Enhancing Rehabilitation Outcomes with a Virtual Reality-Integrated Robotic System for Arm-Leg Gait Training

Atharva C. Paralikar
M.Eng. – Robotics
University of Maryland
College Park, Maryland
atharvap@umd.edu

Bharadwaj Chukkala
M.Eng. - Robotics.
University of Maryland
College Park, Maryland
bchukkal@umd.edu

Hemanth Joseph Raj
M.Eng. - Robotics.
University of Maryland
College Park, Maryland
hemanth1@umd.edu

Joseph Pranadeer Reddy Katakam
M.Eng. - Robotics.
University of Maryland
College Park, Maryland
jkatak73@umd.edu

***Abstract* — Arm swing is an integral component of human gait and has been shown to improve rehabilitation outcomes for patients with neurological deficit-induced impairments. However, most existing rehabilitation robotic systems for walking do not include arm swing, limiting their effectiveness. Robotics systems for rehabilitation have been well in the market for a while now, for various purposes, among that rehabilitation of upper/lower body extremities for stroke survivors has been quickly creating a market for itself. Although there have been quite a lot of developments in how robotic rehabilitation has been proven more effective than manual physical therapy, that efficacy has been observed to increase as such by providing better repetitive movement to the part being rehabilitated but not so much on the patient's cognitive vigor or their motivation. However, there is a way to tackle that issue with finesse and improve the pace of recovery. We hypothesize an enhancement to the current paper, although tangential, the enhancement by itself has shown to have quite the potential to alter the perception of the user and improve the cognitive ability to fasten the recovery process. The proposal is to enhance the robotic system by adding a Virtual Reality head mounting device that has been tethered to the patient. This will consist of a custom world in which the patient will engage in gaming and is presented a virtual reality-integrated robotic system for arm-leg gait training. This proposal aims to improve rehabilitation outcomes by incorporating synchronized arm and leg movement, robotic therapy and gamification through Virtual Reality.**

Keywords— robotic rehabilitation, physical therapy, virtual reality, gamification

I. Introduction

Our system builds on previous work in the development of rotational orthoses for walking with arm swing but incorporates a virtual reality device to provide immersive, interactive training experiences for patients. The virtual reality component allows patients to engage in a variety of gait training scenarios, including overground walking, obstacle avoidance, and stair climbing, which can be customized to individual patient needs and goals.

This proof of concept has been undergoing a lot of research on patients with mobility impairments, and much of the research found that it improved gait speed, balance, and coordination compared to traditional rehabilitation methods. In addition to that, patients and clinicians have reported increased motivation and engagement during training sessions with the virtual reality component. Research suggests that the integration of virtual reality into rehabilitation robotic systems has the potential to enhance rehabilitation outcomes for patients with mobility impairments.

A. Background

The coordinated movement of the arms and legs during walking is modulated by interlimb neural circuits and is considered to be a fundamental and primitive movement pattern. Clinical studies have shown that incorporating arm movement into gait rehabilitation can improve outcomes for patients, including improved balance, sensation, and motor function. However, the lack of gait robotic products with arm swings has led to the use of other approaches for clinical research, such as arm-leg cycling and therapist-assisted arm-swing during locomotion training. These approaches have demonstrated the benefits of incorporating arm movement into gait rehabilitation but have limitations in terms of scalability and usability.

II. A Brief Study of the Original Paper

A. Details of the paper

The paper we are referring is "Mechanical Design and Control System Development of a Rehabilitation Robotic System for Walking With Arm Swing" authored by Juan Fang and Kenneth J. Hunt, Division of Mechanical Engineering, Department of Engineering and Information Technology, Institute for Rehabilitation and Performance Technology, Bern University of Applied Sciences, Burgdorf, Switzerland. Journal: *Frontiers in Rehabilitation Sciences*

B. Summary of the paper

In this study, a better arm-leg robotic system was designed for use in rehabilitation in neurological deficit-related disorders such as stroke and to study interlimb neural coupling. The robotic system was designed to have these capabilities:

1) Active movement of the upper and lower limbs, including the shoulder, elbow, hip, knee, and ankle joints.

