**Introduction:**

The objective of this report was to create an immersive virtual environment that allows users interact with forces produced by the force dimension delta.3 haptic device. The device provides force feedback, aiming to improve sensory motor skills of individuals suffering from brain injuries. Sensory motor deficiency may occur in individuals who have suffered nervous system damage, such as brain or spinal cord injuries, resulting in hemiparesis. This condition can significantly hinder their ability to carry out daily activities. Therefore, the recovery process becomes essential in restoring their sense of touch and proprioception, as it plays a vital role in improving their overall lifestyle.

Motor dysfunction related to the nervous system can stem from various causes, including, cerebral palsy [1], spinal cord injury, multiple sclerosis [2], traumatic brain injury [3], among others. Nevertheless, one of the primary and prevailing cause of sensory motor dysfunction, particularly affecting the upper limbs, is stroke [4].

With the global aging of populations, the incidence of strokes is on the rise, leading to an increased demand for rehabilitation services from healthcare organisations. Interestingly, there has also been a noticeable increase in stroke occurrences among adults aged 20 to 64, necessitating additional support for individuals experiencing the consequences of strokes [5]. Importantly, recent studies have revealed a decline in the mortality rate of strokes, primarily due to advancements in healthcare, including improved medicines and better post-stroke care [6], [7]. However, this positive trend places a further strain on healthcare organisations as they are required to maintain accessible care for individuals who have suffered from a stroke [8]. As the demand for rehabilitation services increases beyond hospitals, healthcare providers are progressively turning to rehabilitation interventions outside of health centres and hospitals. Consequently, this approach results in a decrease in patients' hospital stay duration. This shift aims to accommodate the growing need for rehabilitation while allowing patients to receive necessary care and support in the comfort of their homes [8].

**Neurophysiological recovery:**

When a person experiences a stroke, blood flow is blocked to an area of the brain, depriving neuron cells of oxygen and glucose, leading to their death. Among these neurons, those within the motor cortex region play a crucial role in facilitating successful motor control of the upper limbs. Consequently, any damage to neurons in this area results in disrupted communication between the brain and the body, leading to upper limb hemiparesis [9]. It’s worth noting that neuronal damage can continue to occur for days after the stroke has occurred, this emphasises the importance of starting and maintaining recovery intervention process [10], [11]. For effective rehabilitation, the damaged neurons must undergo regeneration and reorganisation to create new functional connections, which is referred to as brain plasticity. Both animal and human models have demonstrated that engaging and repeating appropriate upper-limb exercises promotes increased brain plasticity in the activated brain regions. This heightened plasticity, in turn, leads to improved motor control and learning [12]. Understanding neurophysiological changes following a sensory motor control damaging event is important for the recovery process. It is imperative to conduct neurological research pre and post rehabilitation therapy to optimise patients’ recovery [13].

**Recovery process**

Patients’ recovery from a stroke is extremely personalised, with individuals experiencing varied side effects and recovery experience. This difference arises from factors such as the strokes classification, the individual’s health, and the timeliness of treatment initiation post stroke. Diagnosing the stroke is the first step and once this is determined, the treatment process can begin [14]. Medication will be administered to the patients to help reinstate blood circulation to the damaged area of the brain. Once the patient has stabilised, a rehabilitation plan will be provided by a specialised therapists for the patient to engage in once discharged from hospital [14] (See figure 1). Achieving the best recovery for the hemiparetic upper limb, requires appropriate physical therapy intervention, and demands significant dedication to a rehabilitation program from patients within the first 3 months post stroke. However, it is common for patients to struggle with maintaining commitment to their program once they are discharged from the hospital [15]. Recent evidence indicates that consistent home-based therapy yields considerable improvements in recovery compared to traditional clinical-based therapy. Moreover, this approach has shown promising results in enhancing the quality of life for stroke patients [15]. Therefore, encouraging and supporting patients in adhering to their rehabilitation program outside of a medical environment is extremely important to ensure optimal recovery.

**Home – based rehabilitation**

More recently, researchers have been exploring and integrating technology into home-based rehabilitation approaches. It is crucial for stroke patients to actively participate in their rehabilitation with intensity and repetition to increase neuroplasticity and achieve the best possible recovery [11]. Virtual Reality (VR) offers a valuable solution to enhance patient engagement and create a safe, multisensory environment, for patients performing rehabilitation exercises in VR. VR technology presents an opportunity for patients to immerse themselves in an interactive environment, where they can perform specific exercises tailored to their individual needs in a concentrated and repetitive manner. This stimulation of neuroplasticity through VR supports the recovery process, helping patients make significant progress in their rehabilitation journey [16].

The impact of VR on patients' recovery has been the subject of various studies. While some research, such as that by [17], has shown no significant effect of VR in rehabilitation, other studies, like the one conducted by [16] have demonstrated that integrating VR into conventional upper limb rehabilitation can substantially enhance a patient's motor control. Additionally, VR offers several other advantages, including increased accessibility due to lower cost and portability of the technology. Its use does not require the constant presence of specialists, and remote quantifiable feedback and improvement by clinicians can be facilitated. These factors collectively reduce the burden on healthcare organizations in providing rehabilitation services [16].

