

Towards Adaptive Virtual Reality for Stroke Recovery: A Personalized Approach to Rehabilitation

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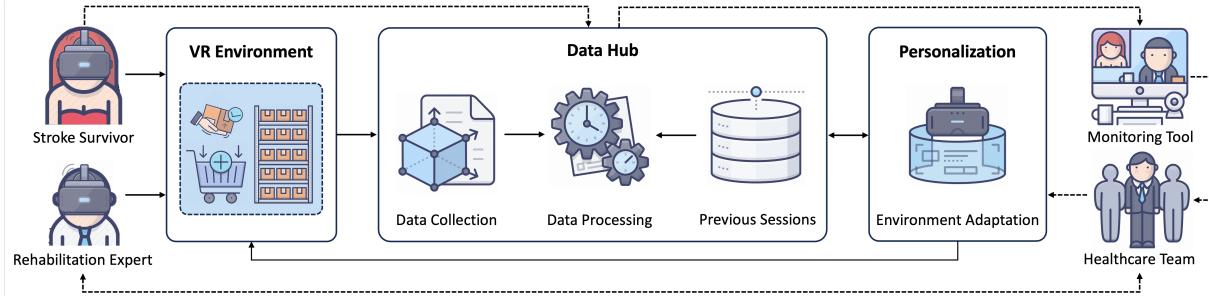


Figure 1: Conceptual model for combining Virtual Reality (VR) and personalization for stroke survivors' recovery. It starts with data collection, using distinct metrics from the survivor and the status of the VR environment. This data feeds adaptive methods, which dynamically adjust the virtual environment based on each survivor's progress. The model also includes feedback loops that ensure continuous personalization and enable healthcare professionals to monitor and refine rehabilitation as needed.

ABSTRACT

Traditional methods for stroke rehabilitation may lead to reduced motivation and engagement among stroke survivors, limiting the effectiveness of recovery. While survivors share a common goal of regaining lost function, they each have unique characteristics, abilities, and rehabilitation needs. Some tasks that are central to recovery may be too difficult for certain individuals due to their limitations, while others might find those same tasks easier to perform. In this context, there is a significant opportunity to explore the role of adaptive systems in tailoring rehabilitation programs to individual needs. This position paper proposes a vision for combining Virtual Reality (VR) with personalized adaptation methods to create a more responsive and tailored rehabilitation experience. These personalized systems can allow tasks to be dynamically adapted to survivor's capabilities, making exercises more achievable, yet challenging, and ultimately accelerating recovery. By leveraging VR's immersive capabilities and integrating personalization, stroke recovery programs can be adjusted to match the specific abilities and progress of each survivor, potentially enhancing motivation, engagement, and overall outcomes. These and other arguments in favor of adaptive, personalized VR rehabilitation are presented, and future directions for research and development are proposed.

Keywords: Human-Centered Computing, Virtual Reality, Interaction Design, Personalization, Stroke Rehabilitation.

1 INTRODUCTION

Stroke is a leading cause of disability and mortality worldwide, affecting millions of individuals each year. A stroke occurs when blood flow to the brain is interrupted, depriving brain cells of oxygen and leading to cell death in affected areas. This neurological event can have devastating effects on a person's physical and cognitive abilities, significantly impacting their quality of life. Stroke survivors often face long-term challenges, including difficulties with mobility, speech, and daily activities, which require comprehensive rehabilitation to regain function and independence. For many, these impairments can be life-changing, limiting their ability to carry out daily activities and reducing their overall quality of life [7, 11, 20].

Rehabilitation plays a critical role in stroke recovery, aiming to help survivors regain lost skills, improve motor function, and adapt to life post-stroke. Through various therapeutic interventions, rehabilitation facilitates neuroplasticity, i.e., the brain's ability to rewire itself, which is crucial for restoring physical and cognitive abilities. Although the recovery process can be gradual and difficult, consistent and well-structured rehabilitation is paramount for improving mobility, coordination, strength, and even mental health, ultimately enhancing the overall quality of life for stroke survivors [2, 3, 16, 17].

However, traditional rehabilitation methods often present significant constraints. Many stroke survivors experience a loss of motivation and engagement due to the repetitive nature of conventional exercises, which can feel monotonous and tedious over time. This lack of stimulation can slow the recovery process, and in some cases, even lead to regression. Additionally, rehabilitation programs may not always adapt to the specific needs and pace of each patient, further contributing to disengagement and suboptimal results [4, 18, 19, 21].

