Project Butterfly: Synergizing Immersive Virtual Reality with Actuated Soft Exosuit for Upper-Extremity Rehabilitation

Aviv Elor, Steven Lessard, Mircea Teodorescu, and Sri Kurniawan
University of California, Santa Cruz, Jack Baskin School of Engineering *
{aelor, slessard, mteodore, skurnia}@ucsc.edu

Abstract

Immersive Virtual Reality paired with soft robotics may be synergized to create personalized assistive therapy experiences. Virtual worlds hold power to stimulate the user with newly instigated low-cost, high-performance commercial Virtual Reality (VR) devices to enable engaging and accurate physical therapy. Soft robotic wearables are a versatile tool in such stimulation. This preliminary study investigates a novel rehabilitative VR experience, Project Butterfly (PBF), that synergizes VR Mirror Visual Feedback Therapy with soft robotic exoskeletal support. Nine users of ranging ability explore an immersive gamified physio-therapy experience by following and protecting a virtual butterfly, completed with an actuated robotic wearable that motivates and assists the user to perform rehabilitative physical movement. Specifically, the goals of this study are to evaluate the feasibility, ease-of-use, and comfort of the proposed system. The study concludes with a set of design considerations for future immersive physio-rehab robotic-assisted games.

Index Terms: Virtual Reality, Soft Robotics, Wearable Robotics, Exosuit, Physio-Immersive Rehabilitation, Physical Therapy, Immersive Experiences, Serious Games, Human Computer Interaction

1 Introduction

According to the latest US Census in 2010, there are more than 40 million older adults (defined as people aged 65 years old or older) living in the US, comprising 13 percent of the US population. This demographic represents a 15 percent growth compared to the 2000 US Census data [19] and is projected to continue to grow. Unfortunately, studies have shown that motor functions decline with aging [45]. The significant older population experiences an increasingly prevalent issue of motor degeneration. Age-related motor performance deficits include coordination difficulty, decreased variability of motor ability, slowing of movement, and problems with balance and gait [37]. Movement slows with aging by as much as 15 to 30 percent. Research by Seidler-Dobrin et al. suggests that older adults emphasize movement accuracy at the cost of movement speed [38]. As a result, older adults show specific deficits in the coordination of bimanual and multi-joint movements. For example, movements become slower and less smooth when older adults use their shoulder and elbow joints simultaneously as opposed to performing single-joint actions[36]. Often postural stability is also compromised with advancing age [40].

In addition to the decline in motor function, aging correlates to the progressive loss of skeletal muscle mass and strength. Frequent exercise represents an effective therapeutic strategy to augment skeletal muscle mass and improve functional performance and quality of life in older adults [22]. Many technological solutions have been researched and developed over the past decade to reduce motor loss, but there is still much to be done.

2 Related Work

One modern approach to address muscular impairment is virtual-reality (VR) therapy. Through the use of VR, stimulating immersive environments can be programmed to increase therapy compliance, accessibility, and data throughput [8, 9]. Psychological and physiological research has featured increasing use of VR in the prior two decades thanks to the ability to simulate realistic and complex situations critical to laboratory-based human behavior investigations [7]. Traditional forms of therapy and rehabilitation usually derive from therapist observation and judgment. Drawbacks of this traditional method are that they are often inaccurate, expensive, and timely [30]. Virtual reality, however, addresses these concerns as a useful tool for improving outcomes compared to conventional therapy by enabling accurate motion capture, telepresence based sessions, and low cost motivating experiences [26, 8]. The immersive visual capabilities of modern VR headsets, such as the HTC Vive and Oculus Rift, have had astounding promise and success with treatments ranging from exposure in Post Traumatic Stress Disorder [34, 28], Borderline Personality Disorder [31], various phobias [39, 14, 7], schizophrenia [35], and many other psychological therapies. Researchers are even reporting that integration VR into the clinical setting can reduce pain similar to the effect of analgesic treatments [15, 17].

Success in VR therapy often relates to the relationship between presence and emotion with technology's ability to bridge them [28]. Increasing the quantity and quality of stimuli in immersive VR is key to influencing user behavior and experience [4, 28]. The past five years have made strides in VR technology – VR is ever more immersive, affordable, and accessible to the average consumer with over 200 million immersive VR Head Mounted Displays projected to be sold by the year 2020 [1, 10]. For these reasons, headset-based VR systems like the HTC Vive and Oculus Rift could appeal to low-income communities. VR as a therapeutic tool has, therefore, become the most effective and affordable it has ever been and is projected by many researchers to continue along this forecasted trajectory.

Many of these studies incorporate Mirror Visual Feedback Therapy (MVFT), the visual or physical stimulation of a "pseudo" movement on the damaged limb to promote recovery [6]. Patients are given sensorimotor feedback by reflecting an abled arm in the position of the impaired arm during exercise [27]. MVFT is suggested to be a beneficial treatment for motor rehabilitation [33, 27], where clinical studies have indicated that MVFT "can serve as a versatile tool to promote motor recovery" in mobility and arm use [6].

