GAVRe^2: Towards Data-driven Upper-Limb Rehabilitation with Adaptive-Feedback Gamification

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***Abstract*— This paper presents Game Adaptive Virtual Reality Rehabilitation (GAVRe^2), a framework to augment upper limb rehabilitation using Virtual Reality (VR) gamification and haptic robotic manipulator feedback. GAVRe^2 integrates independent systems in a modular fashion, connecting patients with therapists remotely to increase patient engagement during rehabilitation.**

GAVRe^2 exploits VR capabilities to not only increase the productivity of therapists administering rehabilitation, but also to improve rehabilitation mobility for patients. Conventional rehabilitation requires face-to-face physical interactions in a clinical setting which can be inconvenient for patients. The GAVRe^2 approach provides an avenue for rehabilitation in a domestic setting by remotely customizing a routine for the patient. Results are then reported back to therapists for data analysis and future training regime development.

GAVRe^2 is evaluated experimentally through a system that integrates a popular VR system, a RGB-D camera, and a collaborative industrial robot, with results indicating potential benefits for long-term rehabilitation and the opportunity for upper limb rehabilitation in a domestic setting.

I. Introduction

Rehabilitation robotics is an active avenue of research with high development and growth rates. The effects of rehabilitation robotics for stroke rehabilitation have spurred heavy commercial investments, which have been explored by [1].

Historically, physicians have studied correlations between motivation and rehabilitation success, with an early study citing factors contributing to a lack of motivation, which in turn hampered a patient's improvements in performing Activities of Daily Living (ADL) [2]. Research into this relationship has continued over the years, exploring factors affecting motivation for rehabilitation.

Patients have been found to feel bored and alone when performing repetitive motions during rehabilitation. Compounded by the lack of control while recovering, the loss of motivation impedes their progress during rehabilitation [3]. Recently, gamification of rehabilitation exercises have underpinned efforts to increase engagement and rehabilitation outcomes.

Our work is inspired by stakeholder meetings which have highlighted the need for an objective patient monitoring system to ensure patients are provided with the best care available to increase their recovery rate. Due to the inherent differences between people's response to rehabilitation, the ability to personalize rehabilitation is crucial for an efficient and positive recovery experience.

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The main contribution of this paper is Game Adaptive Virtual Reality Rehabilitation, a framework that provides flexibility towards upper-limb rehabilitation. The modules cater for a variety of hardware, forming a unique vision for patient-therapist engagement, and individualization so as to meet the needs and preferences of each patient.

Rehabilitation gamification is incorporated into the system using Virtual Reality (VR) technology, allowing patients to complete their exercise routines in a fully-immersive and engaging gaming environment. The flexibility and mobility of the framework overcomes the limited consultation time between patient and therapist during rehabilitation. Statistics recorded during the exercises can be reported back to the therapists allowing for changes to improve patient recovery.

This paper is organized as follows, Section II introduces current literature on robotic rehabilitation and gamification. Section III presents the framework, while Section IV details the modules. Section V presents the results from the evaluation of the framework. Section VI discusses the limitations and possible drawbacks to the current framework, and Section VII provides conclusions and future work.

II. Related Works

A. Rehabilitation Robotics

The introduction of robotics into rehabilitation has been motivated by the strengths that robotics can offer to the field. Physiotherapists traditionally rely on subjective measures and empirical experiences to gauge the progress of each patient. The standardization and reliability of robotic systems allows therapists to engage, through objective data, with patient recovery.

The concept of performance-based robot therapy was first applied in a clinical setting by [4] while further works in rehabilitation robotics have focused on reducing limb impairment through repetitive goal-oriented movements for patients, leading to collaborative robotic systems and frameworks [5] [6].

The learning model for rehabilitation follows the pattern of implicit motor learning [7], sparking interest in patient engagement during rehabilitation [8]. Complementary approaches to enable and improve active engagement during rehabilitation has led to "Assistance-As-Needed" frameworks [9], challenging conventional perspectives for rehabilitation [10].

