Assessing the Feasibility of a Virtual Reality Intervention for Lower Phantom Limb Pain in the Acute Postoperative Period

by

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Author Note

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Abstract

Introduction. There are many individual and systemic barriers that prevent people with lower limb amputations (LLAs) from receiving effective nonpharmacological treatment for their phantom limb pain (PLP), such as low patient buy-in and long outpatient wait times. Early administration of effective treatments, such as graded motor imagery (GMI), via virtual reality (VR) may improve access and efficacy. To address this gap, our multidisciplinary team developed a VR GMI program using an iterative, patient-centered approach. This study aimed to assess the feasibility of administering a longitudinal VR GMI program immediately after LLA through one-month follow-up.

Methods. I recruited inpatients who underwent a major LLA within two months of surgery at a large tertiary care hospital to trial the VR GMI program for 17 days. Feasibility was assessed across three domains: (1) procedural feasibility (interest, eligibility, retention, and follow-up rates compared to predefined thresholds); (2) intervention feasibility (acceptability, adverse events, and average session length); and (3) pilot outcomes (exploratory correlations between the number of sessions completed and/or PLP intensity/interference at follow-up). Qualitative description contextualized reasons for ineligibility, disinterest, and session/study withdrawal.

Results. Of 111 patients screened, 54.44% were eligible and 48.33% were interested. Exclusions could primarily be attributed to patient preference to focus on recovery and physical comorbidities precluding VR engagement. Seventeen participants enrolled; only three (17.65%) completed the full recommended treatment dose (17 days) and nine (52.94%) responded at one-month follow-up. Participants generally rated the intervention as acceptable and engaged for the recommended amount of time. However, adverse events were more frequent than hypothesized.

Low retention and follow-up rates yielded insufficient sample sizes to conduct pilot and exploratory analyses.

Discussion. Findings suggest current recruitment and VR GMI administration procedures are not feasible in the immediate postoperative period and require significant modification. Procedural feasibility may be improved by addressing early discharge, shifting implementation timing, and improving the follow-up procedures. Future adaptations, including stage-specific gamification, may enhance engagement and retention for a future randomized controlled trial.

Keywords: virtual reality, phantom limb pain, lower limb amputation, graded motor imagery, feasibility

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Chapter I: Introduction

Thesis

Phantom limb pain (PLP) is one of the most prevalent forms of post-amputation pain, where uncomfortable sensations such as stabbing, burning, and throbbing are perceived in the missing limb despite it no longer being physically present (Ephraim et al., 2005). Unfortunately, there are many barriers to accessing effective nonpharmacological PLP treatments. One way to address this current gap in care is to administer PLP treatment through virtual reality (VR; Cheung et al., 2023). Such a program would allow for independent and early administration of PLP treatment for people with lower limb amputations (LLAs), effectively bypassing barriers to care. The current thesis will evaluate the feasibility and preliminary efficacy of a novel VR program in the postoperative period of LLA, including inpatient and home settings. Empirical evidence for the feasibility of this VR program will contribute to the growing literature that supports administering VR PLP treatments in the postoperative acute care period and potentially represent a novel acute treatment for PLP.

The Issue

More than 7000 LLAs are performed in Canada each year due to (in order of decreasing prevalence) diabetic, vascular, traumatic, cancerous, and congenital indications (Imam et al., 2017). Approximately 70% of these individuals will experience PLP (Limakatso et al., 2020; Mioton et al., 2020). If left untreated, PLP can significantly reduce quality of life, both psychologically and physically (Christensen et al., 2016; Padovani et al., 2015; Sinha et al., 2014; van der Schans et al., 2002). Specifically, research suggests PLP reduces mobility, which has adverse effects on independence (such as maintaining employment) and social role fulfillment (Christensen et al., 2016; Sinha et al., 2014; van der Schans et al., 2002). PLP has

also been implicated in a variety of other negative sequelae, including poorer sleep quality and affective distress (Ephraim et al., 2005; Padovani et al., 2015; Polat et al., 2021; Trevelyan et al., 2016). Despite the high prevalence and negative outcomes associated with PLP, a staggering 71% of people with LLA do not receive any PLP treatment (Kern et al., 2012; Trevelyan et al., 2016). PLP is more prevalent and severe immediately following amputation (Mioton et al., 2020), highlighting the urgent need to develop PLP interventions that can be administered acutely to support patients and reduce the likelihood of these downstream negative sequelae.

