding" was required in the interactive feedback system. To this end, Poulos drew on her expertise in movement pedagogy training and organized a pattern discovery workshop. In addition, the team collected data about the user population's prior gaming experiences drawing on the nurse psychologist's (Jordan-Marsh) expertise in promoting adherence.

Fig. 3. Pattern discovery workshop with participants performing external rotation exercise

Methods. We invited a subset of participants (N=7) who had already participated in the STOMPS clinical trial to come to RLANRC, demonstrate the STOMPS protocol exercises, and participate in a focus group discussion about their prior experience with

[1] It is important to note that however "good" or "bad" the participants performed the exercises at home, they performed them "good enough" to receive clinical benefits.

gaming. This half-day study was video recorded. Poulos conducted a pattern discovery workshop in order to assess participant range of motion, somatic awareness, and compensatory movements (Fig. 3). Gotsis (designer) introduced some prior experimental and commercial games via video, and invited participants to answer questions as part of a focus group. RLANRC therapists and technical staff were present and participated in the workshop and focus group. The age ranged from 23 to 50 years old (mean (M) = 39 years, standard deviation (SD) = 8.6). Six participants were male and one was female. Five males were Hispanic/Latino, two males were African/American and one female was Caucasian.

Outcomes. The pattern discovery workshop revealed that although participants had performed the exercises many times in the past, they did not remember them well enough to show them spontaneously to our team. Thus, the team demonstrated the movements and asked the physical therapists to issue corrections during subsequent participant performance of the exercises. The choreographer observed that participants lacked somatic awareness for key qualitative aspects of the movement, especially speed, smoothness, start and end points. Participants also lacked movement autonomy and self-correction automation, which was mostly visible by observing their overall distractibility and expectation of directions/corrections under supervision. In addition, the range of motion varied a great deal depending on a participant's injury level (paraplegia vs. tetraplegia). Deficits in fine motor skill and manual dexterity was a complicating factor for executing some of the movements that required manipulation of the Bodylastics. Gotsis then asked participants about the types of games they typically played, their motivations for playing, drawbacks of existing games and asked for comment on the appeal of an initial concept for boat/vessel navigation as part of an exercise game. Focus group discussion audio was transcribed and analyzed by the nurse psychologist.

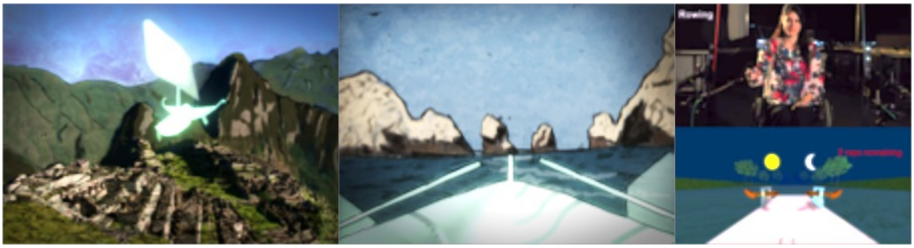

Fig. 4. Skyfarer storyboards for ship in flight (left), rowing exercise concept view (middle), and player performing rowing with temporary graphics (right) (Storyboards by Tristan Dyer)

Summary. An ideal system design would enable skipping exercises based on player ability and participant-specific calibration. The gaming experience of this group was fairly limited, but they were enthusiastic about adventure games. It is not clear to what extent gameplay experience was due to lack of awareness of game types, phrasing of questions, or anticipated inability to engage in a game because of physical limitations. Current popular casual games (e.g., Angry Birds) were not mentioned.

Quality of the graphics was not a criterion, nor was level of violence embedded in play. Participants noted that playing games changed moods, consumed time, and built satisfaction (mastery/achievement). Goals not mentioned included motivating new behaviors, gaining new knowledge, making decisions, or tracking any behaviors (such as exercise), moods, or relationships. Social interaction goals will require extensive exploration before integration into our game. No participant gave any clue that game play (type, duration, etc.) was a topic in health care intakes or interactions. These observations were taken into account as game design evolved.

3.3 Rapid Prototyping

At the core of our development process was rapid prototyping, which allows for immediate testing of ideas while prioritizing economy of resources. RLANRC designed a metal rig that was provided to the design team for attaching Bodylastics to perform the resistance exercises. The design team retrofitted the rig with GameTrak sensors and Kinect [25], which communicated with Max/MSP and later, with Unity3D game engine. The design team developed 30+ game concept prototypes using this system. Max/MSP offers the ability to design and modify complex programming routines by graphically connecting objects with inputs and outputs on a digital canvas and adjusting them in real-time. In our prototyping system layout, the software receives and processes all sensor data from the Kinect and the GameTraks, processes them in real-time and sends clean control data to Unity3D to enable interaction, graphics rendering, animation and sound processing. The benefit of this workflow is that complex data fusion, gesture analysis, filtering and manipulation of incoming movement data can be performed on the fly without the need for writing complicated code in Unity. The prototypes were evaluated by each member of the team and shown to the RLANRC team for feedback, as well as publicly exhibited at conferences. Feedback from this process resulted in a major revision of the metal rig, which allowed for quick customizations for user height and arm length, easy entry with manual wheelchair, and swappable resistance bands through carabiners [26, 27].

