**Introduction:**

The aim of this study is to develop a novel haptic enhanced VR training system for use in upper limb stroke rehabilitation and examine the usability of the system created

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, encompassing 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, the primary and prevailing cause of sensory motor dysfunction, particularly affecting the upper limbs, remains 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 home-based rehabilitation interventions. 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).

When a person experiences a stroke, their brain's neuron cells are deprived 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 in 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).

Achieving the best recovery for the hemiparetic upper limb after a stroke demands significant dedication to a rehabilitation program from patients. 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-home based rehabilitation program is extremely important to ensure optimal recovery.

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 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 that can be utilized at home, providing instant feedback, for patients and clinicians. 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).

While some studies have demonstrated that VR has no significant impact in patients recovery (Laver *et al.*, 2017), it has been shown that integrating VR into conventional upper limb rehabilitation can significantly improve a patients motor control (Saposnik, Levin and null, 2011). VR also provides other benefits such as increased accessibility due to lower cost and portability of the technology, it does not require specialists to be present, and feedback and improvement by physios can be done remotely, which decreases the burden of providing rehabilitation services on health organisations (Saposnik, Levin and null, 2011).

Importantly, repetition of simple exercises does not always improve neural plasticity, however, the implementation of VR and haptic feedback allows clinicians to design exercises orientated towards the patients skill level, and easily adapt the tasks as the patients improve their learning (Plautz, Milliken and Nudo, 2000; Yeh *et al.*, 2017)

* Use of haptic feedback in rehabilitation services
* Use of this along side virtual reality
* Give example of previous haptic robots
* Why haptic feedback is theoretically beneficial for upper limb rehabilitation