Adaptive Virtual Reality Exergame for Individualized Rehabilitation for Persons with Spinal Cord Injury

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Abstract. Typical exergames used for rehabilitative therapy can be either too difficult to play or monotonous leading to a lack of adherence. Adapting exergames by tuning various gameplay parameters based on the individual's physiological ability maintains a constant challenge to improve a participant's level of engagement and to encourage the physical performance of the user to achieve rehabilitation goals. In this paper we developed a pilot exergame using a commercially available virtual reality (VR) system with varied and customizable gameplay parameters and accessible interface. A baseline task VR tool was previously developed to determine an individual player's initial 3-D spatial range of motion and areas of comfort. We observed the effects of adjusting gameplay parameters on a participant's physiological performance by measuring velocity of motions and frequency and effort of targeted movements. We calculated joint torques through inverse kinematics to serve as an analysis tool to quantitatively gauge muscular effort. The system can provide an improved rehabilitation experience for persons with tetraplegia in home settings while allowing oversight by clinical therapists through tracking of physiological performance metrics and movement analysis from mixed reality videos.

Keywords: Virtual reality, rehabilitation, spinal cord injury, shoulder torque, exergame

1 Introduction

Inpatient rehabilitation after sustaining a traumatic spinal cord injury (SCI) plays a critical role in recovering functional capacity, maintaining bone density, endurance, muscle strength, and improving psychological well-being [13, 20, 24]. Rehabilitative therapy of the upper limbs is also crucial for providing functional independence after a high-level SCI [8].The inpatient rehabilitation process involves physical and occupational therapy to determine the primary goals and interventions that are important to maximize recovery of motor function and the ability to perform activities of daily living (ADL). Therapists periodically re-evaluates the patient to assess progress and determine if new therapy protocols are required. However, over the past 40 years the length of stays for rehabilitation for patients with SCIs have decreased by two-thirds from a median stay of 98 days in 1973-1979 to 36 days in 2010-2014 [33]. This substantial decrease of supervised therapy for newly spinal cord injured persons make it imperative to find solutions to continue regular therapy after they are discharged from the rehabilitation hospital [29].

Despite the advantages of regular home-based therapy, there are several barriers to individuals with SCI performing the prescribed therapy regularly and correctly [48]. These include physical barriers such as equipment, availability of resources as well as psychological or social barriers such as perceptions or attitudes towards disability, motivation, and fear of injury. Therefore, the desire to exercise does not match behavior and various studies have found that lack of motivation was a ubiquitous factor in reduced exercise [25, 42]. In order to combat the monotony of traditional exercise regimens, exercise gaming "exergaming" was introduced for individuals with sedentary lifestyles or other ailments such as obesity and cardiovascular disease [57].

Exergames have also increasingly become popular to enable persons with disabilities to participate in appropriate exercises to achieve the required physical intensity but are also engaging to play [32]. Motivation through serious exergaming has been shown to raise patients' interest and improve their adherence to rehabilitation at home [27,35,53]. Variety of research and commercial game platforms, such as the Nintendo Wii$^{\text{TM}}$ (Nintendo, Kyoto, Japan) and Leap Motion (Leap Motion Inc, CA) [1, 10, 14, 19], have been developed for exergaming by tracking players' movements [23, 55]. Several studies involve individuals standing using a balance board, dancing, or stepping in place as the actions being performed [11]. A relatively new foray into the exergaming space has been with virtual reality (VR) tools.

VR is emerging as a useful tool to facilitate exergaming therapy with the potential to support home-based exercise programs [41]. VR-based exergames have emerged as a tool for rehabilitation for diseases such as stroke, traumatic brain injury, SCI, cerebral palsy, Parkinson's disease (PD) and other developmental issues [28]. The use of VR in rehabilitation is particularly attributed to its ability to provide immersive experiential learning experiences in an engaging, realistic but safe environment [44, 49]. The VR system encourages the repetition of active movement, making it ideally suited as a tool for motor rehabilitation. VR's ability to automatically deliver stimulus at known timepoints allows clinicians and therapists to focus on the patients' performance and observe whether they are using effective strategies [43,52]. Clinicians can also use VR to allow patients to achieve a variety of objectives through the varying of task complexity as well as type and amount of feedback [56].