2) Dynamic loading that simulates ground reaction forces during walking, starting with the heel and progressing to the whole foot and forefoot.

3) The ability to produce flexible gait patterns.

The robot for rehabilitation is designed to include arm swing during gait training as it improves the chances of recovery. The patient is made to walk on a curved path on the treadmill. The robot has 10 controllers in total. Two on each shoulder, elbow, hip, knee, and ankle for better muscle joint activation. Force feedback at the foot sole is used. The control system for the robot uses Impedance control algorithms. Based on past work, this robot provides the following improvements:

1) It is thought that the dynamic loading input from the sole of the foot modulates walking patterns, which is advantageous for relearning how to walk.

2) To create proprioceptive sensation input to joints involved in a typical walk, elbow joint activation was also considered.

3) Synchronized arm and leg movements when walking were achieved.

Pros of the paper:

The paper had the following positives. In terms of execution and responsiveness, the robotic system is thought to be practicable. Compared to systems that simply consider lower limb activation, better rehabilitation is achieved. The novel mechanical system has been shown to improve rehabilitation.

Cons of the paper:

While the paper does offer good improvements on the current system, it fell short in a few areas. The inclusion and active participation of the patient amounted to the majority of the success achieved. No force sensors were included to measure the voluntary inputs. No means to naturally stimulate voluntary movement of joints by the test patient. As a result, deviations were observed, and the test patients reported constrained movements.

C. Control Strategy of the robot

We derive the closed-loop transfer function for each of the joints.

For each joint

Inertia $= J$, Spring Stiffness $= K_s$, Damping $= K_d$, External Torque = τ_{ex} , Control Torque = τ_c

The net torque can be written as follows

$$\tau_{net} = \tau_{ex} + \tau_c - K_s\theta - K_d\dot{\theta}$$

We know that

$$\ddot{\theta} = \frac{\tau_{net}}{J}$$

This implies that

$$\ddot{\theta} = \frac{\tau_{ex} + \tau_c - K_s\theta - K_d\dot{\theta}}{J}$$

$$J\ddot{\theta} + K_s\theta + K_d\dot{\theta} = \tau_{ex} + \tau_c$$

Taking a Laplace transformation on both sides

$$Js^2\theta(s) + K_d s\theta(s) + K_s\theta(s) = \tau_{ex}(s) + \tau_c(s)$$

Transfer function: $(\tau_{ex} + \tau_c) \to \theta$

Hence the plant dynamics can be modelled as

$$G_p(s) = \frac{\theta(s)}{(\tau_{ex} + \tau_c)} = \frac{1}{Js^2 + K_d s + K_s}$$

The mechanical impedance of the open loops system $(\tau_c = 0)$

$$Z = \frac{\tau_{ex}(s)}{s\theta(s)} = Js + K_d + \frac{K_s}{s}$$

The impedance controller to be used as the function

$$G_c(s) = K_v s + K_p$$

Consider the reference position to be $\theta^* = 0$

The error will be given by

$$\theta_e = \theta^* - \theta \quad \to \quad \theta_e = -\theta$$

This gives us the reference output of the controller for $\theta^* = 0$,

$$\tau_c(s) = -sK_v\theta(s) - K_p\theta(s)$$

Substituting the control torque in the transfer function

$$Js^2\theta(s) + K_d s\theta(s) + K_s\theta(s) = \tau_{ex}(s) - sK_v\theta(s) - K_p\theta(s)$$

The closed-loop transfer function is given by

$$G_p(s) = \frac{\theta(s)}{\tau_{ex}(s)} = \frac{1}{Js^2 + (K_d + K_v)\,s + (K_s + K_p)}$$