MVFT requires the superposition of a simulated arm on a phantom limb which enables patients to relieve painful sensation and increase movement [33]. A variety of other conditions were explored with MVFT, including with stroke survivors, where a simu-

*The authors are with the Departments of Computational Media & Electrical Computer Engineering, University of California Santa Cruz, Jack Baskin School of Engineering, 1156 High St, Santa Cruz, CA, USA. Additionally, this work was supported by the Center for Information Technology Research in the Interest of Society (CITRIS) and the National Science Foundation (NSF).

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lated limb is placed in the patients midsagittal plane, thus reflecting movements of the nonparetic side as if it were the affected side to stimulate brain plasticity [42]. However, users with severe motor loss require increased physical assistance to perform MVFT, and can often require therapist intervention, or in the case of this study: a robotic wearable.

A large amount of physical therapy research has transpired on the integration of rehabilitative robotic wearable devices. Several upper-body robotic exoskeletons have been developed and explored over the last ten years with many incorporating VR. Some of these examples include the PERCRO (Perceptual Robotics laboratory) L-EXOS system [11], Rutgers CyberGlove and Master II-ND (RMII) force feedback glove [21], and Therapy Wilmington Robotic Exoskeleton (T-WREX) [18]. Through combining VR with exoskeletons that provide arm gravity support, clinical testing showed a range in improvement of mobility, strength, and satisfaction [5].

One attribute common to these exoskeletons is the use of rigid structures. A significant flaw experienced by traditional rigid exoskeletons is their inflexibility, and the burden users bear when wearing them. Devices which have few degrees-of-freedom (DoF) or heavy components inhibit some movements. This physical constraint can lead to imbalanced muscular growth and control, which can injure users of these wearable robots [44]. As a result, softer devices such as Lessard et al. exosuits have emerged as a flexible alternative to traditional rigid exoskeletons [24, 25]. This study aims to leverage such soft exosuits during VR therapy through the use of Compliant Robotic Upper-Extremity Exosuit (CRUX), as shown in Figure 1, to explore feasibility, ease-of-use, and comfort.

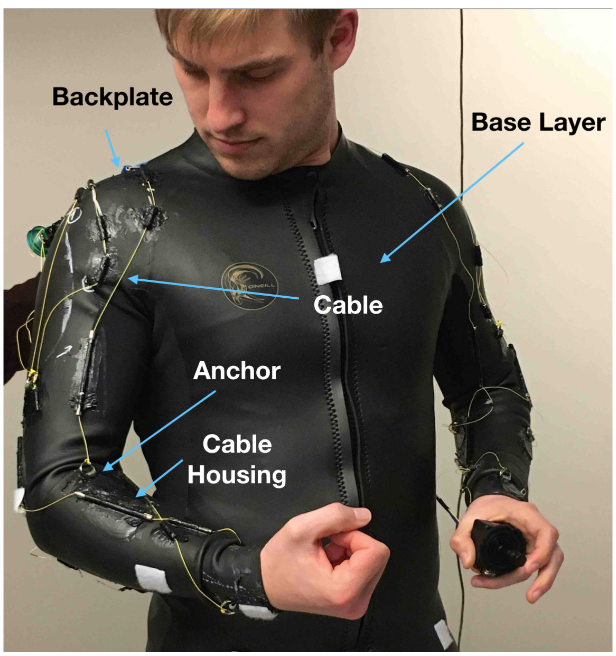

Figure 1: A demonstrator wears CRUX [25] (without IMUs). CRUX is an augmentative wearable soft robot for upper-extremity rehabilitation and can be combined with VR through Project Butterfly to enable immersive rehabilitation.

3 System Design

The VR experience developed, Project Butterfly (PBF), is a game that motivates users to perform upper body motion primitives by having them protect and control a virtual butterfly in a meadow while the system collects real-time data using the HTC Vive. Figure 3 displays an example of PBF gameplay. CRUX was integrated accordingly to provide additional tactile feedback and physical assistance.

3.1 The Soft Robotic Wearable

The purpose of using the CRUX exosuit was twofold: to physically stimulate movement to achieve an ideal position, and to immerse the user deeply into the VR environment. Since immersion is a crucial factor in the influence of user behavior and compliance [4], PBF paired with CRUX may significantly improve the user's rehabilitation experience.

The designed exosuit, shown in Figure 1, is capable of lifting the user's arm in different directions to create smooth multi-jointed movements. The concept of tensegrity for soft robotics inspired the mechanics of CRUX. Tensegrity (a portmanteau of "tensile" and "integrity") defines structures as internally prestressed, free-standing, pin-jointed networks in which the cables or tendons are held in tension against a system of bars or struts [16].