Although robotic systems for both upper and lower limb rehabilitation have been developed in parallel [11], fundamental differences in their aims have caused fragmented approaches towards upper-limb rehabilitation. Lower-limb rehabilitation aims to re-gain or improve locomotion skills requiring systems with large form factors to support patients with their balance

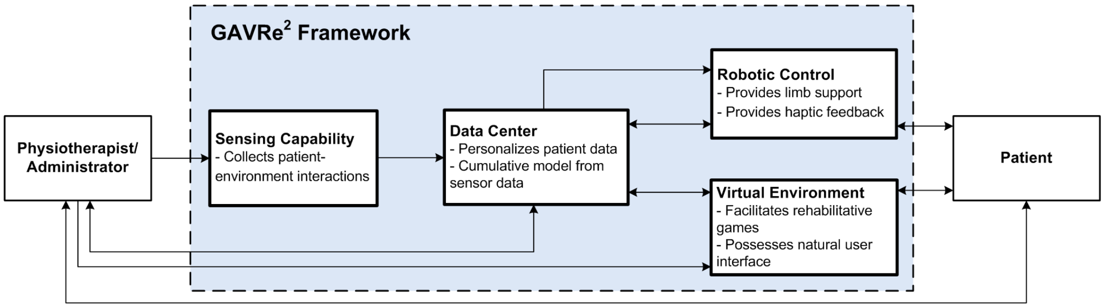


Fig. 1. The GAVRe^2 framework (**G**ame **A**daptive **V**irtual **Re**ality **Re**habilitation) designed for modular, personalized rehabilitation.

and strength. This has led to several system with similar implementations and designs [12].

Upper-limb rehabilitation primarily aims to improve ADL performance. Since these activities vary significantly, upper-limb rehabilitation systems have generally targeted a specific part of the limb, leading to diverse systems with varying form factors and capabilities [13]. Moreover, there is a lack of frameworks or meta-models to approach upper-limb rehabilitation.

The efficacy of robotic rehabilitation over conventional techniques has been explored extensively but remains an active avenue of research. Most clinical trials of robotic rehabilitation indicate significant improvements over conventional methods. However, these are confined to short-term effects targeting acute stroke patients [14] and few works exist for long-term follow-ups [15]. Furthermore, most studies suffer from small sample sizes, or don't directly compare the system with conventional methods, making it difficult to generalize the effects of the robotic rehabilitation systems.

B. Rehabilitation Gamification

Contemporary literature indicates that patients lose motivation during rehabilitation, which has implored professionals and researchers to explore complementary approaches to improve patient engagement. [16] discusses the concept of task grading with goals which *"provide enough challenge... [to] build up body structures, functions and capacities"* while *"providing too much challenge can lead to failure"* due to frustration and disappointment.

Finding the "just-right-challenge" has lead therapists to explore gamification of the rehabilitation process to increase motivation. The neurological process behind gamification benefits is explored in [17] where "reward-related dopaminergic systems in the brain" trigger changes required for cognitive recovery. Accordingly, researchers have targeted the characteristics of gamification [18].

Using these characteristics, researchers have produced the GAMER and PACT frameworks [19] to design *"serious games"* which do not have entertainment, enjoyment or fun as their primary purpose [20]. One key aspect of these frameworks is the inclusion of stakeholders during their design process, leading to integrated and positive outcomes through games better suited and more engaging for patients.

In general, rehabilitation gamification aims to increase active engagement with rehabilitation exercises through in-game interactions, non-trivial or ability-compliant goals, and a reward scheme for positive reinforcement.

C. Virtual Reality

Using Virtual Reality (VR) technology in rehabilitation is a concept which has gained significant traction in recent years. This is, in part, due to the availability of affordable VR systems and the capability to systematically augment or limit sensing capacity. Coupled with the ability to provide tractable data, such as accurate head tracking, and data collection in fully immersive environments, active discussions are occurring in the medical field [21] exploring the benefits of incorporating VR in post-stroke rehabilitation.

