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Prototyping Exoskeleton Interaction for Game-based Rehabilitation

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ABSTRACT

Exoskeletons are increasingly used for rehabilitation. To support the design of new and engaging ways of interacting with an exoskeleton, we have developed a low-cost toolkit that interfaces a LEGO Technic arm exoskeleton with serious gaming. The toolkit enables easy modifications and options for the integration of a range of sensors. Additionally, it can be applied for use in gaming via a screen display or virtual reality (VR) systems. The toolkit provides real-time data streaming valuable for researchers and clinicians to analyze how the exoskeleton is being used. We present two case studies with the exoskeleton being used as an input and output interface for serious gaming.

CCS CONCEPTS

• **Human-centered computing** → *Human computer interaction (HCI).*

KEYWORDS

Human-Computer Interaction, Human-Robot Interaction, Assistive Robotics, Exoskeletons, Prototyping, Rehabilitation, Game design, Gamification, Body Ownership

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1 INTRODUCTION

Robotics are an outstanding tool for rehabilitation that relies on frequency, intensity and consistency of the prescribed exercises [12]. Rehabilitation activities are specifically geared to promote the re-education process and encourage the development of lost skills while accommodating for specific physical, cognitive or affective impairments [6]. In the last decades there has been an immense progress on rehabilitation robotics research and development, with three technologies being dominant: endpoint manipulators, cable suspensions and exoskeletons [17, 23]. Most of these devices are expensive, non-portable and cumbersome to set up. Therefore, their use for rehabilitation therapy can only be carried out in clinical settings and with professional assistance [5, 9].

Many universities and research groups have designed robotic exoskeletons, for instance [7], [15], and [21] as exoskeletons can potentially provide mobile, user-friendly therapy at home [14] which may allow patients and their families to fit training sessions in to their own schedule. Moreover, exoskeleton's usage as an interface in rehabilitative serious gaming can increase motivation leading to better rehabilitation outcomes [12]. At home rehabilitation requires the devices to be low cost, flexible, safe and intuitive to use.

To pursue these potentials, we have built an exoskeleton prototyping toolkit, which serve us in exploration of interaction design concepts. The designs contribute to a couple of research projects that we are currently engaged in, one focusing on robotic rehabilitation of stroke patients and another on rehabilitation of children with Cerebral Palsy (CP) after they have undergone muscle lengthening surgery. In this paper we share our experiences of using the toolkit platform in two case studies, namely exoskeleton as an input device in gaming, and exoskeletons as a motion output interface for VR. Documentation and instructions on how to use the toolkit, including a construction manual, a part list, and software resources, may be found on GitHub[1]. Besides the EduExo education kit[2] for students, teachers, and makers, we are not aware of other low-cost do-it-yourself exoskeleton toolkits available.

[1]https://github.com/REHYB/LegoArmExoskeleton
[2]https://www.eduexo.com/

The paper is structured as following: First we present the technical components of the toolkit. In case study 1 we observed a child with CP using one of our exoskeleton prototypes to play a serious game by stretching and contracting his leg. Case study 2 utilizes the exoskeleton as an interface to provide motion feedback on collisions in a virtual environment. Additionally, in an extension of case study 2, gaze tracking from a VR headset was used to activate tasks that sent output signals to the exoskeleton to begin moving the arm up or down. The paper wraps up with a discussion on our observations with regard to the performance of the LEGO exoskeleton, its use as an interface for rehabilitation via serious games, and the current limitations of our work.

2 IMPLEMENTATION

This section presents the components of our LEGO exoskeleton prototypes: physical construction of the exoskeleton, the features of the software program and scenes, and the virtual reality setup. The presentation refers to the arm version of the exoskeleton applied in case study 2, while case study 1 used a modified versions of the exoskeleton to make it fit the legs.

The physical construction of the LEGO exoskeleton was made from 623 LEGO Technic pieces and used Velcro straps to secure it to the limb, see figure 1. The exoskeleton uses three LEGO EV3 Large Servo motors[3] to move the exoskeleton. It has two motors built in around the elbow making it capable of applying torque on the joint for flexion and extension, and it has one motor moving a cuff around the wrist providing torque for pronation and supination (rotation of the wrist). A motor is located on either side of the exoskeleton and jointly they are able to produce a maximum of 200 Ncm with a gear ratio of 5:40. While these motors are now retired they may be found in numerous web stores (new and second-hand).