However, past VR exergaming systems often encompass extremely large hardware setups that are generally not portable in nature. Their expensive nature also makes them impossible for use as part of a home-based rehabilitation system. Additionally, the existing setups are designed for individuals who do not have limitations with manual dexterity since they often require substantial finger strength [26]. This lack of hand function common in tetraplegics make it difficult to hold and depress various buttons on a typical VR game controller. Design customization to meet the need and limitations of tetraplegics needs to be a significant consideration in gameplay development. Most games available in the market require the use of buttons, making it impossible to use in individuals with limited hand function, and difficult to be modified for use in individuals with impaired dexterity [39, 52]. Thus, there is a critical need for VR exergames to be developed that are customized to the unique limitations of tetraplegics, which are fun to use and provide therapeutic benefit.

Additionally, when considering development of exergames, it is critical to track and quantify the progress of movements made by individuals performing at-home therapies [15, 17, 18]. Current techniques to determine functional ability include the functional independence measure (FIM), manual muscle testing (MMT), Range of Motion Scale (ROMS), and the Modified Ashworth Scale [22, 34, 46]. These subjective tests require trained clinical therapists to obtain a good inter-rater reliability [15]. Moreover, these methods are time consuming, labor and resource intensive and are often dependent on patient compliance [28,47].Developing objective tests that can track patient progress and functionality at home would alleviate many of the aforementioned issues and nicely fits into the more recent migration of many health care providers to offer more telemedicine home-based assessments. In order to fill this gap, we developed a baseline tool [37] and an exergame that uses a commercial off-the-shelf head mounted VR gaming system, the HTC Vive©. The Vive is a relatively low-cost, portable system which can be easily setup in the home environment. Since shoulder torques are positively correlated with perceived muscular effort [9], the tool we developed also incorporates a method to calculate static joint forces and torques at the shoulder, as a measure of muscular effort. Moreover, we also explored the role of altering various gameplay parameters to identify the impact on perceived user effort as well as the impact on muscular effort. Surveys were conducted at the end of the games to understand the perceived fatigue levels and feedback about gameplay mechanics. This work could quantify perceived effort that the users likely felt during gameplay enabling a better/iterative rehabilitation experience for the individuals with SCI and their therapists.

2 Methods

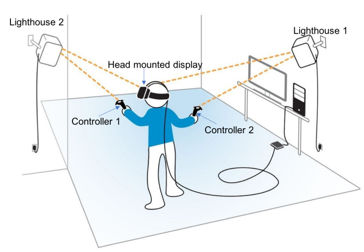
2.1 Recruitment of Participants

We recruited six participants (one female and five males) from the Rehabilitation Hospital of Indiana, and the mean age of the participants was 37.5 $\pm$ 9.9. All participants had a cervical (C) SCI ranging from C4- C7 level injuries. At the time of their participation, participants had been injured, on average, for 15 $\pm$

11.2 years. All study protocols were approved by an Institutional Review Board. Prior to the study, informed consent was obtained from all the participants.

2.2 HTC Vive and mixed reality setup

The HTC Vive© is a commercially available VR system which uses a head mounted display to immerse the individual into a virtual world where virtual distances match real world distance (Fig. 1a). Therefore, the gestures and tasks performed virtually are directly translatable to the physical reach of the individual during rehabilitation. Previous rehabilitation exergaming systems have employed 2D flatscreens, which do not permit any depth perception. Completion of this visual feedback loop is vital for effective reaching tasks during rehabilitation [40]. The Vive comprises of two base stations, called lighthouses, which have spinning IR lasers that flash and sweep a beam of light alternatingly. The head mounted display (HMD) and trackers have a constellation of IR receivers that use flashes and beams of IR light to determine the position and orientation. The position data is calculated at a 90Hz refresh rate [2]. In order to make the controllers more accessible, we used Vive trackers that were mounted to game objects to be tracked by the base stations. A 3D printed shim was designed to allow the tracker to be secured firmly to a participant's end effector with a Velcro strap (Fig. 1b). VR tools and games were developed using the Unity3D™ (Unity Technologies, San Francisco, CA) game engine to work with the Vive trackers. The games involved designing 3D models to be rendered during gameplay written in C# to detect and handle collision events.