The simulated environment from fully-immersive VR systems, similar to simulated imagery in our brains, have been shown to affect weight perception [22] which can reinforce the use of mental faculties in rehabilitation [23]. "Embodied cognition", through brain and bodied stimulation, was postulated by [24] to provide measurable improvements in rehabilitation outcomes. Most recently, a randomized control trial studying the effects of semi-immersive VR for upper-limb rehabilitation confirms that a mixed approach (VR augmented rehabilitation) produced better outcomes based on conventional metrics [25].

III. Framework

The proposed framework, Game Adaptive Virtual Reality Rehabilitation (GAVRe^2), is an integrated approach towards rehabilitation gamification through the use of a fully-immersive VR experience. The customization of certain agnostic modules allow personalized rehabilitation for patients, and forms a network of exercise data which can be analyzed.

An example approach for using GAVRe^2 can be seen in Figure 1, mapping how modular components can interact with each other. Underpinning the framework is the Data Center, connecting all agnostic modules through data acquisition, and the Virtual Environment, which provides the fully-immersive game scenario used during rehabilitation. Feedback is obtained through the Sensing Capability and Robotic Control modules.

Based on the requirements of the rehabilitation program, additional components can be easily integrated, providing additional avenues for data collection. As patients complete therapy sessions, the Data Center uses the collected data to update the rehabilitation program while integrating expert therapist knowledge.

The modular nature also means that a variety of approaches to administering rehabilitation are possible (i.e. if the patient is already motivated, then the VR environment may be unnecessary) based on the therapist's recommendation.

IV. Methodology

To evaluate the GAVRe^2 framework, experiments were conducted using three basic modules for haptic feedback of upper limb rehabilitation: Robotic Control; Virtual Reality; Visual Feedback (Sensor).

A. Robotic Control

Robotic control was realized using a Universal Robots UR3 to provide physical support and haptic feedback for the patient's upper limb. A 3D printed cast was manufactured to support the weight of the patient's limb. To measure the interaction between the manipulator and the environment, a 6-axis force-torque sensor (ATI Axia80) was fitted between the limb cast and the end effector.

To enable the interactions between the robotic manipulator and the patient, an admittance control scheme is employed utilizing the force-torque sensor readings to generate an appropriate motion trajectory for the robotic arm [26]. The desired velocity of the end effector ($\dot{x}$) is calculated using a wrench (F_{EE}) obtained from the force-torque sensor measuring the interaction between the patient and robot. An admittance gain matrix (K_a) is used to obtain a suitable task-space velocity command.

$$\dot{x} = K_a \cdot F_{EE} \tag{1}$$

Typically, the desired end effector velocity is transformed into corresponding joint velocities using the inverse of the kinematic Jacobian of the manipulator. However in the presence of kinematic singularities the inverse of the Jacobian matrix becomes degenerate, resulting in erratic and dangerous motions of the robot. This poses a significant problem in applications such as robotic rehabilitation where human safety is of paramount importance [27]. To address kinematic singularities, damped least squares is implemented and a *damped* Jacobian inverse (J^*) is used to obtain the appropriate joint velocity for the desired task-space motion.

$$\begin{aligned} \dot{q} &= J^*(q) \cdot \dot{x} \\ J^* &= J^T(JJ^T + \lambda^2 I)^{-1} \end{aligned} \tag{2}$$

Appropriate values for admittance gain and damping coefficient (λ) were chosen after experiments were conducted, selecting values which do not interfere with the existing safety systems of the manipulator.

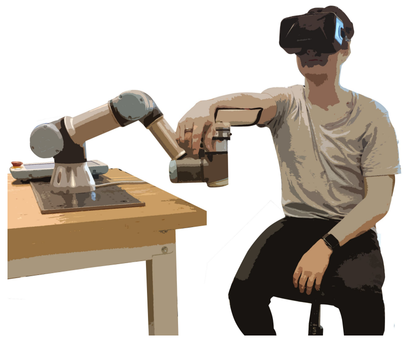


Fig. 2. A system based on the GAVRe^2 framework used for experiments. The three components are the UR3 robotic arm, Oculus Rift VR headset, and the PrimeSense Carmine camera.