To help address the limitations of traditional rehabilitation, there is growing interest in exploring new methods. Virtual Reality (VR) technology has recently emerged as a promising tool for enhancing stroke rehabilitation by offering immersive and interactive environments that can make exercises more engaging. Moreover, VR enables the creation of highly controlled, varied, and stimulating rehabilitation scenarios, allowing for the simulation of real-world tasks that encourage active participation. Moreover, it provides immediate feedback, helping stroke survivors track their progress and

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improve motivation over time [1, 5, 8, 15].

Yet, in some cases, even VR alone is insufficient to meet the diverse needs of stroke survivors. This highlights the need for further innovation, particularly in the realm of personalizing VR environments to adapt to the unique characteristics of each survivor and their individual pace of improvement. Personalization can address the varying levels of ability among survivors, ensuring that rehabilitation programs are appropriately challenging yet achievable [2, 6, 9, 14, 22].

In this vein, this paper proposes a vision for combining VR with adaptation methods to create a more responsive and tailored rehabilitation experience. Among these, personalized systems can dynamically adjust environment based on each survivor's capabilities, making exercises more accessible while still offering the right level of challenge to drive progress. These and other arguments in favor of adaptive, personalized VR rehabilitation are presented, alongside future directions for research and development.

2 ARGUMENTS FOR OUR PROPOSAL: VR PERSONALIZATION FOR STROKE REHABILITATION

Next, various arguments to support our position are described.

- Given the constraints of traditional rehabilitation methods, which often lack the flexibility to accommodate individual patient needs and progress, there is a pressing need for adaptive technologies that can dynamically adjust to the varying capabilities of stroke survivors;
- Advances in VR technology allow the creation of immersive environments that can be customized to individual needs, leading to more engaging and effective rehabilitation experiences;
- VR platforms can simulate real-world tasks, allowing survivors to practice functional activities in a safe, controlled setting that is adjusted to their current capabilities, promoting a sense of achievement and progress;
- VR experiences enable healthcare professionals to supervise or intervene in the rehabilitation process whenever necessary, fostering a sense of social interaction and guidance that can enhance patient motivation and engagement;
- Nowadays, various data collection methods can be employed to aggregate information and gain insights into a survivor's state at any given moment, enabling more informed decisions regarding their rehabilitation journey;
- Personalized VR environments can be designed to offer scalable difficulty levels, ensuring that tasks remain neither too easy nor too difficult, thus fostering continuous survivors engagement and motivation;
- Personalization may also consider insights from previous rehabilitation sessions, allowing for more informed decision-making and tailored experiences that align with the unique characteristics and progress of each survivor;
- New, intelligent algorithms are beginning to emerge that can quickly process the data collected during rehabilitation sessions, providing valuable insights to guide the personalization of the VR experience;
- Healthcare professionals will retain the capability to intervene whenever necessary while leveraging the benefits of adaptive virtual environments for each stroke survivor;
- Empowering patients to engage in rehabilitation from home with tailored, driven exercises while therapists remotely monitor progress and outcomes, thus expanding access to rehabilitation services.

3 CONCEPTUAL MODEL FOR PERSONALIZED VR IN STROKE RECOVERY

The conceptual model of Figure 1 illustrates a personalized VR approach to enhance stroke rehabilitation by dynamically adapting the distinct elements of the virtual environment to the individual needs and progress of each stroke survivor. Central to the model is the seamless integration of data collection, processing, and environment adaptation, enabling continuous adjustments to rehabilitation tasks and scenarios to better reflect the current state of the survivor.

The model begins with the **VR Environment module**, where both stroke survivors and rehabilitation experts can be actively engaged. The VR environment can provide immersive experiences designed to replicate real-world scenarios, helping survivors work on motor, cognitive, and emotional rehabilitation. In such a context, the survivor can perform tailored tasks within the VR setting, while the expert monitors and provides assistance or recommendations if necessary. In turn, personalization ensures that these tasks are not static but adapt in real-time, based on the survivor's evolving capabilities, as well as taking into account input from the rehabilitation expert and even a larger team of healthcare professionals when necessary.

Key to this dynamic personalization is the **Data Hub module**. Data is continuously collected from the VR environment, capturing detailed information about the survivor's performance, movement, response times, and interaction with tasks. In this effort, additional data sources beyond the VR environment can also be taken into account. For instance, collecting physiological data provides valuable insights into how the stroke survivor is physically responding to the VR experience, offering a more comprehensive understanding of their condition [10, 12]. Other potential data sources could include gaze tracking, gesture recognition, or speech analysis, which can provide further insights into the stroke survivor's cognitive and physical engagement during the VR experience, enriching the understanding of their overall progress. Furthermore, self-reported data, including pain levels or subjective feelings of progress, could be collected through surveys or user interfaces, enriching the overall dataset with the survivor's personal perspective. To end, all data gathered will be processed and compared with previous rehabilitation sessions stored in a database (if they exist). By analyzing both real-time data and historical patterns, it will be possible to gain a comprehensive understanding of the survivor's current state, challenges, and progress. By incorporating these various sources, the system can develop a more holistic and accurate understanding of the individual's rehabilitation journey, leading to more tailored and effective adjustments.