A base layer of neoprene held CRUX together. Cables are routed along the neoprene to integrate a network of "anchor points," which serve as the rigid components in an otherwise flexible system. The exact placement of the cables was determined by recording arm movement on people as they stretched out and expressed their full range of motion [25]. Through examining extensive motion capture of the arm, the area on the skin which sheared the least was determined to find the most stable places to plant anchor points [25].

Bicycle housing routes the cables onto anchor points to actuate different parts of the arm just as how tendons pull limbs. Six micro DC motors were mounted on a modular backplate and connect to the cables of the exosuit via 3d printed spool, and are manipulated through a microcontroller powering the system with a 3-Cell Lithium polymer battery. Each motor is capable of exerting 88 N of force (125 oz-in). Figure 1 depicts CRUX being operated by a demonstrator. The selected material of CRUX affords a compliant and lightweight design. Like similar soft exosuits, CRUX is lightweight. However, CRUX weighs 1.5 kg [24] compared to the 6.8 kg lower-limb gait-assisting exosuit developed by Wehner et al. [46] or the 2.27 kg suit by Alvara et al. [3] for upper arm force amplification

The suit's controller was designed to have the weak arm follow the movement of the healthy limb. This mirroring of limbs instigates mimetic controller design. Mirroring the movement from one side to the other side of the body was inferred from MVFT to increase motor recovery and stimulate brain plasticity [42]. Figure 2 depicts the CRUX being fitted to a user by an evaluator for upper arm force amplification.

To enable the mimetic control of the healthy arm onto the weak limb, wireless connectivity capability was added to connect with the Inertial Measurement Unit (IMU) networks. An IMU is an electronic device that measures and reports a body's specific force and angular rate using a combination of accelerometers, magnetometers, and gyroscopes [2]. The IMU network added to the exosuit consists of 4 IMU nodes where each node can measure 3-axis orientation of itself and then send this data back to the microcontroller. The IMU nodes on CRUX are enclosed in a 3D printed case with adjustable Velcro straps to accommodate various body sizes.

A plunger button must be engaged by the user to allow for exosuit movement. This safeguard prevents accidental actuation when the exosuit is in master-slave mode. If the user feels that the motor is performing movements that are undesired, the user can release the plunger button, effectively disengaging the motor.

In complementary locations, nodes are positioned on both arms at the lateral forearm (midway between the wrist and the elbow) and the lower medial triceps (slightly above the elbow) [25] as seen in Figure 2. Each node transmits pose data to the central controller to support the closed-loop function enabling the pose following from the healthy arm onto the impaired arm. It should be noted that while the VR device can perform motion capture in place of the IMUs, creating this dependency would limit the flexibility of CRUX for future use. For future example, the suit may be used beyond VR MVFT to assist with active daily living activities, where the controls and level of assistance are calibrated during the VR therapy sessions.

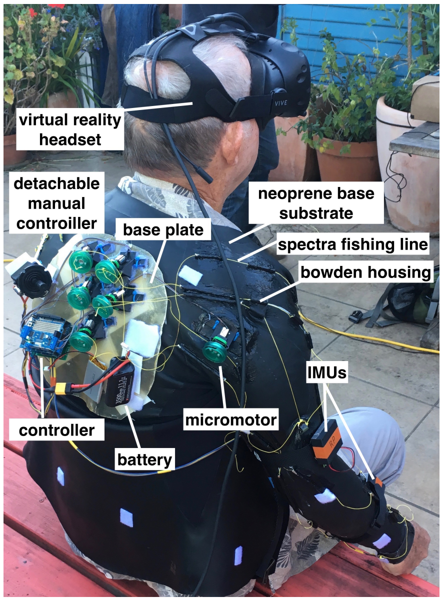

Figure 2: A participant exploring CRUX [25]. Control is achieved by using IMU Nodes and an internal controller for leader-follower mimicry. A user can control their impaired arm using their healthy arm to match the movement path.

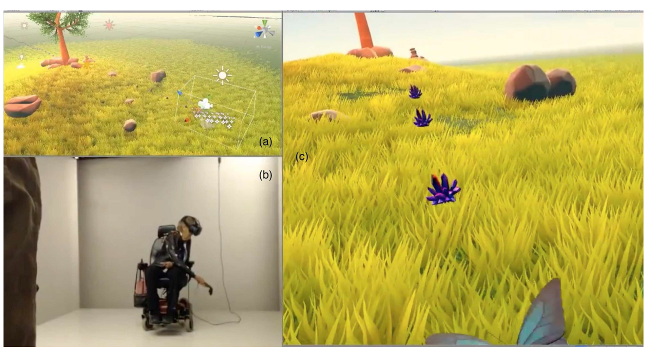

Figure 3: A user playing Project Butterfly. a) is the study proctor's on-screen view b) is the in-person view of the study proctor and c) is the in-game view from the user's perspective.