B. Virtual Reality

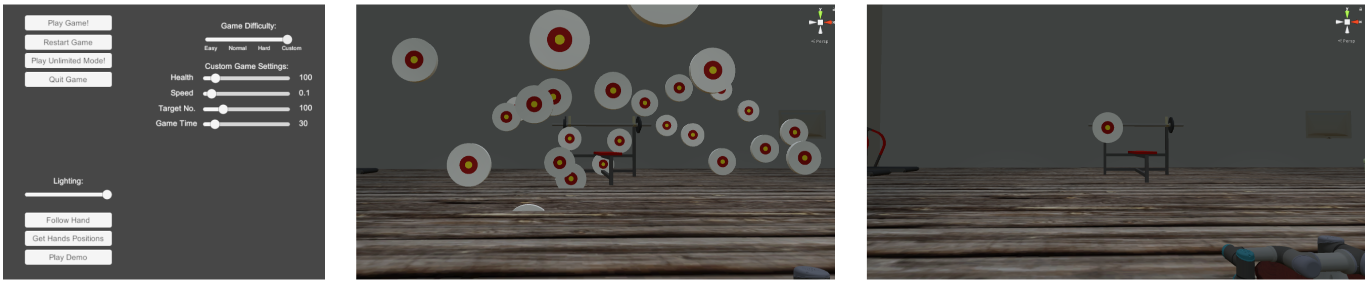
To our knowledge, there is little work on rehabilitation gamification which utilize fully-immersive VR environments. Most works exploit semi-immersive VR environments by using external sensors, such as cameras or Inertial Measurement Units, to *insert* patients into the environment.

The VR environment was designed using the Unity game development platform in Windows, communicating with other modules using the open-source ROS (Robot Operating System) package ROSBridgeLib. The package creates a websocket that provides agnostic communication protocol connections, allowing cross-platform communications.

Development of a fully-immersive scenario with a VR headset requires considerations of portability, robustness, and application, as different headsets have unique application-specific trade-offs. The Oculus Rift headset was chosen over the HTC Vive due to its portability, requiring a sole portable sensor to track head movements. The trade-off of lower accuracy (the Rift is unable to track head movements above 180 degrees accurately) is not critical for our application since generally the user is seated. Compatibility with the SteamVR plugin was also a consideration for choosing the Oculus Rift.

Gamification of the rehabilitation process was completed using 4 different game modes which can be selected by the therapist. The games provide targets for the patient to shoot using a virtual laser beam projected from the end effector of the robotic arm. This requires the use of several different muscle groups in the limb to hit the targets. Hence, by carefully positioning the targets, a way of promoting the use of specific muscles can be achieved. User side effects such as nausea and disorientation [28] were mitigated through the synchronization of the real UR3 with the virtual UR3.

1) Free-run Mode: This game mode spawns a set number of targets where the patient attempts to destroy as many as possible within 30 seconds, as shown in Figure 3(a). The settings for the mode are set by the therapist through 3 default difficulties. Personalized configurations can also be set by the therapist, changing target health, speed, number of targets, and game time.



(a) (b) (c)

Fig. 3. Screenshots of the VR virtual environment; (a) is the user interface for therapists to customize and choose game modes for the patient; (b) shows the targets spawning for Free-run Mode; (c) shows the target for Tracking Mode.

2) Timed Challenge Mode: For more directed muscle movements, this mode spawns single targets in series. When the target is destroyed, another target is spawned, requiring the patient to collect as many points as possible within 30 seconds. This game mode allows therapists to design particular target placements to induce desired limb motions of the patient.