(a)

(b)

Fig. 1: a)Mixed reality setup with HTC Vive and Green Screen b)3D printed mount to fix camera and tracker geometry

Mixed reality system. A mixed reality system was developed to allow clinicians to observe participant interaction within the virtual environment. It provided a combined view of the gameplay that incorporated both a real video with the virtual environment and virtual objects overlaid in the correct position and orientation. This mixed reality system utilizes a position tracked camera using an HTC Vive© tracker, a green screen and the traditional HTC Vive© VR setup Fig. 2a). The mixed reality videos were generated through the Liv software (LIV Inc, San Francisco CA) in real time, and saved for analysis. A virtual camera was setup in Unity3D in the exact same position the camera in the real-world. A one-time calibration was required to set up the mixed reality system. This was done through the Liv software wherein the physical distance of the camera relative to the participant and the Vive tracker are mapped to the virtual space. The camera's field of view and orientation are also calibrated through the software to match the representation in the virtual environment.

(a) (b)

Fig. 2: a)Mixed reality setup with HTC Vive and Green Screen b)3D printed mount to fix camera and tracker geometry

In order to tackle the challenge of calibrating the camera lens' optical parameters such as focus and field of view we accounted for a translational and rotational offset between the camera and the tracker. Several attempts were required to align the real and virtual videos and re-calibration required large overhead times during participant studies. To prevent this, a tracker camera mount was 3D printed to keep the translational and rotational offsets fixed (Fig. 2b). This greatly reduced the time needed for re-calibration during each set up. The video feed from the real and virtual camera were combined using the Chroma Key composting technique (Unity Mixed Reality Capture).

2.3 Exergame Design

An exergame was developed based on physical therapists' recommendations to physically challenge the participant but not overly so as to discourage continued gameplay [5, 31]. The exergame developed involved targeting virtual balloons that were spawned randomly around the participant (Fig.3). A virtual model of a light saber was attached to the participant's tracker that was used to target virtual balloons. These multicolored balloons were designed to pop when the lightsaber targeted them for a specific duration. The color of the balloon would change to a fluorescent pink when it was successfully targeted, i.e. the light saber was inside the balloon. In order to avoid inadvertent pops resulting from flailing motion or other unplanned motion, a small delay was added before a balloon would pop. The baseline delay was chosen to be 100ms. At the end of a successful pop, a popping animation and a loud realistic balloon pop sound was played as visual and auditory notifications to participants.

We modified two different parameters to measure the resultant change in participant biomechanical responses. The first gameplay parameter was the scale (size) of the balloons and the second was the delay required for the balloon to pop after targeting. Two different trials were designed to investigate how participants interacted with the game and how each of these parameters affected the participants' interaction/performance. During both trials, the coordinates of the participant's HMD, end effector tracker, number of popped balloons, and the location of the tip of the light saber were all logged throughout gameplay.

The scale trial comprised a 2-minute-long gameplay with balloons were either at full scale (1) or at half scale (0.5) which were presented/spawned at an equal probability. All the balloons had the baseline pop delay threshold of 100ms. The participants were asked to play the game and try to pop as many balloons as they could during the duration of gameplay. We measured the 1) number of balloons that were popped, 2) average velocity while approaching the balloon [36] , 3) fatigue levels reported on a five-point Likert scale, and 4) static torques. The delay trial comprised a 2-minute-long gameplay where spawned balloons were all at full scale. However, half of the spawned balloons would pop at the baseline pop delay threshold (100ms); whilst the other half of spawned balloons would only pop at the increased pop threshold (300ms).Participants were asked to pop as many balloons as possible. They were not provided information regarding which balloons had the longer delay. In addition to the aforementioned measurement metrics, we also measured the time to failure, which was defined as giving up on popping the balloon.