The mechanical impedance of the closed loop

$$Z_{CL} = \frac{\tau_{ex}(s)}{s\theta(s)} = Js + (K_d + K_v) + \frac{(K_s + K_p)}{s}$$

Two sets of impedance parameters were used with low and high gains, the system ran in two situations with and without test person. To quantify the movement tracking accuracy, root-mean-square error (RMSE) of each joint trajectory was calculated on an evaluation interval from $t_0\ to\ t_1$.

$$RMSE_{\theta} = \sqrt{\frac{1}{N}\sum_{i=t_0}^{t_1} \left(\theta_e(i) - \theta_t(i)\right)^2}$$

where N is the number of data points in the interval t_0 to t_1. θ_e and θ_t are the experimental and target joint angles, where the shoulder, elbow, hip, knee, and ankle joints are considered. Using the hip segment position as the origin (0, 0) of the reference frame, the segmental trajectories of the ankle and toe were calculated using:

$$X_{ankle} = l_t sin\theta_h + l_s sin(\theta_h - \theta_k)$$
$$Y_{ankle} = -l_t cos\theta_h - l_s sin(\theta_h - \theta_k)$$
$$X_{toe} = X_{ankle} + l_f \sin sin\ (90 - \theta_h + \theta_k - \theta_a)$$
$$Y_{toe} = Y_{ankle} + l_f \cos cos\ (90 - \theta_h + \theta_k - \theta_a)$$

D. Discussions

The movement of the arm-leg frames from the system alone, without a test person, was like the reference trajectories with mean RMSE in 10 joints of 1°, which demonstrated that the first design requirement was met. The flexible topology of the control system makes it convenient for future expansion, for example using additional drives for the body-weight support system. The synchronous arm-leg walking patterns were implemented, which met the technical feasibility criterion of implementation. Impedance control algorithms enabled the system to assist in walking on the curved treadmill, which provided the basis for the generation of a curved toe trajectory. Normal overground gait patterns include a rhythmical oscillation of the body trunk/hip joint center as well as synchronized movement in the arm and the legs.

E. Results of the paper

The paper measures how the robot performs when it's uncoupled and coupled with the patient for each of the joints. For each, it charts how the system performs throughout the gait cycle and this plot is compared to the target trajectory. The results obtained from the robot are very close to the actual target trajectory.

Few results from the paper are shown below in figs. 1 and 2

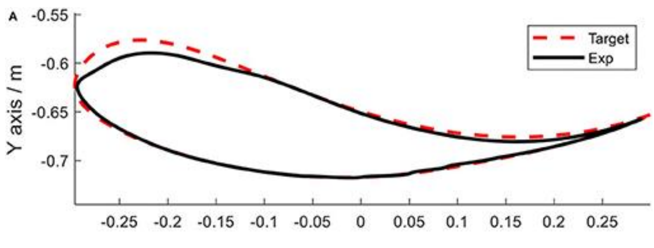

Fig. 1 Foot trajectories – Ankle

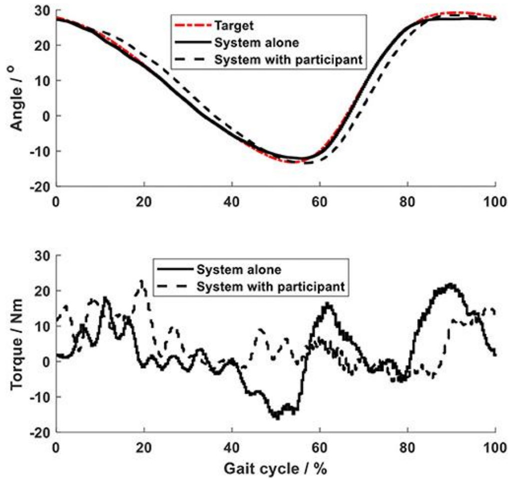

Fig. 2 Angle and Torque vs. Gait Cycle – Hip joint

III. LITERATURE REVIEW

For our proposed enhancements to the paper, i.e., integrating Virtual Reality and adding a gamification aspect to it requires a literature review of clinical studies and research papers that work in those areas, so we have worked towards the same.