3) Tracking Mode: To increase patient-therapist engagement, a tracking mode was devised to allow for mirroring exercises. To facilitate patients outside of healthcare facilities, this mode allows therapists to create a target using a depth camera to track their right hand. Points are given based on which part of the target the virtual laser beam is hitting, emphasizing accuracy with increasing point scores near the bullseye. This game mode is timed, allowing for consistent progress tracking for each patient. This game mode has potential to allow real-time interactions by adding a video conferencing plug-in to allow for real-time and remote feedback by therapists.

4) Pre-planned Path Mode: Patients and therapists have limited face-to-face consultation time during rehabilitation sessions. To maximize the benefits of robotic rehabilitation, the completion of repeated exercises is necessary. The pre-planned mode allows the therapist to record a pre-planned path for the patient to follow in their own time, changing configurations such as target speed and health. This game mode is suited to repeat exercises which patients perform in their own time between each therapy session.

In all of these game modes, each patients' scores are tracked and recorded in the data center, allowing for post-session analysis by the therapist.

C. Visual Feedback

Remote allocation of targets for the Tracking Mode and Pre-planned Path Mode is obtained through depth information from a PrimeSense Carmine RD1.08 camera. The open source middleware library PrimeSense Natural Interaction Middleware (NiTE) has been adapted to track the right hand of the user and communicate with Unity. The coordinates of the hand are transformed into the VR simulated environment frame of reference and recorded, forming the path users follow using the UR3.

The path formation can be autonomous (subject to temporal constraints) or conducted manually. Both modes provide a single path for the target in the game.

V. Experimental Results

Two different groups of *healthy* people (10 and 19) participated in a series of experiments that were conducted to test the robotic manipulator and a system implementation of GAVRe^2 framework.

A. Robotic Manipulator

A blind experiment was conducted to ascertain the effects of the admittance gain matrix (K_a) on user experience, user ability, and their preferences. A total of 10 participants tracked a drawn path with a laser pointer projecting from the end effector of the UR3 with an admittance control scheme.

Upon the completion of 3 tests, participants were given a short survey to determine the what they thought was the best configuration. The path of the end effector was tracked during the 3 tests for each participant, as shown in Figure 4. During testing, 2 out of the 10 participants' results were invalidated. These resulted from human and technical errors such as discrepancies in instructions, erroneous calibration of robotic arm prior to testing, and corrupted data sets discovered in post-test analysis.

Participants were not provided time to familiarize themselves with the control scheme on the robotic arm. During the experiments, each participant was only told, in a neutral manner, to follow the drawn path. A damping coefficient of $\lambda = 0.1$ was used for all tests based on heuristic testing of the damping effect on exertion to manipulate the robotic arm.

Table I outlines the results of the experiment. Each participant chose a best setting while least error is the lowest mean perpendicular error between the tracked path and the actual path.

TABLE I
THE BEST ADMITTANCE GAIN MATRIX COEFFICIENT FROM ELIGIBLE USERS IN A BLIND TEST. (NUMBER OF ELIGIBLE USERS = 8)

Admittance Gain	Best setting		Time Taken (s)		
	User chosen	Least error	Min	Median	Max
0.020	3	2	19.04	24.32	39.44
0.025	4	2	15.92	22.16	47.28
0.030	1	4	16.24	25.80	47.04

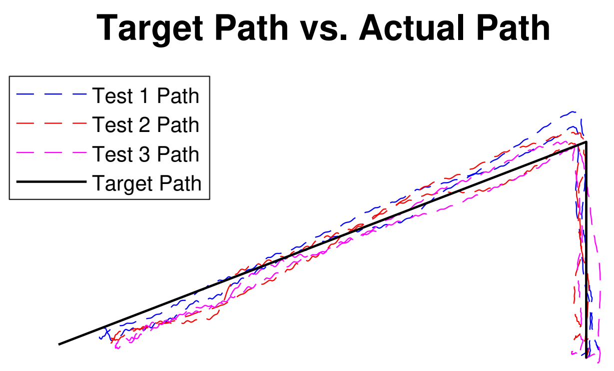


Fig. 4. An example of one participant's tracked path using the UR3 robotic manipulator with an admittance control scheme. Each blind test was conducted with a different admittance gain value.