3.4 Game Design Concept

Turpin and Gotsis led the game design process. Some game themes emerged from the beginning of the project and persisted (for example, a vessel). Participants found the concept of a traveling vessel interesting during the focus groups discussions. The most popular early prototype was the external rotation exercise, which used a metaphor for pulling a bucket of water from the sea, collecting it with each repetition and using the energy to propel a little boat forward. Since adventure travel was named as a desirable genre, we situated the game within the action-adventure genre, which would conveniently enable us to change locations to mitigate boredom in the future. The design team anchored the narrative concept on some cultural theories behind the mystery of how the Nazca lines in Peru were created [28], although the game itself did not take place in a recognizable location (Fig. 4). The game borrows thematic elements from Pre-Colombian values and cosmology [29]. The game backstory is that the player is an ancient *Skyfarer* who holds the secret of creating symbolic markings on the land and is tasked with preserving them.

Table 2. Feature implementation status: ❶ designed on paper ❷ standalone digital playable ❸ integrated into *Skyfarer* ❹ biomechanically validated

USAGE REQUIREMENT	DESIGN/STORY IMPLEMENTATION	RATIONALE
Modular/optional game mechanics	Action adventure; player completes (skippable) ordered segments; pre-game settings calibrate each action performance parameter.	Customize time and/or strength constraints and/or preferences
Per exercise phase (e.g., stretching, resistance)	Stretching: player is underwater, holding each stretch brings them up until they breach surface and see boat (tracked with Kinect) ❷	Prepare player mentally and physically
	Resistance/weight: collect water to fill container and light ship beacon (external rotation ❹); row out of channel (rowing ❹); lift-off and align with sun/moon (diagonal pull down ❹); fly into sun/moon to collect energy (diagonal lift ❷) (tracked with GameTrak®)	Enable performance of core exercises as prescribed
	Muscle resting: player draws their mark on land with previously collected energy (tracked with Kinect) ❷	Provide optional activity between exercise sets that maintains narrative
Per side of body (left / right)	Each stretch or exercise can be customized per side with variable resistance and rig adjustment; customize drawing area boundaries/duration according to minimize over-exertion ❹	Accommodate player's time or strength constraints and preferences
Per exercise type (e.g., external rotation, rowing)	Each exercise type fulfills a unique story requirement, but can be skipped if necessary ❸	Accommodate player's time or strength constraints and preferences
Per exercise set (e.g., second set only)	Each set is incorporated into the story (1st set, daytime – fly into the sun, 2nd set nighttime- fly into the moon, 3rd set twilight – fly into enchanted sky) ❶	Motivate completion of all three sets through story line
Repeatability/ replayability	Rewards and variety of virtual worlds	Maintain motivation and sustainability
Within session	Each segment completion results in advances in narrative with natural performance fluctuation ❸	Motivate and reward completion
Over multiple sessions	Virtual environment variety; natural performance fluctuation; marks on land fade over time ❶	Promote curiosity; accommodate fatigue and/or pain
Cooperative/ competitive	Players can see each other's boats that glow stronger per performance; players may leave drawings/notes for each other within the world ❶	Promote social play, presence and connectedness
Intuitive movement feedback	Movement quality rewarded with natural feedback (e.g., bucket spills when movement is not smooth) ❹	Avoid addictive rewards; promote sensorimotor awareness

More specifically, the player's routine become part of an ancient ritual in which the ancient *Skyfarer* collects "sweat of the sun" and "tears of the moon" from the sun and moon reflections in the water during the external rotation exercise. The magical fluids combine and combust to light the ship's beacon. The player then rows out of the water channel by executing the rowing exercise. Using the diagonal pull down exercise, the player ascends to the sky from a sun or moon hitching post (*intihuatani* or *killahuatani* in the Quechua language). This action aligns the player and their vessel with the sun/moon and gives them a top-down view of the world as they ascend. With the final exercise of diagonal lift, the player flies into the sun/moon, collecting energy, which is used to "burn" their mark onto the land from above.

The exercises are to be repeated for three sets each. This repetition was implemented into the game narrative as day, night, and eclipse. These exercises are performed with the GameTraks and Bodylastics. Kinect is only required if the player wants to stretch, or make their mark using gestural drawing (Table 2).

3.5 Biomechanical Study

In order to prepare the game for scientific evaluation through a biomechanical study, we compiled a reduced version that offered a slice of the whole experience. We used only the right side of the body to perform the test. The game design team synchronized data from the GameTraks with the optical tracking system at the RLANRC Pathokinesiology Lab, as well as with their fine wire electromyography (EMG) system. This study was led by a physical therapist and biomechanist (Haubert/Requejo).

