**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 and contribute to the rehabilitation process 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, paresis, changes in somatosensation, and diminished ability to execute accurate movement [9], [10]. 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 [11], [12]. 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 [13]. 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 [14].

**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 [15]. 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 [15] (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 [16]. 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 [16]. Therefore, encouraging and supporting patients in adhering to their rehabilitation program outside of a medical environment is extremely important to ensure optimal recovery. Once the rehabilitation process has started, it becomes crucial to evaluate the progression of the recovery process and assess the hindrances of individuals [17] (see figure 1). Evaluation of upper-limb impairment involves recognising the deficiencies which limit normal movement and the initial extent of restricted activity results from these impairments [10]. Continuous assessment throughout the rehabilitation process remains imperative, because it provides feedback on the efficacy of the selected intervention, determining if positive outcomes stem from the selected intervention [10]

**Rehabilitation without presence of a specialist**

More recently, researchers have been exploring and integrating technology into 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 [12]. 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 [18].

The impact of VR on patients' recovery has been the subject of various studies. While some research, such as that by [19], has shown no significant effect of VR in rehabilitation, other studies, like the one conducted by [18] 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 [18].

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 [20], [21]. 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 [14], [22]. 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 [21], [23]. 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 [24]. 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 [25].

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:**

**User engagement and adaptability:**

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. [26], [27]. 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 [28]. One study using attractive and repelling forces found that repelling forces have increased physical demand and may discourage patients when performing repelling exercises [27]. Interestingly, a proposal by [29] 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 [29]. 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.

**Haptic technology in rehabilitation:**

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 [14], [30]. 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 [31], 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 [32]. 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 [32]. 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 [33]

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 [34]. These results support the incorporation of haptic technology and VR with rehabilitation protocols and demonstrates the potential of this technology integration for customisable rehabilitation [34]. Another paper supporting the use of haptic feedback for upper-limb rehabilitation used electromyographic measurements to evaluate progress [35]. 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 [35].

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 [36].

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 [22]. The authors suggest that this could be due to the severity of their upper limb dysfunction [22]. 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 [14]. 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 [29]

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 [25]. 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 [25]. 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 [37].

**Haptic technology for rehabilitation progression and assessment:**

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” [38]. 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 [38]. 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.

**Conclusion**

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.

**Analysis and specification**

Problem formulation:

* Research and analysis were conducted on relevant literature in the previous sections. Previous research conducted surrounding topics of benefits of haptic devices and gaps in the literature where haptic rehabilitation falls shorts was determined to establish the problems to address, user requirements, and system requirements.
* Statement about the problem I will be addressing.

System description:

* Describe the delta.3 haptic device description using the blue books and force dimension specs
* Technological considerations
  + Unity game engine description for game design
  + Force dimension delta.3 haptic device
  + The virtual reality headset I will be using

System goals:

* The solution should provide a safe, immersive environment for users to perform tasks to assist developing upper limb motor control
* The system should be able to collect quantitative kinematic data that can be analysed for (a) research or (b) for patients’ analysis in rehabilitation progression
* The solution should require minimal clinician in person input so patients can perform tasks without specialist assistance
* The system should be adaptable for individual needs depending on the severity of upper limb impairment

System deliverables:

* The system will provide a safe work environment for users to perform their testing and training
* The system will execute the tasks and produce force output appropriately
* The system will record data detailing the users accuracy by measuring velocity and positional error
* The collected data will be in a .json file, which can be analysed using data analysis techniques such as matlab, python or excel

User requirements:

* Who is using my product: specialists, therapists, carers, physios etc
  + Write what they will expect from the program
* User research: in this report I will be analysing use of different forces on motor control development using repel training or no force training

Functional dependencies:

* User input: the movement of the force dimension delta should be synchronised with the end effector object in virtual reality
* The force feedback produce by the haptic device is delivered during training, if necessary, and not during baseline phase or testing phase
* Haptic rendering: forces from the haptic device should be generated appropriately depending on the user’s position and velocity input
* User adaptability: the system must have a simple design to ensure the force production can be adapted comfortably to the users’ requirements
* Safety constraints: the haptic device must operate within safe boundaries and prevent harm to users. This is done by setting a max force and distance output that the haptic device can produce