B. Framework System

An evaluation of our system based on the GAVRe^2 framework was conducted, with a new group of 19 participants, in the experiment setup shown in Figure 2. Each participant was provided some time familiarizing themselves in the VR environment before attempting an experiment using the Free-run Mode.

At the end of the experience, each participant was given a survey to evaluate the experience, based on the 1-10 Rating Scale, age range, amount of gaming experience, and prior experiences with VR and robotic arms.

VI. Discussion

A. Robotic Manipulator

The admittance gain matrix dictates the responsiveness of the end effector motion and we postulate a higher K_a would result in a better experience of the control scheme. However, the disparity between what users experience and their objective results (Table I) indicate that participants perceived the best configuration based on their comfort rather than the results from the experiment objective.

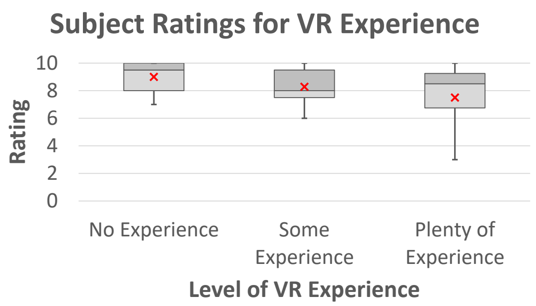


Fig. 5. Box and whisker plot of subject ratings of the VR experience on a 1-10 scale.

Concretely, all participants took similar times to achieve the same task despite the responsiveness difference of the control scheme. We also observe that although the task was implicitly a planar task (2-Dimensional due to laser projection), all participants manipulated the robotic arm using all 3 axes for their comfort.

The control scheme for the robotic arm requires two parameters to be tuned. From our experiments, it is evident that individualized parameters are required for user comfort. Utilization of the data center can be done by personalizing parameters for each user, augmenting their experience. These can be realized by calibration maneuvers which can be conducted at strategic points in their rehabilitation progress. Adaptive parameter tuning is another avenue which can improve user experience dynamically.

B. Framework System

From the user study, we observe that there is no explicit association between system rating and age or prior gaming experience. However, Figure 5 highlights a clear correlation between prior VR experience and the participants' rating of the VR module for the various game modes.

The generality of the scores between age, gaming experience, and VR module rating, shown in Table II, highlights the potential of GAVRe^2 to increase motivation and engagement during rehabilitation. Alternate strategies are also viable due to the modular nature of the framework (i.e. non-VR methods such as engaging with communities to increase peer-to-peer interactions during rehabilitation).

TABLE II
MEAN RATINGS FOR VR EXPERIENCE BASED ON AGE GROUP AND GAMING EXPERIENCE USING A 1-10 RATING SCALE. (OVERALL PARTICIPANT MEAN = 8.42) A RATING OF N/A INDICATES NO PARTICIPANT FITTING THE TWO RESPECTIVE CATEGORIES.

Gaming Experience (GE)	Age Range			GE Mean
	15-24	25-34	35-44	
<once per month	8.25	10	7.5	**8.29**
1-3 times per fortnight	10	N/A	10	**10**
2-5 times per week	9	8	N/A	**8.67**
Daily	9	3	N/A	**7.5**
Age mean	**8.83**	**7.25**	**8.33**	

A similar trend was observed with the robotic arm, indicating a correlation between prior robotic arm experience and rating of the robotic arm module. However, contrasting the prior experiences with VR, only 5 participants out of the 19 have had previous experience with a robotic arm

The two correlations suggest that eligibility requirements should be considered for prospects looking to use GAVRe^2 framework for upper limb rehabilitation. As the primary purpose of GAVRe^2 is to increase motivation and engagement, prospects who have had prior experiences with VR and/or robotic arms might not reap the benefits of the framework.

VII. Conclusions

This paper has presented Game Adaptive Virtual Reality Rehabilitation (GAVRe^2), a modular framework for upper limb rehabilitation, exploiting sensory-modified gamification and haptic feedback using Virtual Reality and a robotic arm. The proposed framework integrates independent modular systems to improve patient-therapist engagement for rehabilitation.