3.2 The Immersive Virtual Reality Experience

A motion primitive is defined as a distinct movement achievable by a single joint which creates a unique degree of freedom (DoF). Thus, upper body motion primitives can be thought of as indivisible building blocks that can be combined and permuted into a broader range of potential movements. The HTC Vive, one of the highest grossing VR Entertainment Systems [1] developed by the Valve and HTC Corporation, can be used as a powerful tool to both track these motion paths and motivate the user to achieve these motions. The Vive is a VR Head-Mounted Display that implements room scale 4x4 m outside-in tracking technology by utilizing a "lighthouse" system of lasers which enable the user to interact with the virtual environment through accurate motion capture in a 3D virtual space [20]. Complementary to the HTC Vive are two handheld controllers that feature dynamic haptic feedback which enhances spatial orientation [20]. The HMD provides a 110-degree field of view and 90 Hz refresh rate [41]. Motion capture is tracked at 120 Hz using infrared laser sweeping and photo-diodes that enable for recovery of position and orientation [20]. The HTC Vive also features a safety guidance system preventing users from potential injury in the real world environment [41, 32]. The worst case tracking jitter of the system has been reported to be under 2.1mm with an accuracy of an absolute 2mm error [23]. Resultingly, the HTC Vive allows for the ability to extract accurate gameplay data while providing an enveloping experience of touch, sound, and sight.

Paired with an HTC Vive controller, the exosuit assists the user during VR gameplay. Testing of the system targeted two pairs of motion primitives: elbow extension/flexion, and shoulder abduction/adduction. Biceps received assistance by replacing the user's CRUX supported HTC Vive controller as a bubble shield and having them protect the butterfly from incoming rain and projectiles through a therapist-specified customized range of motion path. Haptic feedback is enabled so that the user is indicated with strong pulses whenever the motion primitive was not followed (failure to encapsulate the butterfly inside the bubble). To increase the incentive and track compliance, the user receives a scoring point per every half second that they mirrored the required motion primitive. This multi-sensory feedback guided users according to the objective of the game.

To generate the environment and the mechanics of PBF, the Unity v2017.1.0b4 Game Engine along with the SteamVR Unity plugin v1.2.0 became the chosen development tools. Both Unity and SteamVR hold a large amount of open-access documentation, including flexibility with programming languages such as Javascript and C# [43]. Using Unity's built-in physics engine, the Rigidbody class was used to model the butterfly along with spherical colliders that detected contact with the butterfly. Assignment of the moving projectiles and the butterfly with the rain were set to a time-dependent spatial state, allowing for global physics-based events to influence data capture. Runtime data collection was captured using C# and Microsoft .NET Framework at speeds of 90Hz and higher.

To assist the user evaluation process, PBF includes a dynamic evaluator GUI, seen in Figure 4, which automatically prompts the evaluator or therapist to measure the length of each participant's arms through the motion capture (measuring the x-z plane maximal distance between the VR HMD and the Vive Controller) or manually entered ranges. This calibration stage is achieved entirely in Unity during run-time with the HTC Vive so that user's who may not have access to CRUX in the future can still play PBF without physical assistance. Figure 4 also features the option to change the repetitions per minute of each motion primitive, and data exportation rate of each game session. In short, the evaluator GUI allowed the evaluator to tailor the game to each unique individual and customize data throughput.

The game-themed goals became protecting a butterfly from heavy rain and projectiles using a bubble (as the avatar for the controller of the weak arm), which focused on bicep curl and lateral arm raise exercises. Users are instructed place to the bubble around the butterfly to achieve a high score, and to "protect the butterfly". These mechanics required the users to smoothly follow the flight of the butterfly within +/- 0.1m of the required motion path. As a result, the biceps and lateral arm raise minigames became scripted movements of high accuracy and scripted timing repetitions when a user performed a motion primitive.

Lastly, a tutorial started before every game that the evaluator could enable to adjust the user to the VR environment. In the tutorial, users were asked to identify three images placed on their left, on their right, and behind them. Identification in the 360 VR environment was implemented to familiarize the user with virtual reality and show them that they can look in any direction. Additionally, a "How to Play" menu was added to teach evaluators how to test users, and in-game instructions were added to clarify the goal of each minigame. This pre-gameplay stage simultaneously introduce users not only to virtual reality mechanics (such as 360-degree views) but also to PBF specific mechanics like the arm movements required to earn a higher score. These designs were intended to tailor the game to each unique individual smoothly and intuitively, all while increasing the incentives to perform the objective of the game.

Figure 4: Dynamic Project Butterfly Evaluator Interface. This UI and the data it gathered allowed for more balanced games for each subsequent participant.

4 Usability Study

The study investigated the usability of PBF synergized with CRUX system design, which includes ease of use, comfort, and set baseline feasibility with nine elderly users having motor dysfunction. Users were observed playing the virtual reality game with the exosuit as they performed tasks that identified the ability of targeted muscles and muscle groups. The nine elderly participants in usability evaluations represented three patient segments:

1. Three retirees from Elderday Adult Day Health Care Center, Santa Cruz, CA, represented a mental disability use case because they were affected by memory loss or dementia. Evaluations with these users were conducted at Elderday.