Non-functional dependencies:

* Performance
* Availability
* Reliability
* Safety: emergency stop
* Compatibility with different software’s
* Ethical consideration: user consent and data usage
* Security of user data

**Methods**

The design of this system is adapted from previous rehabilitation systems using the same or similar haptic devices. It drew inspiration from reaching and grabbing tasks designed for upper limb rehabilitation discussed in the literature review section and will be further discussed in this section

**Experimental setup: make sure I include pseudo code figures to help explain my system design**

Hardware setup

* Headset
* Force dimension delta (communication rates)
* Unity and VR headset implementation
* Force dimension delta implementation with unity
* Desktop

Software setup:

* Target movement design
* Forces design
* VR design
* Data collection design

**Experimental design:**

Participants: paragraph to describe who the participants were etc

* Participants are randomly selected healthy individuals, who will be informed to use their dominant side to perform these activities.
* Participants with upper-limb impairments were ethically not okay to ask due to the rushed nature of this project. This needs to be tested on healthy participants first before being introduced into a clinical study setting
* Participants will be sitting at a desk comfortably, with the haptic device located in-front of them so when they reach forward with their dominant arm, that where the end effector ball on the haptic device will be for them to grasp **(see figure – image of someone participating)**.
* The experimental procedure is split up into 3 phases. Phase 1 is baseline phase, where the participant will perform each trial within the phase without any forces acting on their movement. Phase 2 is the training phase. This is where either a repelling force or no forces will be applied to the haptic device throughout the phase 2 trials. This is to compare the effects of a repelling force on the accuracy of movement performed by the participant. Phase 3 is the testing phase. No forces are applied to the haptic device in this trial. The data from this phase will be used to analyse movement accuracy, between the different training conditions, and between phases. **(see figure – figure showing the different phases)**
* Each trial will be split into 15 seconds of movement, followed by a 3 second rest. There will be 20 trials per phase, and participants will be allowed to take as much time as they need before moving onto the next phase **(see figure)**
* Throughout the 15 seconds of movement, the participants will be asked to move an object in unity, which is represented by the haptic device, as close as they can to a target object that is moving randomly throughout the space in VR.
* The purpose of the 3 second break is to allow participants rest time, and delaying fatigue.
* Forces applied will remain the same throughout each phase, however the type of force applied will be dependent on the phase.
* The speed of the target object will vary throughout the entire study, depending on the size, frequency, and amplitude of the sine wave produced **(see figure)**. Further details of how this movement is generated will be described further in this section. This purpose of this is to add to the variety of movement patterns the participant is performing

**Data analysis**

Here say what the data was you collected i.e. frame rate/ frame by frame at 100 Hz

What did you do with the data i.e. your analysis script in python

Target movement design

The motion of the target within this project holds significant importance. To begin, the movement must encompass the entirety of the workspace area the haptic device can manoeuvrer in, while remaining within the bounds of the devices range. Should the target move beyond these bounds, the end-effector object in the unity environment would be incapable of reaching the target. This guarantees that users can constantly hit the target, thereby enabling the game to provide reliable feedback about the users’ movement error with respect to the target. Secondly, the trajectory of the target should cover a wide expanse of the workspace available in a random manner. The aim of this movement is to achieve a comprehensive understanding of the users upper limb motor control and assess the accuracy of their movements in these positions [39].

Initially, to create the random movement pattern, Perlin noise algorithm was used. Design by Ken Perlin [40], this method can produce controlled randomness. By operating on a three-dimensional grid of points, the algorithm calculates pseudo random gradients that determines random directions. Through interpolation, these values are blended to achieve a smooth continuous variation of movement [41]. However, for the specific way forces were intended to be integrated into unity, this method became too complicated. This will be discussed further in the force’s implementation section.

A new algorithm was designed to fit the force design implementation. The algorithm involves generating initial point and a target point, after which a sine wave is generated between these two points along the x, y or z axis (**see figure**). The determination of whether the sine wave should align with the x, y, or z axis was computed randomly using ‘UnityEngine.Random.Range(0, 3)’ where the values 0, 1, 2 were assign to x, y, z respectively. Subsequently, the target object tracks this sine wave to reach the target point. As the target object approaches the target point, that point becomes the new initial point, and a new target point is generated to ensure the movement continues (**see figure**). This allows for random movement throughout the 3D space, effectively spanning a substantial area within the workspace.