An experiment and a study was conducted based on a test system composed of a robotic arm, a camera, and a VR headset. A total of 29 subjects participated to evaluate our system based on level of interaction and comfort.

Our results demonstrated the need for personalized parameters for robotic arm control, and suggests that prior experience with any particular component provide indications for diminished user experience.

Future work will evaluate the flexibility of GAVRe^2 by implementing systems with different components and compare user experience and comfort levels. Future work will also include larger sample sizes for statistical significance and use the available data to learn appropriate robotic arm parameters to gauge any changes in user comfort levels.

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REFERENCES

[1] J. Laut, M. Porfiri, and P. Raghavan, "The Present and Future of Robotic Technology in Rehabilitation," *Current Physical Medicine and Rehabilitation Reports*, vol. 4, no. 4, pp. 312–319, 12 2016.

[2] J. F. GARRETT and J. S. MYERS, "Motivation and rehabilitation." *Occupational therapy and rehabilitation*, vol. 30, no. 5, pp. 296–9, 10 1951.

[3] J. Luker, E. Lynch, S. Bernhardsson, L. Bennett, and J. Bernhardt, "Stroke Survivors' Experiences of Physical Rehabilitation: A Systematic Review of Qualitative Studies," *Archives of Physical Medicine and Rehabilitation*, vol. 96, no. 9, pp. 1698–1708, 9 2015.

[4] H. Krebs, J. Palazzolo, L. Dipietro, M. Ferraro, J. Krol, K. Rannekleiv, B. Volpe, and N. Hogan, "Rehabilitation Robotics: Performance-Based Progressive Robot-Assisted Therapy," *Autonomous Robots*, vol. 15, no. 1, pp. 7–20, 2003.

[5] M. G. Carmichael and Dikai Liu, "Towards using musculoskeletal models for intelligent control of physically assistive robots," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 8 2011, pp. 8162–8165.

[6] H. Mukai, C. Sato, I. Abe, and T. Kikuchi, "Development of rehabilitation robot for hand ReRoH," in *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 12 2017, pp. 2063–2068.

[7] H. Krebs, B. Volpe, and N. Hogan, "A working model of stroke recovery from rehabilitation robotics practitioners," *Journal of NeuroEngineering and Rehabilitation*, vol. 6, no. 1, p. 6, 2 2009.

[8] A. A. Blank, J. A. French, A. U. Pehlivan, and M. K. OMalley, "Current Trends in Robot-Assisted Upper-Limb Stroke Rehabilitation: Promoting Patient Engagement in Therapy," *Current Physical Medicine and Rehabilitation Reports*, vol. 2, no. 3, pp. 184–195, 9 2014.

[9] M. Carmichael, "A musculoskeletal model-based Assistance-As-Needed paradigm for assistive robotics," Ph.D. dissertation, University of Technology Sydney (UTS), 2013.

[10] G. King, C. Imms, D. Stewart, M. Freeman, and T. Nguyen, "A transactional framework for pediatric rehabilitation: shifting the focus to situated contexts, transactional processes, and adaptive developmental outcomes," *Disability and Rehabilitation*, vol. 40, no. 15, pp. 1829–1841, 7 2018.

[11] S. Hesse, H. Schmidt, C. Werner, and A. Bardeleben, "Upper and lower extremity robotic devices for rehabilitation and for studying motor control." *Current opinion in neurology*, vol. 16, no. 6, pp. 705–10, 12 2003.

[12] W. Huo, S. Mohammed, J. C. Moreno, and Y. Amirat, "Lower Limb Wearable Robots for Assistance and Rehabilitation: A State of the Art," *IEEE Systems Journal*, vol. 10, no. 3, pp. 1068–1081, 9 2016.

[13] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 11, no. 1, p. 3, 1 2014.