2.4 Joint Muscular Force Calculation

Joint reaction forces and torques were calculated to understand the level of muscular exertion [21]. Four important assumptions were used to perform inverse dynamics to calculate joint forces: 1) anthropometric data, including the participants' arm segment's center of mass and weight of arm segment in proportion to total body weight, 2) link segment model of the human body, which is a simplified representation of the complex limb joint as simple revolute joints and arm segments with masses and moment of inertias located at the center of mass of the segments [54], 3) kinematic data obtained using HTC Vive trackers, and 4) external force measurement performed through inverse kinematics. In order to calculate joint forces for each gesture performed by participants during gameplay, the human arm was modelled kinematically as a serial-link robot following

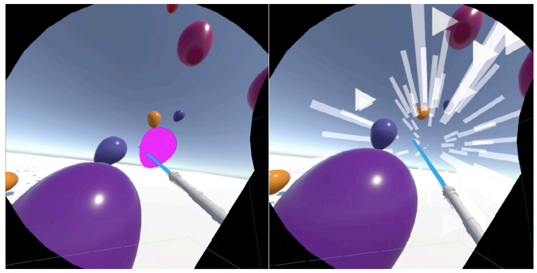
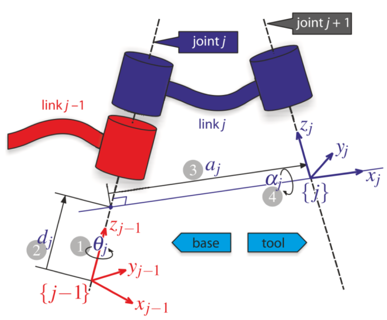


Fig. 3: Left: balloon turning fluorescent pink indicating it was targeted. Right: Balloon popping animation indicates that the light saber targeted the balloon for a sufficient amount of time (> 100 ms).

the Denavit-Hartemberg (D-H) notation [38, 51] and implemented through the MATLAB Robotic Toolbox [6]. The D-H notation consist of five parameters [7] that are used to describe each link to the previous link in the series (Fig. 4).

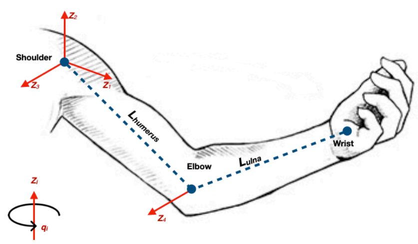


d_i	Link offset	Distance from the origin of the previous frame to the x_i axis along the z_{i-1} axis,
θ_i	Joint angle	Angle between the x_{i-1} and x_i axes along the z_i axis
a_i	Link length	Distance between the z_{i-1} and z_i axes along the x_i axis
α_i	Link twist	Angle between the z_{i-1} and z_i axes along the x_i axis
σ_i	Joint Type	R for revolute and P for prismatic joint

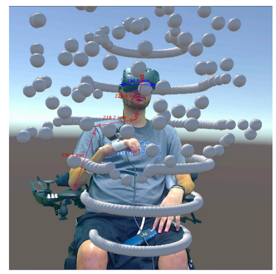
Fig. 4: Geometry of D-H parameters. [7]

In addition to these default D-H parameters, absolute joint constraints [3] were added to each joint to prevent orientations that are unachievable biomechanically. Figure 5a illustrates that the first three joints are at the exact same point in 3D space but offset by 90°, these joints correspond to the degrees of freedom at the shoulder joint. The fourth joint is at the elbow offset from the first three joints by the length of the humerus or upper arm. The fourth joint has a length of the ulna or forearm. The wrist joint was not modelled, as the gameplay did not involve wrist motion.