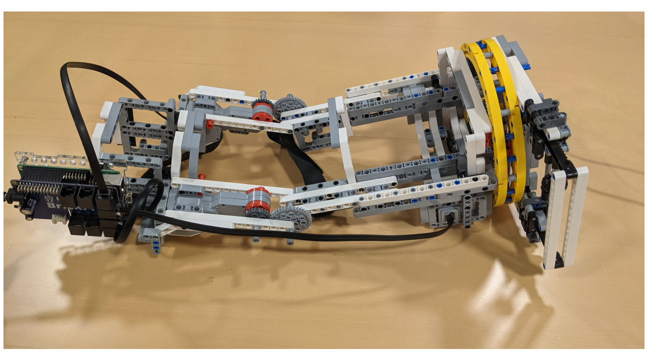

Figure 1: Fully constructed prototype of the LEGO arm exoskeleton used for Case Study 2

The LEGO exoskeleton's control unit is a combination of a Raspberry Pi and an extension board called BrickPi.[4] The BrickPi board serves as an interface between the Raspberry Pi 4 Model B (8 GB) with built-in wireless networking capabilities and the LEGO EV3 motors. The Raspberry Pi 4 was able to run the main python loop of the exoskeleton program ~ 820 times per second (820 Hz), and therefore enabled a fast, high frequency logging and communication between the control unit and Unity. Unity is the main system for execution of the events, including motion of the exoskeleton, visual- and audio-related game events, plus sensor data logging.

The communication protocol, UDP, [16] was used to stream sensor data and send commands between the exoskeleton control unit and Unity. Latency was measured in a stimulation round which lasted for 2 minutes. The average latency of 22004 measures were 9.9 MS (STD= 5.2 MS). A python script ran on the Raspberry Pi to continuously receive UDP messages from Unity stating the degree of the angle values of the LEGO EV3 motors and provide updates to Unity about motor position and angle rotation. Furthermore, the exoskeleton's software supports multithreading using python's library[5] enabling the control unit to handle multiple tasks simultaneously such as actuate the motors, write logs and communicate with Unity concurrently on different threads.

A large capacity (15600mAh) XTPower XT-16000QC3 powerbank[6] was used to provide energy for the exoskeleton through the DC connector of the BrickPi system. It was capable of supplying the exoskeleton with extended power range, and provide 12V output. The downside of this power supply is that it is quite big and heavy (405 g), and therefore unpleasant to wear on the arm. Nonetheless, a lengthy power cable allowed us to keep it separately on a table during study. Alternative options are to utilize a belt pouch to hold the powerbank, or utilize smaller, but less durable batteries for more mobile solutions.

A HTC Vive Pro Eye system (including the Head mounted display (HMD), the Vive Controllers and Vive Trackers) communicates with Unity through the SteamVR plugin[7]. This system has been used in a number of research projects (e.g. [2], [20]), and the HMD's integrated eye tracker makes it possible to record users eye movements and study gaze-interaction with exoskeletons. Furthermore, individual Vive Trackers can be mounted on real-world objects or peoples body parts for tracking position and motion [11].

The total cost to build an exoskeleton prototype (not including VR system and computer) is less than $500. Medical exoskeletons typically cost between $33.000 and $150.000 [18, 19]. The total weight of the LEGO arm exoskeleton system is 1.5 kg, including the power supply.

3 CASE STUDY 1: GAME CONTROL WITH AN EXOSKELETON

The basic function of a robotic exoskeleton is to support motion of the user's limbs by reinforcing body position and movements. Limb motion, voice activation, or gaze, for instance, allow users to interface with the robots basic functionality. Additionally, the exoskeleton can be a control device. For example, a user may conduct a limb movement to move a virtual object such as an avatar or a cursor on a screen, or control another physical robotic device.

In Case Study 1, a 10-year-old child with CP used our exoskeleton to play a game. He had previously undergone muscle lengthening

[3] https://www.LEGO.com/en-us/product/ev3-large-servo-motor-45502
[4] https://www.dexterindustries.com/brickpi/
[5] https://docs.python.org/3/library/threading.html
[6] https://www.xtpower.de/XT-16000QC3-PowerBank-modern-DC-/-USB-battery-with-15600mAh-up-to-24V
[7] https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

surgery [4], and at the time of the study, he had already fully recovered from the surgery with almost full range of motion in the knee. He has a lot of experience with playing video games and was very eager to get involved to provide feedback.