2. Three stroke survivors recruited from Cabrillo College's Stroke and Disability Learning Center (SDLC), Capitola, CA, represented a physical disability use case because they were affected by neglect syndrome, meaning the motor functions of one side of their body was impaired by their stroke. Evaluations with these users were conducted at SDLC.

3. Three retirees living independently within their community, outside of daycare or hospice, which do not have a significant physical or mental disability. Evaluations with these users were conducted at the University of California, Santa Cruz.

All participants ranged between the ages of 60 to 80 years old and were previously unfamiliar with both virtual reality and wearable robotics. These user groups represent three demographics: physical disability, mental disability, and no disability-were selected because the physical and mental disabilities are likely the target demographics for PBF and CRUX. This preliminary study serves as feasibility to justify further studies with larger user group sizes and gain design insights.

For each user, the evaluation began by an proctor giving a detailed explanation of what PBF and CRUX are, answering questions as needed. Then the user was given a tutorial period where they walked through the "How to Play" menu and played the game without being recorded. The tutorial consisted of playing two rounds of the biceps minigame and the lateral arm minigame for one minute each. The first round with the minigames was played without wearing the CRUX exosuit and the second was played while wearing it to allow for MVFT. This allowed the user to try out the controller and learn PBF's basic game mechanics. The point score from the tutorial period helped the evaluator calibrate each user (adjusting arm length and speed).

After the tutorial period, the test commenced with the user playing recorded sessions while wearing the CRUX exosuit and playing 1-minute minigames, shown in Figure 6. Sessions were recorded using a webcam, collecting gameplay scores and positional data, and conducting post-session interviews which allowed for the collection of quantitative and qualitative data. User evaluation interviews were executed by asking users questions pertained to their experience from a prepared form with questions such as:

- Open-ended questions:
  - What day-to-day tasks do you struggle with?
  - How many years have you been doing physical rehabilitation therapy?
  - Do you enjoy video games?
  - How can the virtual reality game be improved?
  - How can the exosuit be improved?
- Rate the statement on a 5-point Likert scale:
  - **Q1:** My current therapy is engaging.
  - **Q2:** The virtual reality game was enjoyable.
  - **Q3:** I became fatigued while playing the virtual reality game.
  - **Q4:** The virtual reality game distracted me from pain when doing physical movement.
  - **Q5:** If I had access to virtual reality therapy games, I would use it in the future.

After evaluations, proctors reviewed gameplay and interview data and commented additional thoughts or observations. Note that resulting answers from **Q1-Q5** can be seen in Figure 5.

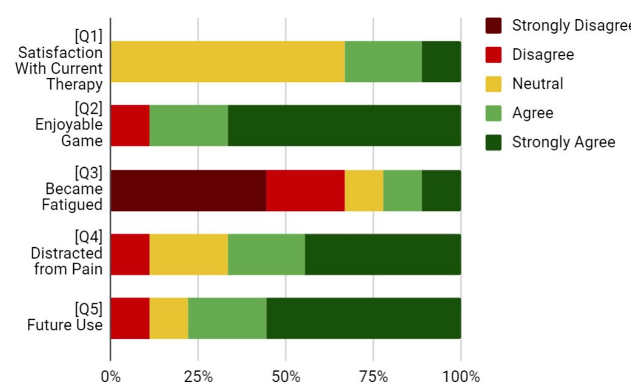

Figure 5: Nine user responses of 5-point Likert Scale Questions pertaining to PBF

Figure 6: A user performs lateral arm raises during a Project Butterfly game session with CRUX. To boost their scores, users had to mimic the flight path of the butterfly, which in this case was an up-and-down motion most easily copied by raising one's arm up-and-down similarly.

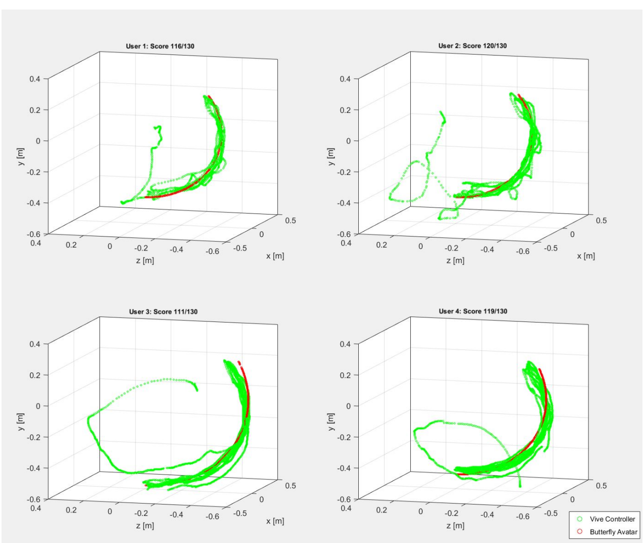

Figure 7: Position of the CRUX assisted controller during the lateral arm raise mini-game. These graphs depict four users attempting to mimic the movement of their targets (the butterfly avatar). Red is the butterfly, green is users movements. Red arcs which are closely matched by green trajectories (as shown in these graphs) mean that users are successfully completing in-game objectives, which are tailored to test their physical limits when wearing the exosuit.

