**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 (Poitras *et al.*, 2021), spinal cord injury, multiple sclerosis (Adamovich *et al.*, 2009), traumatic brain injury (Subramanian *et al.*, 2022), among others. Nevertheless, one of the primary and prevailing cause of sensory motor dysfunction, particularly affecting the upper limbs, is stroke (Anwer *et al.*, 2022).

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 (Katan and Luft, 2018). 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 (Lackland *et al.*, 2014; Seminog *et al.*, 2019). 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 (Coupar *et al.*, 2012). 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 (Coupar *et al.*, 2012).

**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 (Chae *et al.*, 2002). 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 (Puig, Brenna and Magnus, 2018; Teasell and Mbbs, 2018). 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 (Daly and Ruff, 2007). 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 (Piggott, Wagner and Ziat, 2016).

**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 (Anderson, 2021). 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 (Anderson, 2021) (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 (Toh, Chia and Fong, 2022). 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 (Toh, Chia and Fong, 2022). 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 (Teasell and Mbbs, 2018). 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 (Saposnik, Levin and null, 2011).

The impact of VR on patients' recovery has been the subject of various studies. While some research, such as that by (Laver *et al.*, 2017), has shown no significant effect of VR in rehabilitation, other studies, like the one conducted by (Saposnik, Levin and null, 2011) 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 (Saposnik, Levin and null, 2011).

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 (Turolla *et al.*, 2013; Yeh *et al.*, 2017). 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 (Piggott, Wagner and Ziat, 2016; Maris *et al.*, 2018). 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 (Plautz, Milliken and Nudo, 2000; Yeh *et al.*, 2017). 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 (Adamovich *et al.*, 2004). 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 (Cappa *et al.*, 2013).

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 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 contribute to a patients’ recovery process while reducing the strain on health care organisations providing rehabilitation services. It will also 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. (Dvorkin *et al.*, 2009; Larson *et al.*, 2011). 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 (Ramírez--Fernández, Morán and García--Canseco, 2015). One study using attractive and repelling forces found that repelling forces have increased physical demand and may discourage patients when performing repelling exercises (Larson *et al.*, 2011). Interestingly, a proposal by (Özen, Buetler and Marchal-Crespo, 2021) 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 (Özen, Buetler and Marchal-Crespo, 2021). 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. (Pacilli *et al.*, 2014; Piggott, Wagner and Ziat, 2016). Focussing on upper-limb rehabilitation using robotics with 3 degrees of freedom, several techniques have been proposed to assist upper-limb rehabilitation.

In an experiment using the force dimension delta.3 device, 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 (Villar Ortega *et al.*, 2022). 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 (Villar Ortega *et al.*, 2022). 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 (van Dokkum *et al.*, 2014)

Using a similar haptic device to the force dimension delta, referred to as the novit falcon, the authors proposed an innovative protocol to evaluate upper-limb motion capabilities. This involved analysing kinematic data obtained by the haptic device used (Scalona *et al.*, 2019). 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 (Scalona *et al.*, 2019). 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.

EMG Evidence for activities in upper limb increasing when force feedback is applied by haptic device (Nagaraj and Constantinescu, 2009; Gutiérrez *et al.*, 2020) (make this brief)

Previous robotic devices being used for upper limb rehabilitation, summary of devices then critically review Studies using the force dimension delta and other 3DOF devices and what they found

The use of force feedback and what benefits can come from using VR and the force dimension delta device

Conclude by saying how my game and design is novel and will contribute to the field of neurorehabilitation

**Literature review plan:**

* What are the challenges in upper limb rehabilitation
* What current techniques are there in upper limb rehabilitation
  + With or without use of robotics
  + Using robotics and/or virtual reality
* What current techniques are there to measure progress of patient’s rehabilitation program and why using a force dimension haptic device will allow better understanding of progression