The processed data is then introduced into the **Personalization module**, where distinct methods may be used for applying this information and adapt the VR experience accordingly. Some of the most relevant approaches include:

- **Rule-based:** predefined rules can be applied based on the survivor's performance data. For instance, if certain gestures thresholds or task milestones are not met, the solution can trigger changes in the VR environment, such as reducing task difficulty or increasing support;
- **Bio-feedback:** using sensors that monitor heart rate, muscle activity, or skin conductivity, personalization could be performed based on physiological responses. If high levels of stress or fatigue are detected, the VR environment could be adapted to reduce task intensity, provide relaxation breaks, or offer calming environments;
- **Behavioral tracking:** methods for tracking body movement, posture, and engagement can inform the solution when the survivor is showing signs of frustration, exhaustion, or under-engagement. Adjustments could include simplifying tasks, of-

ferring encouragement, or even introducing gamified elements to keep motivation high;

- **Contextual adaptation:** take into account external factors such as the time of day, the duration of previous sessions, or the survivor's reported mood, it may be possible to adjust the session length or task intensity;
- **Intelligent algorithms:** Machine learning algorithms may be used to analyze patterns in the collected data to predict the survivor's needs and adapt the task difficulty accordingly. These algorithms can continuously learn from the data and refine the personalization process over time.

Altogether, multiple methods may be combined, ensuring that the VR rehabilitation experience remains highly responsive, personalized, and focus on optimal recovery progress. To achieve this, the adaptation must always be done in a way that the overall experience remains challenging but achievable, promoting gradual improvement without overwhelming the recovery process. This adaptability is key to maintaining motivation and engagement throughout rehabilitation, which can be critical to long-term success.

Additionally, the solution may also include a **Monitoring Tool**, allowing a healthcare team to track the survivor's progress based on various metrics and customizable visualizations. This way, they may contribute to the intervention, i.e., by suggesting penalization's to the VR environment when necessary. This component ensures that while the solution operates with a high degree of personalization, healthcare professionals remain involved and can provide guidance, modify settings, or intervene in the rehabilitation process as needed. This ensures that the system supports both autonomous survivor progress, as well as professional oversight.

Overall, the conceptual model proposed emphasizes the importance of continuous data-driven personalization in VR-based stroke rehabilitation. By tailoring the VR experience to the survivor's specific needs and progress at any given moment, the proposed approach aims to accelerate recovery, enhance engagement, and provide a more effective and supportive rehabilitation environment.

3.1 Practical example based on real-life scenario

Next, an example is presented to demonstrate how the conceptual model can be applied in a real-life scenario. For this, let's consider a VR supermarket experience designed for stroke survivors, which has been used at a rehabilitation center with stroke survivors and healthcare professionals, and was created using a Human-Centered Design (HCD) methodology [13, 15]. Survivors enter a virtual environment that simulates a typical grocery store, with shelves stocked with various products they need to collect. A shopping list, displayed on the VR interface, guides them through the task. The list may vary in complexity, ranging from a few simple items to a more extensive selection. After collecting the products, survivors proceed to payment, where they can choose between different methods such as cash, card, or MB Way. All interactions are carried out using gesture recognition through the VR headset (Figure 2).

In this context, combining the VR supermarket with adaptive personalization to the abilities and progress of each survivor can occur in the following manners. Upon entering the VR supermarket, survivors can receive a personalized shopping list, which could vary in length depending on their cognitive and physical abilities. A survivor showing signs of fatigue might be assigned a shorter list with fewer products to collect, while other survivors may receive a longer list with more complex items to locate, pushing them to navigate a larger part of the environment.

Furthermore, personalization could further influence the number of shelves the survivor must visit. A beginner might only need to gather products from a few shelves located in a small, uncluttered area, minimizing the effort needed to move around. In contrast,



Figure 2: Illustration of the VR supermarket scene, where a stroke survivor collects products and places them into a shopping cart before proceeding to the payment process, interacting with the virtual environment using gesture recognition through the VR headset.

survivors with other characteristics may be required to visit more aisles, potentially including more challenging shelves in distant areas of the store, increasing physical effort.

Introducing constraints can also be considered. If the system detects that the survivor is performing too easily, challenges such as obstructed paths or empty shelves can be introduced. This would require them to be flexible and re-navigate, or return to the shelf later to complete the task. For a more advanced survivors, these scenarios can introduce cognitive problem-solving, while for a less advanced ones, fewer obstacles would keep the experience manageable.