5 Results and Discussion

The three primary objectives of the study were to evaluate the baseline feasibility of the system, ease-of-use of the system, and comfort of the system. These objectives are judged according to quantitative metrics obtained from recorded metadata of users while playing PBF. Qualitative data was acquired during post-gameplay interviews using mixed 5-point Likert Scale questions and open-ended questions. The Likert scale questions are summarized in Figure 5.

5.1 System Feasibility

Most participants felt that CRUX augmented their upper limb movements to some degree. Specifically, one participant (see User 1 in Figure 7) mentioned that their arm movements became more "effortless" with the use of CRUX. Specifically in raising their arm laterally, which had been challenging for them before donning CRUX. They further elaborated that it was the first time in weeks that they did not experience painful throbs when raising an arm above their shoulders.

To observe an example of such movement, the position of the CRUX assisted controller and controller target, the butterfly avatar, were graphed against four scored users from SDLC (Users 2 and 4) and Retirees (Users 1 and 3) for the lateral shoulder raise minigame as seen in Figure 7. All four CRUX supported users were able to achieve a score of 111/130 or higher, indicating that these users were compliant to the motion primitive path for over 85% of gameplay. Additionally, the speed of the users controllers, headset, and butterfly avatar (target to follow) is graphed as shown in Figure 8 as well as the acceleration of the user's weak arm controller shown in Figure 9. Each of these users demonstrated significantly different gameplay movements even though they had close scores. When considering Figure 7, User 1 had sharp changes, User 2 had shaky movements, User 3 had smooth moves, and User 4 had smooth and shaky movements. When looking at movement speed in Figure 8, Users 1 and 3 maintained a constant speed, indicating a greater control of their weaker arm. Whereas Users 2 and 4 had significant spikes in movement speed indicating a lack of control in their arms. It should be noted that while the exosuit assists in achieving position, it does not reduce the shaking of the limbs. Figure 9 reflects the findings in Figure 8 through acceleration, where User 1 maintains the most control nearing almost no acceleration, followed by User 2 who spikes but nears zero, and Users 3 and 4 experienced occasional large shaking. Despite the difference in fine-motor strength and precision amongst participants, each user was able to achieve the desired goal of protecting the virtual butterfly. This might suggest that PBF can be accommodating for people at various stages of their physical therapy, thus making it more accessible. Also, while User 1 and User 4 have differently lengthened arms by about 0.2 meters, the compliance of over 85% can be seen visible as their green arm paths overlay the object red path arch in Figure 7. Although these results are promising, the sample size is not statistically significant, which warrants further study as noted in the Limitations Section 6.5.

On the subject of assistance, most participants felt that CRUX affected augmenting their limbs. However, they all asked for stronger motors on the exosuit. When asked for a potential reason to this, most users indicated that they felt that the motors were not powerful enough to make the difference that they were expecting. One user (see User 3 in Figure 7) commented that they understood the function of the device but "[wanted] even more power behind it." Additionally, none of the participants felt that the exosuit made it more difficult for them to move.

5.2 Ease of Use

An interesting observation was that users said they "knew the goal was always to protect the butterfly," which was a gameplay theme

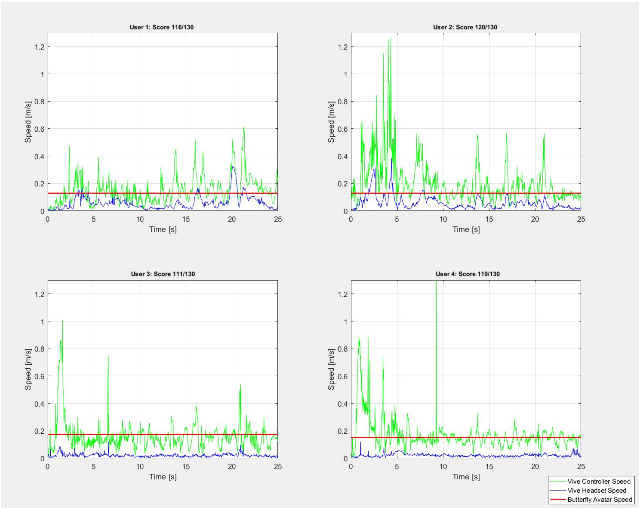

Figure 8: The speed of the user's handheld controller and headset as they attempt to catch the virtual butterfly avatar during the lateral arm raise mini-game. (Green is the speed of the Weak Arm Controller, Red is the speed of the Butterfly, Blue is the speed of the headset)