Methods. Skyfarer with Gametraks only (GT) was evaluated against another game-like experience designed with the Kinect (KN) and a control condition of performing the exercises without any game (NG) [30]. Each participant engaged in a single session lasting about 4 hours. Five males with paraplegia (N=5) agreed to participate. Ages ranged from 22 to 49 years old (mean (M) =35.4, standard deviation (SD) = 9.8). Five participants performed exercises with the GT prototype and without a game; one of the five subjects did not perform the exercises with the KN; a second of the five participants did not perform external rotation with the KN due to technical issues; and the remaining three performed all exercises with the KN.

Table 3. IMI Interest/Enjoyment questions (1= not true at all, 4= somewhat true, 7=very true; Q3 was not used from the standard subscale)

Q1	I enjoyed this activity very much
Q2	This activity was fun to do
Q4	This activity did not hold my attention at all (reversed)
Q5	I would describe this activity as very interesting
Q6	I thought this activity was quite enjoyable
Q7	While I was doing this activity, I was thinking about how much I enjoyed it

Outcomes. Shoulder muscle activity was similar overall during exercise with the GT and KN prototypes, compared to exercising without the game (NG), except during external rotation using the GT where there was greater intensity-time integral of the infraspinatus muscle. This was attributed to the design of the visual system with start/end points (water surface/container at top of vessel) and the intuitive feedback (spilling water when movement was not smooth). We collected data on intrinsic motivation (self-determination theory) [31] using the interest/enjoyment subscale (Table 3). Overall, the NG condition was slightly less interesting/enjoyable than the KN and GT conditions, which scored similarly (Table 4). Testing with EMG is fairly tedious because participants have fine wires inserted in multiple muscles over four hours so we did not expect major differences between conditions. Standard deviation was slightly larger in the NG and GT condition.

Table 4. IMI subscale mean score and standard deviation by condition (N=5)

Study Condition	NG	KN	GT
Mean Score	4.30	4.88	4.73
Standard Deviation (SD)	1.49	1.01	1.69

Summary. Skyfarer was "somewhat enjoyable" during the demanding biomechanical study. Feedback design for external rotation was more effective than other conditions in engaging the muscle. Based on these results, the design team improved the feedback for the rowing and diagonal pull exercises into a new version of Skyfarer that has not been tested formally, but that has been publicly exhibited (see next section). During the study, we also engaged participants in informal discussion of game concepts and listened to their impressions and ideas for upgrades.

3.6 Lessons Learned from Public Playtesting

During the three years of development we have presented and exhibited the game at two conferences in the fields of virtual reality [25] and computer graphics [26] with the added benefit of informal playtesting with a diverse audience that has a good understanding of the technology, design methodologies, and tools we have used. This was useful in order to acquire valuable expert feedback from peers, but also because such users were naïve to the concept. Over 30 visitors tried 12+ prototypes at IEEE VR 2012, and 250+ visitors tried Skyfarer at ACM SIGGRAPH 2013. Post-show reflective sessions convened team members who attended and those who did not in order to explore impressions of what was learned with high volume playtesting, both positive and negative.

During IEEE VR, we observed for ease of performance, concept comprehension, and enjoyment as disclosed verbally or expressed affectively. Although the process was informal, we quickly identified which prototypes/elements were salient and integrated findings into Skyfarer. During ACM SIGGRAPH 2013, we were able to stress-test the hardware and identify how to best equip the rig for multiple participants, which would be useful in a clinic setting, as well as assess stability of the software for non-stop usage. We found that improving the calibration/teaching phase would benefit from framing the exercises within the narrative (e.g., intro tutorial). We also determined that incorporating back alignment feedback, which had been prototyped but not integrated, would be necessary for optimal performance of movement. Some bugs with the software emerged quickly, mostly related to calibration issues with the GameTraks. User responses were overwhelmingly positive, much to our surprise due to the crudeness of the graphics. Most playtesters asked us whether we planned to design this system for a gym or office, which demonstrated wide appeal beyond individuals with spinal cord injury. Several users had shoulder injuries from sports or aging and were calibrated with additional care, with lower resistance bands and fewer repetitions. Proper calibration of the resistance bands and rig length/width led to a greater perceived effectiveness by the users. One user stopped by the day after testing to say that "I saw the game in my dream last night." Finally, at the last day of the conference, we found an individual who used a manual wheelchair since childhood who was very physically active. He was familiar with the exercises, had received care at RLANRC and found the integrated version of Skyfarer to be promising.

4 Conclusion

Our team developed *Skyfarer* through integrating transdisciplinary processes and methodologies. Formative analysis through movement protocol analysis, pattern discovery workshops and focus groups led to rapid prototyping, hardware and software revisions, and a formally evaluated integrated version for biomechanical study. An overarching game theme, game mechanics, feedback system, and calibration features emerged from these processes. Public playtesting, although informal, was very helpful in revealing usability and playability issues in a short period of time, as well exercise hardware robustness, and overall software stability. Our future plans include the integration of additional features into a version that can be readily biomechanically evaluated, and development of a subsequent version that can be playtested longitudinally in clinical settings. Exploring home-based versions of the hardware and developing multiplayer features will be critical to future adoption of these types of systems.

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