Additionally, during the checkout process, the system might remind the survivor that a last product was forgotten, encouraging them to return and retrieve it. This tests memory and multitasking skills in a simulated real-life context. Then, depending on their cognitive level, different payment methods can be introduced, ranging from simpler options like cash to more complex ones like card or mobile payments (MB Way).

Visual and auditory cues can also be adapted based on performance. For example, a survivor who is struggling to find an item may be offered brighter visual highlights or audio support guiding them to the correct shelf. Alternatively, if the survivor is progressing well, the cues may be more subtle, encouraging them to rely more on memory and cognitive skills.

These examples show how personalization can adapt various aspects of the VR environment, from the length of tasks, and complexity of navigation, to the level of assistance provided, ensuring that the rehabilitation experience is tailored, effective, and continuously challenging for each stroke survivor.

4 FUTURE DIRECTIONS: A PROPOSAL

Many issues need to be addressed by the research community with the goal of exploring the impact of using VR for supporting personalized stroke rehabilitation, in particular:

- **Selection, and creation of VR experiences** – The process of selecting a theme, and populating a VR environment with sufficient content for personalization is a key challenge. These experiences must cover a broad range of rehabilitation activities, allowing for personalized adjustments in complexity, difficulty, and interaction based on the survivor's progress;
- **Managing progressive task complexity** – Another challenge is to create goals that can progressively adjust their difficulty based on survivors performance. Balancing task complexity to maintain engagement without overwhelming them is a crucial factor that requires sophisticated adaptive methods;
- **Ensuring modularity and scalability** – Developing modular, flexible VR architectures that can easily scale across different rehabilitation scenarios and survivors profile is a key hurdle. These systems need to be adaptable for both general and individualized use, addressing varying levels of impairment and diverse rehabilitation goals;
- **Explore diverse data collection methods** – incorporate data from various sources, including motion sensors, physiological data (e.g., heart rate), and cognitive assessments, to create more comprehensive personalization and adjust exercises dynamically based on real-time feedback;
- **Establishing large-scale data** – A significant challenge lies in the creation and maintenance of large, representative datasets that capture survivors performance, recovery progress, and behavioral responses. These datasets must be comprehensive, continuously updated for training adaptive methods to improve the personalization of VR experiences;
- **Evaluation and validation of personalized VR systems** – Testing and validating personalized VR systems presents challenges in terms of measuring not only recovery outcomes but also survivors engagement, motivation, and usability. Iterative studies starting from controlled environments to broader field studies are necessary to fully assess their impact;
- **Implementing automatic personalization with professional oversight** – While VR systems should leverage automatic personalization according to each survivor's needs, it is essential that healthcare professionals retain the ability to override system recommendations. This human-in-the-loop approach ensures that the expertise and judgment of healthcare providers are integrated into the rehabilitation process, allowing for adjustments that reflect the survivor's unique circumstances, preferences, and any emerging medical considerations.

In addressing these challenges, the field can move closer to creating truly personalized, adaptive VR rehabilitation systems that offer meaningful improvements in stroke recovery outcomes.

5 CONCLUDING REMARKS

All in all, the authors strongly believe that a valuable opportunity to explore the integration of adaptive VR systems in stroke rehabilitation exists, which can significantly enhance the personalization and effectiveness of recovery programs. These systems will enable the customization of rehabilitation tasks and virtual environments to meet the unique needs, abilities, and limitations of each stroke survivor, thereby making the rehabilitation process more individualized.

By tailoring exercises to match a patient's specific progress, adaptive VR has the potential to boost both motivation and overall rehabilitation outcomes. In particular, it is essential to investigate the feasibility of combining VR with adaptive methods that continuously adjust task difficulty, feedback, and exercise routines in real-time, based on the survivor's evolving capabilities. This dynamic adaptation could ensure that the rehabilitation program remains appropriately challenging yet attainable for every individual. With this, we hope to promote larger engagement in rehabilitation exercises, increasing adherence to therapy, and improved recovery rates.

Yet, several topics remain unanswered before this vision becomes a reality, illustrating that extensive research in multiple disciplines is still necessary. To elaborate, future work must seek to develop and validate adaptive methods that can assess survivors performance in real-time, adjusting the characteristics of VR environments dynamically. Naturally, this is a multidisciplinary effort, requiring collaboration between fields such as computer science, clinical rehabilitation and others to ensure that these systems are both effective and viable in real-life scenarios. Another relevant aspect is to explore the long-term benefits of personalized VR rehabilitation, particularly how it compares to traditional methods in terms of survivors motivation, cognitive engagement, and emotional resilience during extended rehabilitation periods warrants further investigation. These efforts will be essential to fully realize the potential of personalized, adaptive VR in stroke rehabilitation.

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