The arm exoskeleton prototype was modified to fit his height and weight, and conformed to the shape of his leg. While the control unit had to be repositioned on this version, the prototype did attach easily to the leg and did not cause any discomfort.

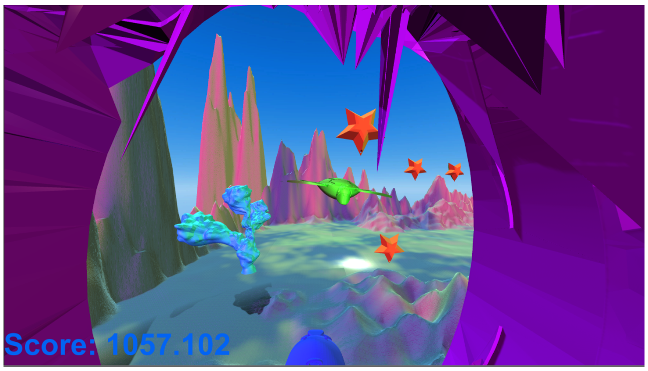

Figure 2: Screen capture of the Unity game developed for study 1. The participants would stretch or contract their leg wearing the exoskeleton to navigate the game's avatar to collect the stars. The exoskeleton's control unit registered changes in the motor's angle and translated the change as input to the Unity game.

We developed a simple game in Unity where the player's avatar is a fish that continuously swims around in an underwater world. The objective of the game is to collect as many of the gold stars as possible to increase their score. The score is displayed in the lower left corner and is tallied as a player progresses in the game. Stars at varying heights will appear in the game encouraging the user to extend/flex their leg.

At the beginning of every session, the range of motion of the knee has to be calibrated. The user is asked to extend their leg as much as they can and this motor position is read and saved. Afterwards, the user are told to bend their knee, and the minimum motor position is recorded and saved. Once the minimum and maximum angles are found, the angles are used to map the range of motion onto the screen. This range of motion (in X angle values) will correspond to the full y-direction that the player in the game moves along. The intention is to have the users stretch their leg as much as they can on their own and for the exoskeleton to assist the movement when the user cannot reach the desired angle. For still shots of the game see figure 2.

The 10-year participant was able to complete the game successfully. After one game the participant did not wish to play again and filled out a questionnaire we prepared. The participant reported that the experience playing the game as "fun", but it was between easy and very easy in difficulty. The exoskeleton was found to be comfortable and would be used multiple times a week if available at home. The participant also provided additional comments and suggestions on how the game could be improved, which we will address in the discussion section.

4 CASE STUDY 2: EXOSKELETON AS AN INTERFACE TO PROVIDE MOTION FEEDBACK

Our second case study explored utilization of the exoskeleton prototype as an interface to reflect back onto the human user with feedback from the serious games played during rehabilitation. To better understand the affect of the feedback to the user, we investigated body ownership illusions when using VR body representations in combination with an exoskeleton. These illusions exploit the fact that self-perception is malleable [22], which means that through crossmodal stimulation the human brain may incorporate and feel artificial body parts as one's own. In clinical settings, crossmodal illusions are used for treating the stroke conditions of hemiparesis (the weakness or impairment of one side of the body) and spatial neglect (when patients fail to orientate, report or to respond to stimuli located on one side) [1, 8]. Specifically, we wanted to explore whether it was possible to induce the so-called virtual hand illusion (VHI) [10] when using our exoskeleton by measuring whether participants believe that a virtual arm they are seeing in VR belongs to their own body.

Fourteen participants were seated at a table while wearing an exoskeleton prototype on their right arm, c.f. figure 3. After putting on a Vive VR headset, the participants found themselves at a virtual wooden table at the same height and location as the real table. Participants saw a 3D model of their right forearm at the same position as their real forearm. Passing through the middle of the virtual forearm, a T-shaped, opaque racket was visible, c.f. figure 4.