As VR continues to evolve, further research and advancements will likely refine its role and efficacy in stroke rehabilitation. One promising area of investigation involves the integration of robotics and haptic feedback into rehabilitation techniques. By utilising robotics and haptic feedback, patients can interact with a diverse range of objects and exercises, such as providing force and tactile feedback [18], [19]. This innovative approach holds tremendous potential in providing a more immersive and customised rehabilitation experience, through haptic exploration, ultimately contributing to improved outcomes for stroke patients. Importantly, repetition of simple exercises does not always improve neural plasticity. However, incorporating multiple forms of haptic feedback allows users to develop cutaneous, proprioception, and kinesthetics senses, which is proposed to improve motor control in patients with upper limb impairment [13], [20]. The implementation of VR and haptic feedback offers clinicians a tool to incorporate multi-modal feedback into rehabilitation exercises tailored to the patients' skill level, optimising neural plasticity and the rehabilitation process [19], [21]. A significant benefit of using VR and haptic technology is its ability to offer immediate data-driven feedback, surpassing human assessment in accuracy and efficiency when evaluating rehabilitation progress [22]. Finally, it provides a motivating system for patients to participate in rehabilitation exercises in a more intense and repetitive manner in contrast to conventional therapy routines [23].

Figure 1. shows where in the stroke recovery process the appropriate intervention using haptic and VR exercises would be. [Include a figure demonstrating haptic technology impact on the brain, and where this would be included in the rehabilitation process of a patient, from stroke event, to recovered]

As the significance of haptics and VR in upper limb rehabilitation becomes increasingly evident, this project aims to integrate the force dimension delta.3 haptic device [insert citation] and VR technology to develop a safe and productive environment for patients engaging in upper-limb rehabilitation exercises. By combining haptics and VR, the aim is to present a novel technique using force feedback to develop a system where patients can develop movement accuracy skills. The system will contribute to a patients’ recovery process without the presence of a specialist and will demonstrate that patients will be able to experience a more immersive and personalised rehabilitation journey, enhancing their engagement and promoting better rehabilitation outcomes outside of hospitals or clinics. This approach holds the potential to improve stroke survivors with upper-limb impairments quality of life and allow them to regain independence performing day to days tasks.

The upcoming sections of this report review existing papers researching VR and haptic feedback in rehabilitation following brain injury. This will involve analysing the use of VR and force feedback for rehabilitation efficacy as well as the development of a rehabilitation system. The VR and force feedback implementation, system design, user interface, and project management will be described before evaluating data collected from healthy individuals.

**Further review of VR and Haptic systems:**

Successful rehabilitation requires discipline and consistent engagement, therefore keeping patients motivated to perform their rehabilitation exercises is extremely important. Previous studies using VR and haptic devices have focused on quality of attention to exercises in patients with cognitive deficiencies. These studies demonstrated that patients were more engaged and attentive with the with the exercises when haptic sensations were incorporated into their rehabilitation exercises. [24], [25]. Supporting this, qualitative findings indicate that gamified therapy using VR and haptic feedback was easy to learn and increased motivation for performing rehabilitation tasks. This approach was the preferred method of participating in rehabilitation therapy [26]. One study using attractive and repelling forces found that repelling forces have increased physical demand and may discourage patients when performing repelling exercises [25]. Interestingly, a proposal by [27] suggests that attractive guidance potentially impedes the learning process in patients recovery. This arises from the possibility that assistive forces hinder somatosensory information interpretation due to a natural reduction in effort exerted when such forces are present. Consequently, attractive forces could lessen the efficacy of the rehabilitation training [27]. This research indicates a heightened level of patient engagement when incorporating haptic feedback and VR, however, it is crucial to appropriately manage the force feedback to maintain a balance between user interest and promoting effective recovery. This balance can be assessed through the haptic device, thereby allowing simple adaptation of the exercise system to cater for a patient’s requirements.

The use of robotics for rehabilitation therapy has been around for more than two decades and a variety of robotic techniques have been proposed to enhance the recovery process [13], [28]. Focussing on upper-limb rehabilitation using haptic robotics, several techniques have been proposed to assist and assess upper-limb rehabilitation.