The length of individual participant's upper and forearm were derived from participants' video recordings taken during gameplay. Fig. 5b demonstrates how anthropometric measurements were made using the open source physics video tracking tool, Physlets Tracker, from the video recording of the participant. The known value of the HMD's width (shown by the blue in Fig. 5b) was used as reference for calibration. This measurement was performed three times for each participant and the average length was used for data analysis. A new coordinate system was defined with the HMD coordinates as the origin. Therefore, the tracker coordinates and all the virtual objects were referenced to the HMD position.



(a)

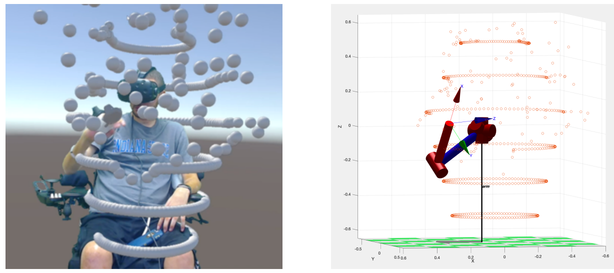


(b)

Fig. 5: a)Kinematic model of the human arm with reference frames associated to the various degrees of freedom b) Anthropometric measurements of the participant (shown in red) from recorded mixed reality videos.

Inverse kinematics was performed using the kinematic arm model from the tracked and translated coordinates relative to the HMD coordinates of the end effector. Inverse kinematics returned the joint angles necessary to achieve the specific pose and yielded several possible solutions for the position of the elbow as there is no unique solution. Locations of the elbow which were not biomechanically viable were discarded and in order to obtain a conservative estimate, a natural and comfortable "elbow down" [6] start pose was determined empirically for each individual (Fig. 6). The inverse kinematics tool accepts a start pose as an input argument to use as a starting point, which determines the final orientation of the calculated pose. Inverse kinematic algorithms have been developed in the past with maximizing human comfort by minimizing joint torques [58]. An inertial model of the arm was also created by modelling the two arm segments as cylinders.

The mass and center of mass of the arm segments were calculated as a percentage of the body weight obtained from standardized anthropometric data. The upper arm and forearm masses were 2.66% and 1.82% of the entire body weight for men and 2.6% and 1.82% for women respectively. The distance of center of mass from the proximal joints were 48.5% and 44% respectively [4,12]. The inertial parameters for the principle axes for the arm segments modelled as solid cylinders were then calculated using the equations below.



(a) (b)

Fig. 6: Initial location of the elbow based on comfort shown in a) mixed reality view with "elbow down" orientation and simulated with b) a kinematic model of the arm with "elbow down" orientation

$$I_{xx} = \frac{1}{2}mr^2 \tag{1}$$

$$I_{yy} = I_{yy} = \frac{1}{2}m(3r^2 + h^2) \tag{2}$$

3 Results

Scale Trial Metrics. Participants targeted 40% more larger balloons than smaller balloons (Fig 7), however this was shown to be non-significant ($p>0.05$) through ANOVA testing. Non-parametric permutation testing showed a significant difference ($p<0.05$) in the velocities of arm movement when popping the smaller balloons compared to the larger balloons. The average velocity of the arm was 25.4% higher for the larger balloons compared to the smaller ones. Representative velocity profiles (Fig. 8) show that for the larger balloons, the change of velocity of the arm was sharper at or immediately prior to the balloon popping event (indicated by red dashed lines). On average the participants reported a fatigue score of 3.0 ± 1.26 after playing the balloon popping game with different sized balloons.

We identified a positive correlation between the total torque at the shoulder and the distance of the balloons from the shoulder ($r^2 = 0.73$). The further the distance of the balloon- the more muscular effort was required to reach the balloon. Fig.9a shows the performance of an individual with greater upper limb motor function compared to an individual with lesser motor function (Fig.9b). The individual with greater motor function did not show preference in popping either large or small -scaled balloons and exerted almost equal effort. However, the individual with lesser motor function popped larger balloons more frequently (Fig.9b).