Rehabilitation is an intuitive process, where counterintuitive tasks which are redundant and repetitive are practiced normalizing certain movements targeting a muscle group or a joint [1]. Rehabilitation or Physical therapy is a sensitive area that requires the expertise of more than one physician working very closely with the patient. The natural gait pattern of a regular person that is walking, is incredibly hard to manually replicate, which leads to lesser time dedicated to actual training/rehabilitation subsequently resulting in an inefficient therapy session for the patient. Moreover, it does not gather and provide objective data about the patient after constant monitoring. Another major downside of physical therapy that is often noticed after a prolonged period of repetitive practice is, a lack of motivation to rehabilitate and an increased cognitive load. But exercise is considered a key factor contributing to the treatment and improvement of the patient [2-4].

Considering the last 20 years, the advancement of technology in the field of physical rehabilitation has grown steeply. The usage of Robotics and VR technology has gained a lot of interest in the field of rehabilitation [5, 6]. Robot-assisted rehabilitation is a type of therapy that uses robots to help people with motor impairments improve their movement and function. These robots can provide intensive, repetitive therapy that is tailored to individual patient needs and can also provide quantitative assessment and monitoring [7]. Robot-assisted rehabilitation has shown promising results in the treatment of motor impairments and has the potential to improve the effectiveness of rehabilitation and make it more personalized for patients [8].

To date, mainly two different types of robotic devices have been implemented, for both lower and upper limbs rehabilitation. The first is based on the use of exoskeletons, which are systems constituted by mechanical and electronic components that completely cover the limb, following its anthropometric characteristics, and assist the kinematic or dynamic activity that the patient performs [9, 10]. Unlike exoskeletons, robotic end-effector devices work by interconnecting to the limb's distal end, thus allowing the natural kinematic activation of the movement without specific constraints and, thus, with more degrees of freedom [11, 12].

Just like robotics, Virtual reality (VR) technology is being used increasingly in the field of rehabilitation. VR systems are based on computer-generated 3D environments that allow users to interact with them using auditory, visual, and haptic feedback [13-15]. VR has three key characteristics: immersion, presence, and interactivity. Immersion refers to the degree to which VR can provide multisensory stimuli and a high degree of matching between the user's actions and the cues generated by the system. [16]

Consequently, the interactivity of the patient with the immersive Virtual Environments (VE) plays a major role in influencing their experience and perception, consequentially his/her sense of presence. The level of immersion a VR device or system can provide to the user can be a good mode of categorization. The devices can be categorized into fully immersive, semi-immersive, and non-immersive [17]. Each of the categories can be characterized by different factors, fully immersive VR systems with the use of tools like head-mounted display (HMD) devices or cave automatic virtual environments (CAVE) are called fully immersive because they enable the highest degree of immersion and interaction with the VE. These systems do so by completely altering the patient's perception of reality. On the other hand, we have semi-immersive systems that provide moderate levels of immersion and interaction. They oftentimes consist of huge monitors or projectors that partially alter what the patient perceives, what the patient perceives are part VE and part real world. Lastly, we have non-immersive systems that allow minimal immersion and sub-par interaction with the VE. These include much simpler devices, supposedly a computer or a tablet.

After extensive research and many clinical trials and experiments, the utility and efficacy of VR have been well understood and properly recognized, and a standard will also be soon established in the field of neuromotor rehabilitation. The integration of VR and Robotic technology applied to rehabilitate a patient has allowed for providing a safe and controlled environment for the patient to perform a repetitive task while working with a tethered or untethered robot that assists with rehabilitative rhythmic movements. While the robot works tirelessly and more efficiently than regular physicians and also gathers objective data by keeping the patient under constant monitoring, VR provides the patient with personalized simulated real-life environments that give the patient an opportunity to exercise safely and increase motivation and compliance with the treatment [18].