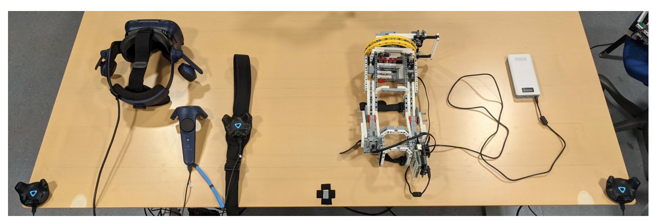

Figure 3: The setup of the experiments in the lab. It presents all the equipment used: i) Electric adjustable wood table with two Vive Trackers in the lower corners to align the table's position in virtual reality and to calculate the midpoint indicated by black tactile "hole" where the participant's elbow is to be positioned. ii) HTC Vive Pro Eye HMD, iii) HTC Vive controller, iv) a Vive Tracker to position and track the participant's shoulder in VR, and v) the LEGO exoskeleton prototype and powerbank

The wood table was kept in alignment with its digital twin in the virtual environment by utilizing Vive Trackers on the near corners. The trackers' positions also helped calculate a midpoint, marked by a small tactile "hole", in which the participant would rest their elbow to keep their arm in alignment with the virtual arm. At the midpoint, a Unity object was placed in the virtual space to serve as the "elbow". A third tracker was worn by the participant on the shoulder to calculate shoulder object position. The upper arm was visualized with a cylinder with a skin texture, stretching dynamically between the elbow and shoulder object positions and creating an illusion of the upper arm following subtle movements.

During the experiment, a ball would fall down every 3 seconds onto a random position of the racket causing a pronation and supination (rotating the wrist to left and right) and elbow flexion and extension (bending and extending the elbow) on the virtual arm. These movements were translated to the actuators of the exoskeleton which were then moving the participants' real arm similarly to the virtual arm. This way the participant felt the impact of the ball on their real arm at the same time as they would see it hitting the virtual arm. Three types of balls with different weight and sound on impact (tennis ball - lightest, baseball ball - medium weight, pool ball - heaviest) were used. At the impact moment the system could provide a spatial 3D sound matching the sound of the current type of ball.

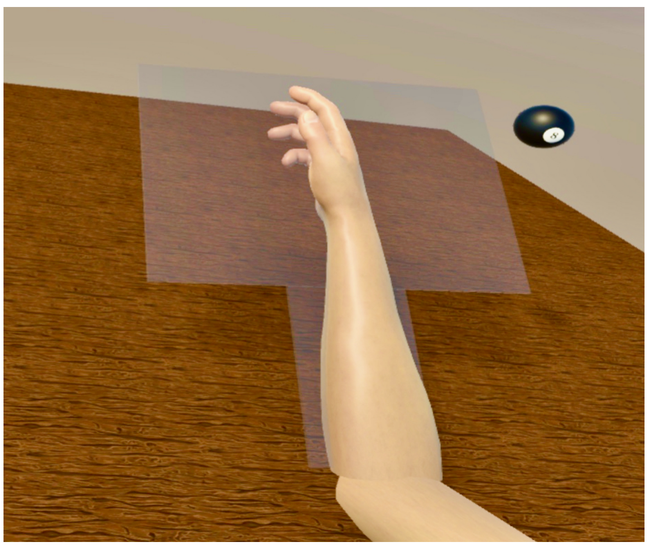

Figure 4: Participant's view in the VR scene. A ball is currently falling onto the opaque racket attached to his arm and upon impact the exoskeleton will move the arm accordingly.

After each block, which lasted 2 minutes and consisted of 40 balls dropping, the participants would make a 7-point Likert scale rating on 10 questions in a modified version of the Longo et al. questionnaire to measure their experience of subjective embodiment [10]. An example of a question would be: *During the block it seemed like I was looking directly at my own hand, rather than at a virtual hand.* From the 10 Likert scale responses we calculated an embodiment score for each participant on each conditions (see below).

We manipulated the order of conditions according to a Latin Square design for each of the 4 blocks that participants tried: In two of the blocks the exoskeleton would move the participant's arm in the same direction at the elbow and wrist joint as the virtual arm was moving. In the other two, when the virtual forearm was moving down at the elbow upon impact of the ball (relative to the weight of it), the exoskeleton would push the participants' arm up, and the wrist rotations was also in-congruent (the exoskeleton rotation of the wrist being in the opposite direction of the virtual). Finally, one of each of the two congruent and two in-congruent blocks would have sound of the balls impact while the other would be silent.