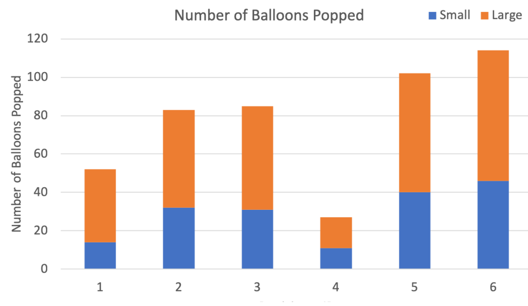


Fig. 7: Preference of balloon based on number of balloons popped

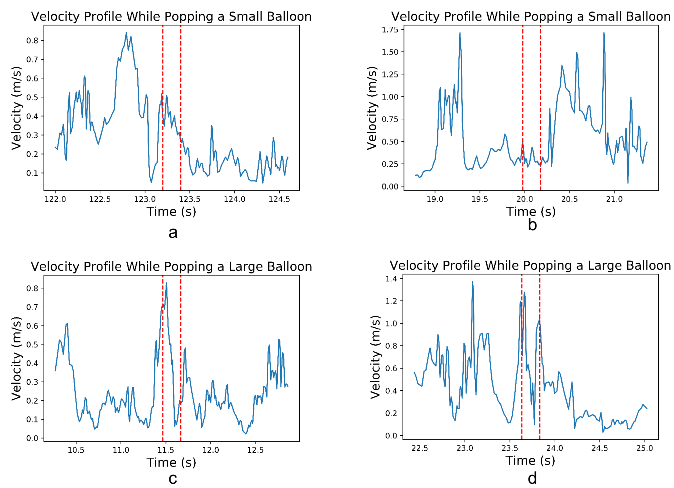


Fig. 8: Representative velocity profiles while popping balloons of different sizes. Red dashed line indicates popping event. (a and b) Small Balloons for two different participants. (c and d) Large Balloons for two different participants.

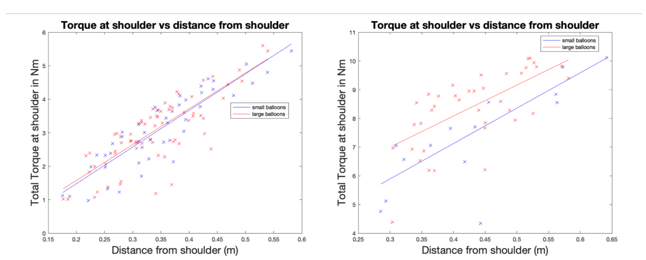


Fig. 9: Static Torque calculations at the shoulder for different sized balloons versus distance from shoulder for two different subjects – a) participant with greater upper limb motor function and b) participant with lesser motor function. The red markers represent large balloons whilst the blue markers represent small balloons.

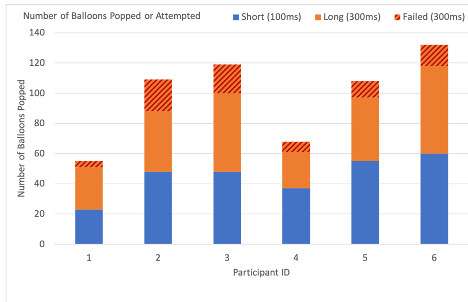


Fig. 10: Number of balloons attempted/successfully popped with different pop delays for each participant.

Delay Trial Metrics. Participants successfully popped 10% more short delay (100 ms) balloons than long delay balloons. On average participants had a failure rate of 23.8% of all the long delay (300 ms) balloons attempted (Fig. 10). The overall average duration a participant spent inside a long delay balloon before failing was 190.36ms. The non-parametric permutation test showed a significant difference in the velocities between popping balloons with short pop delays (100ms) and those with long pop delays (300ms) ($p < 0.05$). The average velocity was 33.3% higher for the balloons with short pop delays. The velocity profiles of the different pop delays (Fig. 11) showed a trend wherein the velocity of the hand changes at a lower rate when popping the balloons with longer pop delays.