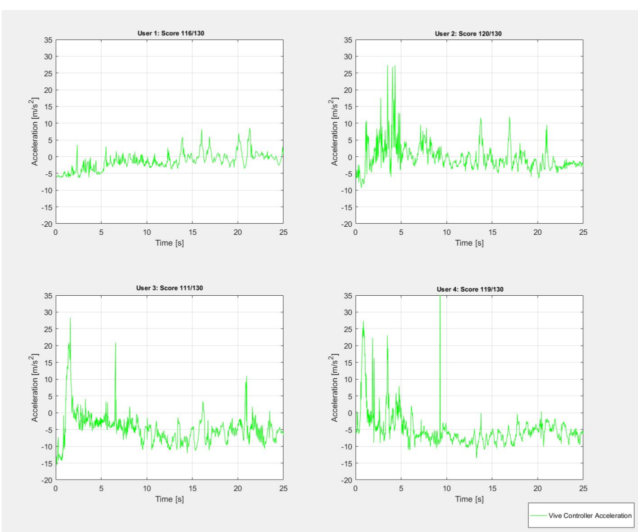

Figure 9: The acceleration of the user's handheld controller as they attempt to catch the virtual butterfly avatar during the lateral arm raise mini-game. Users with high scores and large fluctuations in acceleration are able to react quickly to in-game obstacles, suggesting a higher level of control and strength than those who cannot. (Green is the acceleration of the Weak Arm Controller)

added when brainstorming ideas with potential users. Creating in-game goals which center around an archetypal emotional response may have generated a quicker understanding of gameplay mechanics in the evaluated users. When asked what they thought of the difficulty, almost all participants thought it was appropriately challenging. This makes sense as the game's difficulty was adjusted based on their first gameplay before and during the tutorial period.

By automating all control and dynamic elements of both CRUX and PBF, there was an increase in compliance when performing motion primitives as well as reducing the contention between the suit and virtual reality. Users tended to agree that they noticed the exosuit was assisting them smoothly as if part of the gameplay, due to the mimetic control, suggesting that automating CRUX user-input may have benefited players immersion.

5.3 Comfort

Users asked for greater ventilation in CRUX, due to the form-fitting style of the neoprene. Additionally, since CRUX was prototyped using commercially available wetsuit neoprene, not all users equally fit the base layer. The majority of the participants still responded that they enjoyed playing the minigames with CRUX as seen in Figure 5.

Through observation and commentary, no one seemed displeased with the aesthetics of the minigames. Some users complimented the aesthetics, citing the goal of butterfly protection as "fun," "engaging," and even "meditative." This is particularly exciting news since many people unfamiliar with video games are often intimidated or dissuaded from immersive virtual environments, especially considering that five out of nine participants responded that they dislike video games. The user who mentioned that the games were "engaging" initially discussed their reservations towards video games and how they preferred "real things." When users are psychologically comfortable with a system, they are more likely to benefit from it.

From these observations and recordings, we have found that most users believe PBF was useful in helping them move their arms as seen in Figure 5. Combining CRUX's master-slave system and PBF's butterfly protection mechanics actively encouraged players to perform the required movements while being distracted from their physical therapy as agreed by six out of nine users (and one additional neutral response). These users found PBF enjoyable and agreed that the game did distract themselves from the exertion of physical moving. Seven out of nine users stated that they would regularly use PBF & CRUX in the future for exercises if it were available to them.

5.4 Discussion

Both the quantitative and qualitative data generated suggested that in the short term, the system can help users achieve in the moment tasks by augmenting users upper body strength to enable them to move their upper limb more easily. In the long term, the paired-system serves as a boost to help them train their weaker upper arm and make it stronger over time. In the case of stroke survivors from SDLC who suffer from neglect syndrome, it additionally helped them in recognizing what independently driven movement on the neglected side feels like again. Qualitative lessons learning suggest the following:

- The exosuit must afford independence on behalf of the user. In the gameplay sessions, the experimenters helped users to don and off the suit. If this suit is indeed to be used as a home-based exercise system, users must be able to put on and take off the suit by themselves, which at the moment is still challenging.

- Using a neoprene top as the base to CRUX limited those who could wear it and made it hot when worn over an extended period and difficult to adhere. In future iterations, exosuits like CRUX needs to be more easily customizable, for example by replacing neoprene in the exosuit with elastane (e.g., Lycra).

- Future iterations of robotic support should make the augmentation slightly more powerful, so the aid from CRUX is more apparent to users.

- Given that the PBF and CRUX are new to players, they must be acquainted with the technologies individually. When given even just a few minutes to become acquainted, players made much better use of the CRUX when playing PBF and were less overwhelmed.

Through the study, a set of design guidelines was compiled for other practitioners of wearables and VR games to augment upper limb movements and motivate exercises, especially in older adults and people with motor impairment:

- Exosuit needs to be designed to be more flexible to fit a variety of body sizes and shapes.

- Exosuit augmentation needs to be noticeable, perhaps by adding an in-game UI element such as the bubble lighting up when the suit is activated. This will hopefully keep the user immersed while also providing exosuit control indication to the user.