Main reason for using haptics devices

* Idea 1: The use of force feedback to improve the efficacy of patient recovery
  + Assistive forces, good and bad, and do they work?
  + Resistive forces, good and bad, and do they work?
* Idea 2: Data that the force feedback device can provide
  + Providing more insight into a patients progress with more force data provided
  + The adaptability of VR and haptic device to match the patients progress, so programs can be individualised as sensory motor damage is different in everyone
  + Gamify to give loads of feedback during and after the rehabilitation exercises
  + This product as a result of all the data that it can provide can be an indication of relapsing of unsuccessful surgery
  + Objective assessment vs subjective assessment (clinician vs robotic)
  + Effective haptic tests can analyse a patients kinaesthetic or tactile sense
* Idea 3: Motivation of patients when they are discharged from hospital
  + Paper showing improved motivation using game based rehabilitation
  + (Piggott, Wagner and Ziat, 2016)
* Idea 4: Current upper limb rehabilitation techniques using VR and Haptic feedback and how these are better than conventional therapy and feedback
* Idea 5: what current robotics are used for upper limb rehabilitation
  + **Conventional rehabilitation techniques and assessment**
    - Include a paragraph about how sensory motor control is assessed in neurorehabilitation research, and how my project will benefit the assessment (Piggott, Wagner and Ziat, 2016)
    - Include what my device will be able to measure and how is this better for understanding and assessing patient treatment therapy and upper limb rehabilitation
    - Include kinaesthetic measurement and proprioceptive data feedback from haptic devices

**Literature review: papers**

* Make sure to say that the novit falcon provides similar range of movement and force feedback to the force dimension delta
* Using delta device for develop robotic texture discrimination task to assess and train touch sensibility (Villar Ortega *et al.*, 2022) **Idea 1, 2**
* Using delta device to create model predictive controllers as assistive robotic forces my hinder the rehabilitation process, to create assistive forces (Özen, Buetler and Marchal-Crespo, 2021) **Idea 1, 2**
* Using novit falcon, there was an assistive force game on computer, showed that can distinguish between unhealthy and healthy subjects in a follow the path game (Gutiérrez *et al.*, 2020) **Idea 1, 2**
* Use of novit falcon to find that force feedback regulates the smoothness, accuracy, and duration of the subject’s movement, whereby converging or diverging force fields influence the range of variations of the hand speed (Cappa *et al.*, 2013) **Idea 1, 2**
* Novit falcon: Effect of force feedback using EMG readings on upper limb (Nagaraj and Constantinescu, 2009) **Idea 1,2**
* Novit falcon: Finding haptic devices easier to learn and use – good user feedback and motivation for using haptic devices (Ramírez--Fernández, Morán and García--Canseco, 2015) **Idea 3**
* Novit falcon: Interacting with paintings and providing force feedback applied as a water simulation and collisions (Le *et al.*, 2013) **Idea 1**
* Using novit falcon: producing opposing forces to reach a target (Scalona *et al.*, 2019) **Idea 1**
  + Read this! I can make mine different by making the forces adapt to the user instead of having static forces
  + This paper proposes a new way to analyse kinematic analysis using forces. I can use this to analyse the difference in accuracy between applying repelling, attractive and no forces in training
  + Mine is different as I will be analysing accuracy of the end effector to target during a 15 second period and then measuring the differences between trained on resistive, or trained on assistive and trained on no forces
  + Use (Özen, Buetler and Marchal-Crespo, 2021) to reason why creating assistive forces may increase task performance but will not actually increase the patients capabilities of interacting with the environment
* The use of force feedback and brain activation using EEG and BCI (Gomez-Rodriguez *et al.*, 2011) **Idea 1**
* Using haptic devices for improving attention and motivation (Dvorkin *et al.*, 2009; Larson *et al.*, 2011) **Idea 3**
* **A paper that’s worth reading as its like mine** (Nielsen and Universitet, no date)(Escobar *et al.*, 2018)

Conclusion:

* Improve patient engagement
* Evidence for robotic technology improving performance and rehabilitation when compared with conventional therapy (Balasubramanian, Klein and Burdet, 2010)
* Taking inspiration from the literature spoken about, I will conduct research using the force dimension delta.3 haptic device. We will design a program that will test the use of force feedback on motor-control accuracy comparing assistive, repelling and no forces

**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 (Piggott, Wagner and Ziat, 2016)
* Reliability of my system?
* This program can also be used to determine relapses in patients as shown by (Gutiérrez *et al.*, 2020) as they can distinguish between healthy and non healthy patients