A recent advancement that needs to be highlighted as a part of our survey is the Lokomat Robot. Although it was a standalone exoskeletal robotic system for rehabilitation until a specific point in time, it was recently integrated with VR to increase rehabilitation efficacy and keep the patient motivated. They have created a reward-based game called Lokosprint with quite an interactive VE, where the patient keeps walking to collect coins in a simulated environment. This was supposed to boost the reward-based working mechanism in the user and as a consequence did, in fact, have a tremendous positive impact on the rate of recovery and decreased patients' cognitive load drastically [19].

One study by Roy et al. has experimented with the use of VR to rehabilitate patients with motor disabilities. As a result of their study, they found that not only did patients find it fun, but the clinicians also gave their consideration that it was a highly engaging and motivational intervention [20]. Su et al. also did a similar study in patients with acute lower back pain where they used VR in the rehabilitation treatment and received a major level of acceptance from patients who had significant improvement in terms of motivation and recovery [21].

There have been multiple other benefits of VR intervention in the rehabilitation process, it has been shown to be effective in improving muscular strength and overall control of body movement in older adults. Kim et al. found that a therapy regimen with VR intervention has brought significant improvement in rehabilitating the hip muscles and increasing the muscle strength in the VR group, they compared this study with a control group which did not show any significant improvements [22]. Another study by Bryanton et al. tested a VR-based exercise regimen on a group of children with cerebral palsy and observed that the children showed higher ranges of ankle activation ranges of motion when there was VR intervention compared to when they were going through traditional physiotherapy [23].

After much review of the effectiveness of VR-based exercise therapy, it can be highlighted that it has not only shown to work positively in the cases discussed above, but also proved effective in treating specific conditions, such as multiple sclerosis, and chronic stroke as well. Matt et al. after an extensive study of various VR intervention cases and different types of VR immersive techniques, deemed that VR-based exercise programs were considered more effective than conventional physiotherapeutic rehabilitation approaches. Although there are a lot of instances to back the efficacy and promote the usage of VR intervention in rehabilitation, further research is necessary to explore the complete potential of VR in rehabilitation and to determine the best ways to use it in different clinical settings [24].

IV. METHODOLOGY

To enhance the current paper, we propose a three-pronged approach. The methodology is as follows, first is the integration of virtual reality into rehabilitation. The second is the gamification aspect with the help of a custom-designed game and the third is the usage of custom-designed hardware i.e., a tilt sensor which can be used to gather information from the patient and can be used to control the actions in the game. Our hypothesis is further expanded in the following subsections which go deeper into how it is exactly designed and integrated into the robotic system. We believe that this three-pronged approach will be a decent enhancement to the robot studied in the original paper.

A. Integrating Virtual Reality into the system

As we have studied in the detailed literature review, Virtual Reality can be used in conjunction with conventional physical therapy sessions during rehabilitation providing better patient outcomes. We all know the benefits of using robots for rehabilitation. They can provide repeatable actions which are necessary for physical therapy. Robots can perform these tasks without succumbing to fatigue. They are also capable of producing these repeatable actions with good accuracy. VR integration will take this to the next level in terms of rehabilitation.

Here is how we propose bringing together robots and Virtual Reality to help offer the best of chances to patients to recover from neurological conditions, predominantly strokes. Our initial design consists of placing a head-mounted device (HMD), i.e., a Virtual Reality headset. We will be using an industry-grade VR headset readily available from the market, of the likes of Oculus Quest 2 by Meta. Once the stroke patient is coupled to the system and has donned the robot, they are ready to start the therapy session. At this point, the VR headset will be placed on the face and then turned on. A representation of the stroke patient can be seen in fig. 3 below.