* + Using sine instead of perlin noise
  + Use of algorithms to make the ball movement smoother
  + Explanation of sine movement and justification for using this
  + Use a figure explaining the movement of the target is random and the follows the target with the haptic device

Force implementation

* Repelling force algorithm
* Attractive forces algorithm
* Force channel design and justification for the channel
  + Using an array activating and deactivating spheres, over a list of spheres being spawned and deleted (list is computationally too heavy, which increased lag)
  + Use a figure showing the forces produced by the spheres and how this will impact the end effector
  + Forces design, how have I created the reppelling forces
    - Using the forceDimesnion SDK
* Experimental design and analysis
  + Explanation of my experiment and justify why I have chosen them
    - E.g 60 trails, 15 second trials, 3 second breaks, chosen break in between phases, chosen force application and justification (training phase)

**Implementation and testing:**

* Force dimension delta.3 device integration in unity and VR
  + TCP / UDP connection wasn’t robust enough – justification for using DLL
  + DLL incorporation to allow communication between device and unity
  + Show how forces can be applied to the haptic device using x, y, z axis and how this coordination system correlates to unity
  + Use a Figure showing the x, y, z axis in unity and the x, y, z axis on the force dimension delta
  + Speed at which the haptic device is communicating with unity to ensure a smooth motion experience for the user
  + Discuss the VR device selected and why it’s appropriate for my system design
* How I have managed to record data and save the files – methods used
  + Using lists to save data in a fixed update method
  + What data types I have chosen to record and why
    - Positional and velocity error
  + Speed of the data recording as this is in fixed update
  + When data is recorded and why
    - Only when the target is moving, and no breaks
* How I have analysed the data
  + Use of jupyterlab to analyse the data outputs

**User interface:**

* User interface design to be simple, with clear instructions on how to complete the experiment and trials
* How will the user interact with my game design to move on from trial to trial, phase to phase and how will this benefit them
* The room design and justification for the design
  + Look at papers that research qualitative data in virtual reality
  + Look for keeping patients orientated and prevent over stimulated senses

**Project management: see word document**

**Results and evaluation:**

* Discuss the data I have collected from healthy participants and present the data using figure created.
* Evaluate the success of my software and rehabilitation design
* How does it compare to previous methods?
* Is it reliable?
* How robust is it?
* Include an evaluation of my project by other users

**Discussion:**

* Achievements of my project
  + One huge benefit of this system is that it provides as adaptable assessment system to collect data about upper-limb impairment, which includes valuable data on specific upper-limb movement impairment. Some current assessment techniques, such as Chedoke Arm and Hand Activity Inventory (CAHAI), and Box & Blocks Test (BB), require some form of motor control to perform them [10]. In this system, it is simple to adjust forces to different severity’s of upper-limb impairment to train and assess rehabilitation
* Deficiencies of my project
* What could’ve I done with more time? Or if things had worked differently
* Need to be able to recognise the problems that remain with my project
* Can apply machine learning to adapt the program forces and difficulty to match the user
* 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 [14]
* Reliability of my system?
* This program can also be used to determine relapses in patients as shown by [42] as they can distinguish between healthy and non healthy patients
* The use of attractive forces was considered however this didn’t challenge participants as we targeted healthy participants. Depending on the severity of the upper limb damage, patients may need to have attractive forces applied in order to stimulate the correct movement patterns and stimulate that motor control
* Talk about the accuracy of the robot, it will always provide accurate quantitative data where as a clinician will interpret patient exercise outcomes differently between sessions and their exercises. Different Clinicians will also interpret patient exercise progression differently as well

**Conclusion:**

* How have I addressed the problem stated in the introduction and relate this to results

**References:**

**Section that explains the sources of all submitted code:**

**Appendices:**

* Diagrams for design of haptic interface –
  + chapter 11 (engineering haptic devices)
  + P.g 91: Kinesthetic interfaces 4.6.3

**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