[14] L. Peng, Z.-G. Hou, L. Peng, L. Luo, and W. Wang, "Robot assisted upper limb rehabilitation training and clinical evaluation: Results of a pilot study," in *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 12 2017, pp. 2740–2745.

[15] A. C. Lo, P. D. Guarino, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, D. G. Federman, R. J. Ringer, T. H. Wagner, H. I. Krebs, B. T. Volpe, C. T. Bever, D. M. Bravata, P. W. Duncan, B. H. Corn, A. D. Maffucci, S. E. Nadeau, S. S. Conroy, J. M. Powell, G. D. Huang, and P. Peduzzi, "Robot-Assisted Therapy for Long-Term Upper-Limb Impairment after Stroke," *New England Journal of Medicine*, vol. 362, no. 19, pp. 1772–1783, 5 2010.

[16] R. Proffitt, "Gamification in Rehabilitation: Finding the Just-Right-Challenge," in *Handbook of Research on Holistic Perspectives in Gamification for Clinical Practice*, D. Novák, B. Tulu, and H. Brendryen, Eds. Harrisburg, PA: Idea Group,U.S., 2016, ch. 7, pp. 132–157.

[17] J. Janssen, O. Verschuren, W. J. Renger, J. Ermers, M. Ketelaar, and R. van Ee, "Gamification in Physical Therapy," *Pediatric Physical Therapy*, vol. 29, no. 1, pp. 95–99, 1 2017.

[18] J. W. Burke, M. D. J. McNeill, D. K. Charles, P. J. Morrow, J. H. Crosbie, and S. M. McDonough, "Optimising engagement for stroke rehabilitation using serious games," *The Visual Computer*, vol. 25, no. 12, pp. 1085–1099, 12 2009.

[19] D. Charles and S. McDonough, "A Participatory Design Framework for the Gamification of Rehabilitation Systems," in *Recent advances on using virtual reality technologies for rehabilitation*. Nova Science Publishers, 2015, pp. 2–9.

[20] D. D. R. Michael, *Serious games : games that educate, train and inform*. Thomson Course Technology, 2006.

[21] E. Wade and C. J. Winstein, "Virtual Reality and Robotics for Stroke Rehabilitation: Where Do We Go from Here?" *Topics in Stroke Rehabilitation*, vol. 18, no. 6, pp. 685–700, 11 2011.

[22] J. M. Suchoski, S. Martinez, and A. M. Okamura, "Scaling Inertial Forces to Alter Weight Perception in Virtual Reality," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 5 2018, pp. 484–489.

[23] S. Braun, M. Kleynen, J. Schols, T. Schack, A. Beurskens, and D. Wade, "Using mental practice in stroke rehabilitation: a framework," *Clinical Rehabilitation*, vol. 22, no. 7, pp. 579–591, 7 2008.

[24] M. Yates, A. Kelemen, and C. Sik Lanyi, "Virtual reality gaming in the rehabilitation of the upper extremities post-stroke," *Brain Injury*, vol. 30, no. 7, pp. 855–863, 6 2016.

[25] P. Kiper, A. Szczudlik, M. Agostini, J. Opara, R. Nowobilski, L. Ventura, P. Tonin, and A. Turolla, "Virtual Reality for Upper Limb Rehabilitation in Subacute and Chronic Stroke: A Randomized Controlled Trial," *Archives of Physical Medicine and Rehabilitation*, vol. 99, no. 5, pp. 834–842, 5 2018.

[26] M. G. Carmichael and D. Dikai Liu, "Admittance control scheme for implementing model-based assistance-as-needed on a robot," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, vol. 2013. IEEE, 7 2013, pp. 870–873.

[27] M. G. Carmichael, D. Liu, and K. J. Waldron, "A framework for singularity-robust manipulator control during physical human-robot interaction," *The International Journal of Robotics Research*, vol. 36, no. 5-7, pp. 861–876, 6 2017.

[28] S. Sharples, S. Cobb, A. Moody, and J. R. Wilson, "Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems," *Displays*, vol. 29, no. 2, pp. 58–69, 3 2008.