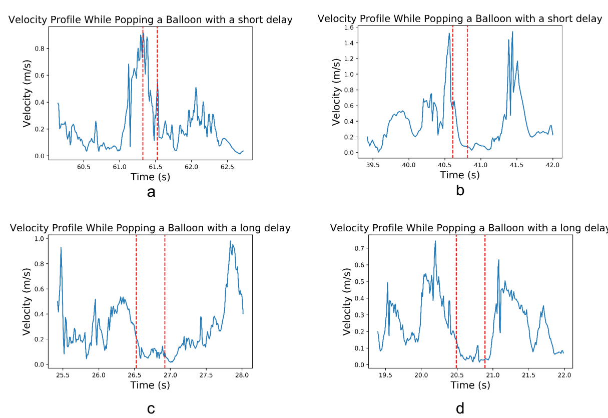


Fig. 11: Representative velocity profiles while popping balloons of different pop delays. Red dashed line indicates popping event. (a and b) Profiles for short delay to pop. (c and d) Profiles for long delay to pop.

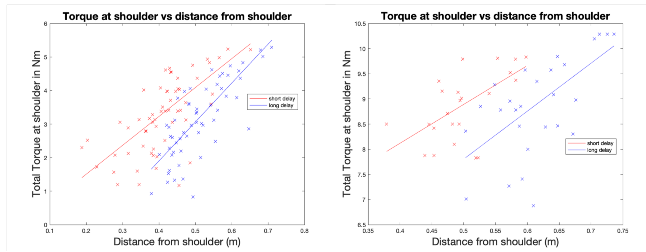


Fig. 12: Static Torque calculations when popping balloons with different delays related to distance from shoulder for two different subjects – a) participant with greater upper limb motor function and b) participant with lesser motor function.

On average the participants reported a higher fatigue score of 3.83 ± 0.94 after playing the balloon popping with different pop delays. There was a positive correlation between the total torque at the shoulder and the distance of the balloon from the shoulder ($r^2 = 0.62$). As anticipated overall participants popped longer delay balloons further away from the shoulder (Fig.12). Individuals with limited motor function had a larger difference in targeting short delay balloons over long delay balloons (Fig. 12b).

4 Discussion

Through adaptive exergaming approaches such as modifying the gameplay parameters explored in this paper, it is possible to manipulate the performance and required exertion levels of players. Games are perceived to be boring if they are determined to be too easy [5, 50]and frustrating if they are found to be too difficult [31, 59]. Thus, it is imperative to operate within the individuals' physiological limits including functional reach, spatial areas of comfort [37], and within the peak static torques to achieve maximal engagement and thereby, the therapeutic potential of the exergame.

Impact of changing exergame parameters on gameplay performance. Changing the two parameters of the exergame resulted in changes in performance of the participant, which has clear benefits toward providing individualized rehabilitative therapy. Visible cues, such as using different-sized balloons, in the exergame example that we developed resulted in a clearly defined user preferences, which could be manipulated to encourage progress of rehabilitation metrics of individuals with upper limb motor impairments.

Rehabilitative metrics that could be automatically calculated during gameplay included changes in the velocity profile. For smaller balloons, the change in gesture velocity occurred over a longer period of time, suggesting the need for more precise, deliberate but slower movements when targeting small balloons. Wherein the participants' change in velocity was sharper at or immediately prior to balloon popping event for larger balloons. This is in agreement with Fitts' law, which states that the time required to rapidly move to a target area is affected by the width of the target and the distance to the target [60]. Fitts' law has been widely used to describe reaching motions and has been applied to a variety of different upper-extremity exercises. With this in mind, the size of the balloon in the exergame was manipulated to encourage participants to perform more deliberate motor skills through the targeting of smaller balloons.