In an experiment using the force dimension delta.3 device [29], the authors developed a “virtual reality-based robotic” system, that would test the user’s tactile sense by exposing them with multiple textures through the haptic device. The researchers implemented both assistive forces or a force-free condition to guide the users towards the textured surfaces [30]. The findings noted a significant increase in tactile discrimination when trained with either force condition. Nonetheless, there was no distinction in tactile discrimination between guided or unguided forces [30]. While the findings in this paper are promising in developing tactile senses, and their conclusions support the use of haptic feedback for tactile recovery, the research presented does not explore the use of a variety of forces, such as repelling forces. A variety of forces are important when considering everyday tasks where individuals are recovering from sensory motor deficiency. Consequently, they neglect kinematic data with repelling forces which could prove vital in understanding individuals rehabilitation progression [31]

An interesting study involving children with upper-limb impairment caused by neuromotor damage unveiled compelling findings. The study demonstrated that VR and haptic assisted therapy led to enhanced movement smoothness in linear path tracking exercises. Moreover, it demonstrated significant improvement in manual finger dexterity [32]. These results support the incorporation of haptic technology and VR with rehabilitation protocols and demonstrates the potential of this technology integration for customisable rehabilitation [32]. Another paper supporting the use of haptic feedback for upper-limb rehabilitation used electromyographic measurements to evaluate progress [33]. The authors determined that even with small forces applied to the haptic device, there was significant increased in muscle activation suggesting potential use of haptic feedback for muscle training and rehabilitation [33].

These studies are supported by a review study which investigated the efficacy of haptic technology in hand rehabilitation for stroke patients. Interestingly, the authors found that haptic enabled interventions combined with robotics and virtual reality, the rehabilitation progress had more positive outcomes when compared with interventions using fewer technologies [34].

Contrastingly, a study done using the robotic upper limb training system I-TRAVLE, participants with upper-limb deficiency caused by chronic stroke, showed significant improvements in robot generated measures such as movement velocity, however clinical outcomes did not show significant improvement [20]. The authors suggest that this could be due to the severity of their upper limb dysfunction [20]. This could also be due to a lack of initial quantitative analysis of activities of daily living, as task performance does not always translate to life skills. This is important to consider when suggesting protocols in upper limb rehabilitation [13]. This study shows that the type of tasks designed and implementation is important when considering haptic rehabilitation, which could be dependent on the timeliness of intervention as well as the type of haptic feedback provided [27]

Using a similar haptic device to the force dimension delta.3, referred to as the Novint Falcon [citation], researchers assess participants’ smoothness, accuracy, and duration of participants movement, while executing tasks under certain conditions involving repelling force, attractive force, or no force conditions. Additionally, they examine whether the integration science-related learning and engagement increases participant engagement [23]. As anticipated, the authors observed that repelling forces increased the participants movement errors, whereas attractive forces reduced movement errors. Furthermore, inclusion of scientific learning also increased participant engagement and motivation, supporting the use of virtual reality to keep patients engaged with rehabilitation exercises [23]. While the research provides interesting insight into the use of force feedback on movement, it does not definitively establish whether patients trained using force feedback can effectively reduce movement error when performing normal tasks. It is important to assess skill improvement in the context of rehabilitation, to determine the efficacy of the proposed exercises [35].

In another study using the novit falcon haptic device, the authors proposed an innovative protocol to improve evaluation of upper-limb motion capabilities. This involved analysing kinematic data obtained by the haptic device, including “duration of movement, length ratio, lateral deviation, aiming angle, speed metric, and normalized jerk” [36]. The system developed used different levels of repelling forces applied to a reaching task for the user to perform. The tasks involved moving an end effector towards a target and then back to the centre again, while measuring kinematic indices for quantitative user feedback [36]. This paper contributes knowledge into the evaluation of sensory motor recovery progress; however, it does not determine the efficacy of using forces in improving upper-limb rehabilitation. The designed tasks exhibit a level of predictability as the targets remain static throughout the trials. Consequently, the system may fail to capture data from areas where individuals may have movement impairment.

Taking inspiration from the concepts of patient motivation and engagement, along with the utilisation haptic technology for upper – limb rehabilitation and rehabilitation assessment, the primary goal of the presented systems design aims to integrate and improve upon the discussed current rehabilitation systems. This will be achieved through incorporation of force feedback, the acquisition of quantitative kinematic feedback and integration VR to create a unique immersive experience for users to interact and progress with.

**Methodology:**

* Look at haptic software design
* Diagrams for design of haptic interface –
  + chapter 11 (engineering haptic devices)
  + P.g 91: Kinesthetic interfaces 4.6.3
* Include a section about the haptic device, describe is DoF and joints, and what it can provide (this could be done in my methods section)
* Implementation using DLL
* Using sin for movement
* Using array to manage force spheres (lists are computationally too heavy)

**Things to consider:**

* Factors influencing haptic perception (EHD – 57)
* Evaluation of haptic systems (EHD – 587)
* Advantages and Disadvantages of parallel mechanism (force dimension) (EHD – 272)
  + Parallel mechanical design – 3DoF
* Hypothesis: motivation of patients participating in an immersive VR rehabilitation exercise will by higher than that of patients doing standard rehabilitation force exercises

**Discussion**

* Can apply machine learning to adapt the program
* The force dimension delta device is very expensive however, there are cheaper options for similar devices (novit falcon)
* Use of TMS to stimulate higher motor cortex activity [13]
* Reliability of my system?
* This program can also be used to determine relapses in patients as shown by [37] as they can distinguish between healthy and non healthy patients