Participants' reported higher sense of embodiment when the movements of the exoskeleton were congruent with the virtual arm motion seen in the VR (mean = 5.185, on a scale from 0 to 6, with 6 being the maximum score) compared to the conditions when the exoskeleton was moving the wrong direction (incongruent) (mean = 2.273). A two-way repeated measure ANOVA revealed this difference to be significant: $F(1, 12) = 44.262$, $p < 0.001$, $\eta_p^2 = .787$; one outlier participant was removed from the analysis. The reported embodiment scores were slightly higher in the cases when the stimuli was coupled with sound effects (mean = 3.951) compared to the conditions with absence of sound (mean = 3.508). However, the two-way ANOVA revealed this difference to be non-significant: $F(1, 12) = 1.814$, $p = .203$, $\eta_p^2 = .131$. The interaction between congruence and sound was not significant either.

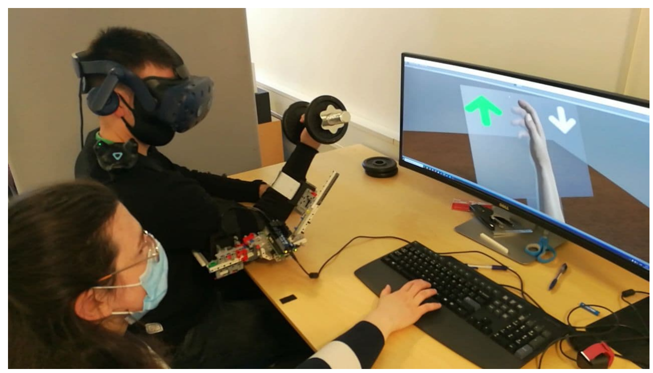

Figure 5: Gaze tracking in the VR headset are utilized for up and down input control of the exoskeleton's motors. The participants view is shown on the monitor. When looking at one of the arrows will make the exoskeleton go up or down.

In an extension to Study 2, we utilized the integrated eye tracking sensors from the Vive Pro Eye HMD while using the exoskeleton prototype to lift light weights. The added modality of gaze allow us to test gaze as exoskeleton input in a virtual environment similar to the ball-experiment. In this version, the hand racket was used as a virtual control panel. In Figure 6, the participant highlights the up arrow with their gaze turning it green to provide feedback of gaze activation, followed by the exoskeleton motors rotating the elbow joint in an upward direction. Activating the down arrow, naturally rotated the motors to move the exoskeleton downwards. Twelve participants used this input for more than 400 gaze activations each without any difficulties.

5 DISCUSSION

Our exoskeleton toolkit was effective for real-time handling of data streams and commands between the PC and the exoskeleton. We had zero data loss, and the average delay between the Unity system and the exoskeleton was no more than around 10 milliseconds. It is easy to modify for different studies and new sensors can be added to the toolkit, for instance gaze input.

The main observation from Case Study 1 was that the exoskeleton could be used as an effective input device with a personalized setting for knee joint range. In Case Study 2 we found that participants did experience a virtual arm illusion when the motions of the arm was congruent with the visual events, but not when it was in-congruent. This is a promising finding towards further clinical studies, since the illusion has important therapeutic implications on e.g. the treating of hemiparesis and spatial neglect, and suggests that exoskeleton movements can increase the immersion in virtual reality games. However, we did not include a condition with no motions at all, nor a 2D, screen-based version of the arm. Therefore, more experiments are required to evaluate the potential effects. It is our recommendation that the table set up we developed (c.f. figure 3) and the collision stimuli applied in our second case study would be considered for these kind of experiments.

5.1 Serious Games

While utilizing VR for rehabilitation training may provide extra benefit over traditional rehabilitation, one must consider the additional complexity of the system that leads to increased development time and required resources [12]. System complexity will also need to be taken in account when implementing a system for use in at home rehabilitation where simplicity and ease of use are priority. Additionally, it should be considered whether VR provides a significant enough benefit to justifies the extra cost and complexity of VR over 2D virtual environments that can be displayed on tablets or monitors.