Participants had significantly preferred to pop larger balloons over smaller ones targeting almost 40% more large balloons than small balloons. This could be accounted to the higher visibility of the larger balloons as well as providing an easier target for participants. The participants also described targeting the smaller balloons as "requiring more finesse". Thus for rehabilitative purposes balloon sizes could be manipulated during gameplay to either improve the success rate of individuals with profound motor impairments to prevent frustration or making play more challenging. Likewise, the distribution of large to small balloons can be modified according to therapeutic needs. During this study, there was an equal proportion of large and small balloons being populated during gameplay [31, 59]. Additionally, the participants were presented with an equal number of balloons with short or long pop delays. From the data we observed that on average participants successfully popped 10% more short delay than long delay balloons, though they were visually indistinguishable, unlike the balloon scale trial. On average participants had a failure rate of 23.8% for all the long delay balloons attempted. The lack of visual differences coupled with the failure rate suggests increased difficulty lies in holding the hand in position while tracking the balloon for 300ms to pop. This is in agreement with literature which shows that static holding tasks are harder to perform than a dynamic task [16, 30]. The gameplay results showed that participants spent 190ms inside a long delay balloon before ultimately failing suggesting that if the pop delay was lowered to this number, we would observe a greater success rate. The results also showed a significant difference in the velocities between popping balloons with short pop delays and those with long pop delays as expected. While popping a balloon with a long delay, the individual needed to slow down and use fine motor control to maintain the hand position inside the balloon before popping. By altering the delay parameter can change rehabilitation outcomes, such as rewarding the user for performing holding tasks as opposed to a flinging motion often used in short delay popping events.

Joint force calculation to measure physical effort. We developed a method of calculating static joint forces based on a number of assumptions that were characteristic of participants playing our exergame. In previous studies, joint forces at the knee and hip were calculated using strain gauges to measure the pedal forces [54] with kinematic data recorded using video cameras and retroreflective markers. However, we were able to estimate static joint forces from the data collected when using our VR-based exergaming system, including kinematic data obtained from the HTC Vive trackers and participants' anthropometric data, and calculated using traditional inverse dynamics methods.

As expected, a high positive correlation was shown between the total torque at the shoulder and the distance of the balloon from the shoulder. With increasing distance, the center of mass of the arm is farther away from the shoulder. The change in position of the center of mass leads to a mechanical disadvantage due to the increased moment arm. Therefore, the torque required at the shoulder needs to be higher to support the arm at this extended pose. When evaluating static torques for balloons with different delays, we observed a trend wherein balloons with long delays were generally popped at a farther distance from the individual's shoulder. This could be due to balloons being popped in positions where skeletal loading could be high, thus reducing the torque on the shoulder. This could also be due to balloons slowly drifting upwards causing participants to track the balloons upwards and further away from the shoulder. Through the calculation of torque at the shoulder it is possible to estimate the level of exertion [9]. This would help clinicians develop a better understanding of how challenging a specific movement might be. Moreover, it would be possible to adapt the gameplay parameters to maintain an individual at a constant level of exertion in order to attain therapeutic goals by the clinician and prevent overexerting muscles causing injury.

5 Conclusions

We developed an adaptive exergame using commercial VR systems that incorporated a variety of quantifiable, physiological-based measurements including gesture velocity and muscular exertion through joint force calculation. The VR exergaming system we developed in this paper was focused on providing an improved rehabilitation experience for persons with tetraplegia in home settings while allowing oversight by clinical therapists. Current therapies are not engaging or not adapted to the upper limb motor functions of individual players. Through mixed reality videos, therapists can receive patients' physiological results and observe their movements in real-time during gameplay for evaluation. Observation of gameplay allows clinicians to become aware of any compensatory movements, such as overusing the shoulder muscles to assist in raising the arm, which could improve function in the short term but might be detrimental in the long term [45]. This would allow patients to get regular feedback from their rehabilitation therapists on their progress. Such telehealth applications with clinical oversight are becoming more and more critical as rehabilitation stays have decreased due to limitations in insurance.

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