- Reduce various forms of stimulation to the minimum without affecting the exercise goals without breaking immersion. Feedback and color variations went unnoticed by some of the users as they were not related directly to their goals.

- Stay within the appropriate difficulty of the users in terms of game speed, ranges of motion, etc.

- The user feedback suggests that the users enjoyed protecting the butterfly, as it caused an "emotional attachment." Emotion-driven immersion suggests a powerful tool in creating engaging experiences.

5.5 Limitations

One user responded "Disagree" for questions **Q2** (Enjoyable Game), **Q4** (Distracted from Pain) and **Q5** (Future Use) from Figure 5. The user commented that the novelty of VR was fun, but continuously protecting a butterfly would become boring if they used it for regular therapy. The user requested that future games should have a compelling storyline to keep them interested and motivated. The intent of PBF was preliminary feasibility, and future games should be developed and studied based on lessons learned, trying out game mechanics, and the targeted therapy desired. Concerns that this user poses should be investigated in subsequent games to determine if specific game mechanics are more preferred by users than others.

Only three motion primitives were explored and converted into VR through PBF. Specifically, they were the Lateral Shoulder Raise, Forward Arm Raise, and Horizontal Shoulder Rotation. Future studies should incorporate a more variety of motion primitives to catalyze potential benefits to the users' potential mobility improvements. There may also be potential in incorporating common assessment tools into the VR environment for automated assessment such as the Apley's scratch test (Shoulder Mobility) [12], Wolf Motor Function Test (Upper-Extremity Mobility) [29], Fugl-Meyer Assessment (General Motor Ability) [13]; all of which assess motion primitives for active daily living.

Furthermore, this study would benefit from a larger sample size of the users, more therapists could be involved, and more stimuli and testing must be done to determine feasibility, compliance, and design further. There is a possible novelty effect of the VR, where most of these users were exposed to the VR for their very first time. The results suggest that the game design may account for the novelty effect. However, a long term study must be done to address these possibilities adequately. Subsequently, a long term study is being planned with local hospitals in Santa Cruz, California, to explore the effects of Project Butterfly with CRUX further. An IRB protocol for such is currently under review for approval.

6 Conclusions and Future Work

Project Butterfly reports on the design and evaluation of a unique VR experience paired with a soft body robotic wearable exosuit. The pair of these technologies have been developed as a novel experience to rehabilitate upper-extremities. CRUX reduces the burden and rigidity experienced by users of traditional wearable robots through its softer, more structurally compliant constitution. However, a material other than neoprene should be used to make it more comfortable and less likely to overheat the user. To tailor to a more significant number of DoF, the designed VR game, PBF, is aimed at focusing on motion primitives expressible in soft exoskeletons – actions which the healthy arm can perform that can be combined and permuted into all upper-extremity movement. PBF thus serves as a motivator for the user to complete virtual objectives and consequently, actual motions. The completion of these objectives is assisted through CRUX's augmentation of their upper body strength to perform the game-specific movements. When evaluating the baseline feasibility of PBF and CRUX in augmenting and promoting proper arm movement as defined by the established motion primitives, most users were able to complete appropriately challenging arm movements, suggesting that PBF and CRUX gave users suitable strength of their augmented arm. Additionally, the system's ease-of-use and comfort were analyzed, and most users felt that they were confident capitalizing on the therapy system.

Virtual reality paired exosuits could prove useful to make engaging therapy for users with upper-extremity impairment. For more significant impact, designing a new exosuit peripheral and increasing more types of accompanying VR minigames which augment various muscle groups (i.e., pectoral muscles and dorsal muscles) can further improve the rehabilitation. These muscle groups support upper-extremity actions and strengthening them could bolster arm muscles as a result. In a similar vein, using new materials for a future iteration of a soft exosuit focused for VR could make this technology more comfortable and accessible.

Furthermore, the real-time data produced from the HTC Vive and Vive Tracking units can be integrated with the exosuit. Therapists and users may also potentially benefit from further data extrapolation with the HTC Vive. A complete view of a user's body, achievable through more precise motion tracking and inverse kinematics, and could identify confounding postural issues, such as slouched backs and other movement biases, which a physical therapist would want to be aware of during gameplay. A long term study is being planned with local hospitals to explore the effects of Project Butterfly with a next-generation CRUX design that accommodates more body types, sizes, and weight. Finally, with the plethora of positional and behavioral data output produced from this VR experience, there is potential to integrate machine learning protocols and AI to optimize suit controls and game difficulty to improve rehabilitation results.

The baseline feasibility, ease of use, and comfort created by synergizing an immersive physio-therapy VR game with an actuated soft robotic exosuit had promising results in the potential future of a more accessible, affordable, and personalized rehabilitation. More research is needed to expand upon the preliminary work of this study, discover best practices of soft exosuit integrated VR, and validate clinical utility. Subsequently, there are more butterflies to follow on the path ahead.

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