Many papers discuss how a game interface can increase motivation during rehabilitation [3, 12, 24], however, motivation doesn't just depend on the presence of a game, but also on the quality and design of the game [13]. A simple game may appear as motivating in a short term study. However, if the game does not develop over time there is a risk that the user gets bored of the game and that it will lose its effect [13], which is particularly a problem in short games where the goal is achieved fast and you can only repeat the game. This was very much the case we observed with our participant from Study 1. The participant only wanted to play the game once, and then started suggesting a number of improvements to it. Actually, the game originally developed for Study 1 had obstacles which should be avoided by extending and contracting the leg, and if the player collided with an obstacle the game would start over. However, this version was simplified based on preliminary discussions of the game with a child with CP to accommodate the child's disabilities. Eventually, this child was not able to participate in the experiment. When the 10-year-old child played the newer simplified version of the game, it was to easy. The majority of the feedback we received from him focused on the development of the game such as more obstacles to avoid and improving the story line. This clearly illustrated the importance of serious games adapting to match the play mechanics and difficult level to the user's ability, in order to maintain interest in continued play. Consequently, we are now looking into the possibilities of implementing the exoskeleton as an interface with a range of open-source Unity games [8]. If more games becomes available, the likelihood of matching a users preferences and competences increases.

Another interesting design challenge that we would like to address: How can we build a motivating game that would retrain rehabilitation patients to use objects of everyday life such as a fork and a knife, for instance? A serious game focused on simulating activities of daily living will train the user for very specific tasks while using an exoskeleton, and likely this training may be transferred to the tasks in real life.

5.2 LEGO exoskeletons

While an advantage of using LEGO Technic is that it is easy to adapt, this can also be a disadvantage. During prototyping and testing, adaptability is a good trait. However, LEGO does have its limitations when it comes to being the main material for an exoskeleton. While individual LEGO pieces can withstand large amounts of force, the junction of two or more pieces can be a weak point. Where the motor connects to the LEGO rod is one of the exoskeletons weakest points. When the exoskeleton experiences a lot of resistance, the gears will skid, failing to provide the full torque and offsetting the motor position value. This happened to us a number of times, especially if the participants use force against the exoskeleton motion or carry an extra weight in their hand, as we observed when testing gaze controlled lifting of hand weights in the extension of Study 2.

LEGO pieces come in various lengths and shapes that can serve as the building block for many things, but some shapes or functions are difficult to achieve purely from using LEGO pieces further limiting the quality of the exoskeleton. In order give a more comfortable and secure fit of the exoskeleton prototype for Study 1, a set of inserts had to be made. These inserts were 3D printed in polylactic acid and padded with a closed cell polyethylene foam adhesives which gives them a softer fit. This required additional effort and added to the complexity of the construction.

5.3 Limitations of the case-studies

Our case studies have three important limitations. First, they are not intended to be clinical trials, but considered interaction design explorations of the feasibility of an exoskeleton as an interface for serious gaming. We only included a very limited number of subjects, and only in Study 1 was an actual patient involved. Secondly, the end goal of our design projects are to develop devices for rehabilitation at home that individuals can assemble and modify on their own. However, the early state of the current toolkit requires expertise in both LEGO construction and gaming platforms such as VR technology. The third limitation with the LEGO exoskeleton system is that it is not able to lift the full weight of a paralyzed limb against gravity. Referring to our case study for children with CP, for instance, the LEGO motors can theoretically provide just about 40% of the required torque while performing knee extension, and at this full power the gears may start skidding. However, on a positive note, the torque produced by the exoskeleton will not

[8]https://linuxpip.org/open-source-unity-games/

pose a safety risk that could potentially over extend the users limbs causing injury.

5.4 Future work

We aim to design interfaces for low cost and lightweight exoskeletons that will promote socially cooperative rehabilitation to engage stakeholders including the patient, caregivers and medical professionals in the rehabilitation sessions. We have explored some augmented reality scenarios for training of daily activities, for instance tooth brushing or brooming, in a video related to our research in exoskeleton interaction for stroke patients [9]. Additionally, we would like to test the options for patients and therapist to collaborate remotely. If both of them are wearing an exoskeleton, we imagine that it will be possible for the therapist to provide instructions that the patients exoskeleton will execute in real time and be able to replay for later training. This could mitigate logistical issue of therapists traveling to their patients and make at home rehabilitation more flexible and efficient.

6 CONCLUSION

We have demonstrated a low cost, flexible exoskeleton toolkit that may serve user studies involving patients and support interaction design experiments. While scene and event handling works robustly via the Unity platform, the physical construction by LEGO parts has shortcomings with strength and motor torque power. Thus, the toolkit is deemed suitable for early prototyping and experimenting, but not for therapeutic use.

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