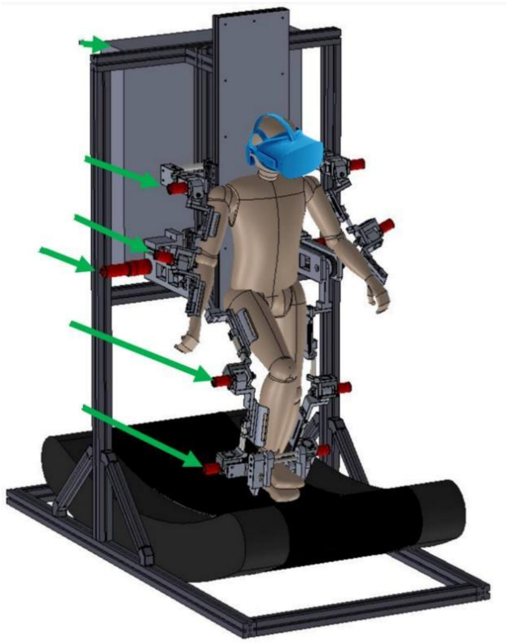

Fig. 3 Representation of the VR-Integrated Robot

Once the patient has donned the robot and the VR headset, it will then initialize the person to be positioned in the game world. A representation of this game can be shown in the following fig. 4. Please note that this is what we would want the virtual world to finally look like. The image below is only for representational purposes.

(Image copyrights belong to VR Fitness Insider [25])

Fig. 4 An Example for the VR world

B. A VR game to aid rehabilitation

As seen in fig. 4 above, we get a gist of the game world the patient will be in. In this, the patient will interact with the game by emulating the actions required to walk on ice during skiing. Since the original robot is designed to aid walking with an arm swing. All the walking actions made will be exactly mapped onto the game to produce a similar gait in the game world. The person skiing through the path will be made to go through various checkpoints to earn game rewards. The aim of the rehabilitation is to maximize rewards in each session. The skiing action will be mapped using a tilt sensor to be worn on the patient's arm. This will be explained in brief in the next sub-section.

The game has been designed using the Unity game engine. For the purpose of this project, we have designed a simple skiing game as a proof of concept. The Unity game engine is popular for designing games from simple 2D games to complex high graphics games. Most of the game dynamics are designed in Unity with some functionalities written in C#. Since it's just in the POC phase, given the timeline of the project, the game can be controlled by the arrow keys of the keyboard. Future work can be toward developing the game in a 3D VR world. A snapshot of the game is shown below in fig. 5. The motions of the arm control the walking speed since the robot incorporates an arm swing in it.

Fig. 5 The Snapshot of the Game

C. Tilt Sensor on an arm brace

A prototype of the hardware has been developed by us to capture the amount of angle movement in the arm made by the patient during rehabilitation using a tilt sensor. It can capture the amount of angle movement in the arm made by the patient during rehabilitation. We also developed a CAD model of a working arm brace to accommodate the tilt sensor, it is shown below in fig. 6. As you can see it is a simple design and can be manufactured with lightweight materials such as Carbon Fiber or machined Aluminium.

Fig. 6 Arm brace with a tilt sensor

As we can see in the above figure, once the patient has been coupled to the robot will don this arm brace. The tilt sensors are placed on the frame of the brace which will capture the movements of the arm during rehabilitation and map them onto the game controls which will make the person move in the Virtual environment. The tilt sensor is based on the 9-axis gyroscope MPU9250. The designed tilt sensor detects the level of the arm that it is put on and can track the angular speed, and tilt. This can be shown by the LEDs in the sample video (attached in the project files) The brace designed for it is designed using SolidWorks. It is meant to be worn on either arm. The design is shown below in fig. 7.

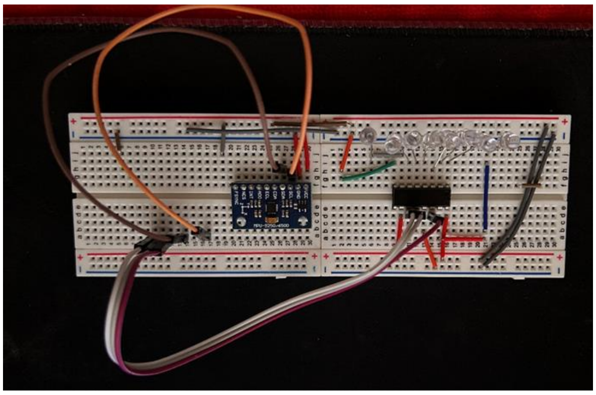

Fig. 7 Electronic Design of the tilt sensor

Our proposal is to make use of these three ideas to serve as an enhancement to the paper we chose. The literature review serves as an empirical basis for our hypothesis.

V. Conclusion

Robotic integration with rehabilitation of impairments caused due to neurological conditions have proven to be highly effective in terms of patient outcomes. The paper we referred developed one such robot which worked toward it by implementing a robotic exoskeleton which rehabilitates not just gait but also arm swing. We proposed enhancements done by means of adding a Virtual Reality dimension to it and gamifying it for an even better patient outcome.

As we see from the literature reviewed, gamification and use of VR technology has been held in high regard in rehabilitation science. It has been observed to be a very effective addition to any kind of rehab program by providing an encouraging virtual environment. The hardware usually consists of various wearable sensors able to track, monitor and in certain cases provide haptic feedback for movement correction. The results available from studies conducted all over show improved rehabilitative response from patients using such therapy regimes. We have introduced this technique to the research surveyed by implementing a VR headset, an arm brace with sensors and a ski game designed in Unity. The motion detected by the sensors translates to movement in the game.

The VR environment provides the patient with much needed encouragement as well as soothing experience by taking the patient away from the generally mundane routine of therapy into a virtual environment that can be programmed to depict different scenes from nature to the patient’s desire. Finally, such a system can be made modular and be used with any other rehabilitation program.

VI. Future Work

The way we see it, future work toward this enhancement would consist of improving the current 2-D game to a full-scale interactive VR game. Another aspect would be toward providing haptic feedback from the game world to the patient thus making the interaction more realistic.

VII. Acknowledgment

The authors of this paper; Atharva, Bharadwaj, Hemanth and Joseph; would like to extend their grateful thanks to Prof. Dr. Anindo Roy for not only teaching the theoretical aspects of rehabilitative robotics but also ensuring that we learned about the practical aspects of it including actual operations at on organizational level. We also want to thank our teaching assistant, Doug Summerlin, for being helping during TA sessions and guiding us through this project.

References

[1] Musculoskeletal simulation based optimization of rehabilitation program. In: Lee L-F, Krovi VN, editors. Virtual rehabilitation, 2006 international workshop on. IEEE;

[2] Kizony R, Katz N, Weiss PL. Adapting an immersive virtual reality system for rehabilitation. JVCA 2003;14(5):261–8.

[3] Research on rehabilitation exercise based on virtual reality technology. In: Ma H, editor. Proceedings of the 10th conference on man-machine-environment system engineering; 2010.

[4] Weiss PL, Rand D, Katz N, Kizony R. Video capture virtual reality as a flexible and effective rehabilitation tool. J NeuroEng Rehabil 2004;1(1):12.

[5] Geidl W, Deprins J, Streber R, Rohrbach N, Sudeck G, Pfeifer K. Exercise therapy in medical rehabilitation: study protocol of a national survey at facility and practitioner level with a mixed method design. Contemp Clin Trials Commun 2018; 11:37–45.

[6] Pedersen BK, Saltin B. Evidence for prescribing exercise as therapy in chronic disease. Scand J Med Sci Sports 2006;16(S1):3–63.

[7] Yakub F, Md Khudzari AZ, Mori Y. Recent trends for practical rehabilitation robotics, current challenges and the future. Int J Rehabil Res. 2014;37:9–21.

[8] Giansanti D. The Rehabilitation and the Robotics: Are They Going Together Well? Healthcare (Basel) 2020;9:26.

[9] Sawicki GS, Beck ON, Kang I, Young AJ. The exoskeleton expansion: improving walking and running economy. J Neuroeng Rehabil. 2020;17:25.

[10] Mehrholz J, Pollock A, Pohl M, Kugler J, Elsner B. Systematic review with network meta-analysis of randomized controlled trials of robotic-assisted arm training for improving activities of daily living and upper limb function after stroke. J Neuroeng Rehabil. 2020;17:83.

[11] Maranesi E, Riccardi GR, Di Donna V, Di Rosa M, Fabbietti P, Luzi R, et al. Effectiveness of Intervention Based on End-effector Gait Trainer in Older Patients With Stroke: A Systematic Review. J Am Med Dir Assoc. 2020;21:1036–1044.

[12] Molteni F, Gasperini G, Cannaviello G, Guanziroli E. Exoskeleton and End-Effector Robots for Upper and Lower Limbs Rehabilitation: Narrative Review. PM R. 2018;10(Suppl 2):S174–S188.

[13] Dockx K, Bekkers EM, Van den Bergh V, Ginis P, Rochester L, Hausdorff JM, et al. Virtual reality for rehabilitation in Parkinson's disease. Cochrane Database Syst Rev. 2016;12:CD010760.

[14] Lange BS, Requejo P, Flynn SM, Rizzo A. The potential of virtual reality and gaming to assist successful aging with disability. Phys Med Rehabil Clin N Am. 2010;21:339–356.

[15] Massetti T, da Silva TD, Crocetta TB, Guarnieri R, De Freitas BL, Bianchi Lopes P, et al. The Clinical Utility of Virtual Reality in Neurorehabilitation: A Systematic Review. J Cent Nerv Syst Dis. 2018;10:1179573518813541.

[16] Mujber TS, Szecsi T, Hashmi MSJ. Virtual reality applications in manufacturing process simulation. J Mat Process Technol. 2004;156:1834–1838.

[17] Howard MC. A meta-analysis and systematic literature review of virtual reality rehabilitation programs. Comput Hum Behav. 2017;70:317–327.

[18] Frozen shoulder rehabilitation using microsoft kinect. In: Mangal NK, Pal S, Khosla A, editors. Innovations in green energy and healthcare technologies (IGEHT), 2017 international conference on. IEEE; 2017.

[19] https://healthiar.com/neuro-rehab-vr-launches-lokosprint-for-lower-limb-mobility

[20] Enhancing effectiveness of motor rehabilitation using kinect motion sensing technology. In: Roy AK, Soni Y, Dubey S, editors. Global humanitarian technology conference: south asia satellite (GHTC-SAS). IEEE; 2013. 2013. IEEE.

[21] A virtual reality lower-back pain rehabilitation approach: system design and user acceptance analysis. In: Su W-C, Yeh S-C, Lee S-H, Huang H-C, editors. International conference on universal access in human-computer interaction. Springer; 2015.

[22] Kim J, Son J, Ko N, Yoon B. Unsupervised virtual reality-based exercise program improves hip muscle strength and balance control in older adults: a pilot study. Arch Phys Med Rehabil 2013;94(5):937–43.

[23] Bryanton C, Bosse J, Brien M, Mclean J, McCormick A, Sveistrup H. Feasibility, motivation, and selective motor control: virtual reality compared to conventional home exercise in children with cerebral palsy. Cyberpsychol Behav 2006;9(2):123–8.

[24] Giansanti D. The Rehabilitation and the Robotics: Are They Going Together Well? Healthcare (Basel). 2020 Dec 30;9(1):26.

[25] VR Fitness Instructor - https://www.vrfitnessinsider.com/this-weeks-vr-game-roundup-ski-the-slopes-visit-new-zealand-and-explore-the-unknown/