PLP Etiology

Peripheral Mechanisms

The development of an effective PLP treatment first requires an understanding of its etiological mechanisms. Some researchers attribute PLP to peripheral mechanisms—such as spontaneous ectopic discharge of the dorsal root ganglia or neuromas at the amputation site—that may be exacerbated by activation of the sympathetic nervous system (Angrilli & Köster, 2000; Boomgardt et al., 2022). Neuromas are also proposed to cause residual limb pain (RLP), which refers to nociceptive pain at the amputation site (also known as the residual limb, or *stump*). The relevance of peripheral PLP mechanisms is supported by the high correlation observed between PLP and RLP, suggesting these phenomena may share physiological processes such as ectopic discharge (Limakatso et al., 2020). However, 2.2%–72% of patients report PLP onset prior to neuroma development, which typically occurs approximately one month following amputation (Stankevicius et al., 2021; Oliveira et al., 2018), and PLP may persist even after neuromas are addressed through targeted muscle reinnervation (Valerio et al., 2019). While peripheral mechanisms may contribute to PLP, complementary etiological theories—such as

cortical reorganization and neuromatrix theory—are necessary to ascertain a more nuanced understanding of PLP.

Central Mechanisms

Cortical reorganization theory posits PLP results from central, rather than peripheral, mechanisms (Boomgardt et al., 2022). According to cortical reorganization theory, the primary somatosensory and motor cortices (neighbouring brain regions responsible for integrating sensory input and motor output, respectively) contain a topographic map of the entire body that is altered following amputation (Makin & Flor, 2020). The cortical region of the topographic map responsible for the amputated limb becomes sensitized to neighbouring electrical activity, resulting in neural rewiring (Moseley et al., 2012). Specifically, the neighbouring neurons infiltrate the cortical region that was previously responsible for the amputated limb. The degree to which this neural infiltration results in deviations from typical sensorimotor cortical topography has been significantly and positively associated with self-reported PLP intensity (Andoh et al., 2020; Flor et al., 1995; Zheng et al., 2021). Following PLP reduction, functional magnetic resonance imaging reveals a reversal in maladaptive neural rewiring (Foell et al., 2014; Huse et al., 2001; MacIver et al., 2008). Significant evidence suggests cortical reorganization theory is the most promising etiological explanation for PLP to date.

The empirical support for cortical reorganization theory extends to both upper and lower limb amputations. While functional magnetic resonance imaging suggests upper limb amputations are followed by infiltration from neurons responsible for the lips (Ichinose et al., 2017; Lotze et al., 2001), lower limb amputations are followed by neural infiltration from the cortical region responsible for the thumb (Zheng et al., 2020). Unfortunately, the role of cortical reorganization in LLA has been understudied when compared to upper limb amputations (Makin

& Flor, 2020). Sparse literature indicates there is a significant negative association between PLP intensity and functional connectivity between the supplementary motor area and related structures following LLA (Zhang et al., 2018; Zheng et al., 2021). While the implications of cortical reorganization beyond the somatosensory and motor cortices have yet to be explored, the potential differences in PLP etiology between upper and lower limb amputations should be acknowledged.

Psychological Mechanisms

The extent to which psychological mechanisms contribute to and maintain PLP is a controversial topic in the literature. An abundance of large survey data supports a strong and significant association between PLP perceived to be disruptive to daily life and clinically significant depressive, anxious, and post-traumatic stress symptoms (including intrusive thoughts and behavioural avoidance; Darnall et al., 2005; Desmond & MacLachlan, 2006; Ephraim et al., 2005; Hogan et al., 2022). Research has yet to elucidate the directionality of the relationship between PLP and negative mental health correlates, although it is suspected to be bidirectional (Fuchs et al., 2018). While PLP may contribute to biopsychosocial dysfunction by deterring mobility and prosthetic use (van der Schans et al., 2002), maladaptive cognitive and affective processes may also lead to and maintain PLP. According to the neuromatrix theory developed by Melzack (2001), chronic pain occurs when the complex neural network responsible for nociceptive perception—known as the pain neurosignature— undergoes maladaptive modification by unique life experiences (including sensory, motivational-affective, and cognitive input). In the case of chronic PLP, neuromatrix theory posits the central sensitization of the sensorimotor cortex described within cortical reorganization theory should not be attributed to nociception and proprioception alone, but cognitive and affective processes as well (Moseley et

al., 2012). When considering the development of a novel PLP intervention, numerous etiological theories and their treatment implications should be considered.

PLP Treatments

Pharmacological Interventions

Currently, pharmacological interventions are among the most administered PLP treatments (Kern et al., 2012; Rich et al., 2023). Common prescriptions include gabapentin (among other NMDA inhibitors and antagonists), tricyclic antidepressants, and opioids (Hall & Edabe, 2018). However, a recent meta-analysis suggests pharmacological PLP interventions are ineffective compared to a placebo (Wang et al., 2023). This non-efficacy is likely because medication does not act directly on the sensorimotor cortex to reverse maladaptive neural deviations in cortical topography (although opioids have been shown to have indirect upstream effects on cortical organization in a small sample; Huse et al., 2001). Such results may explain several findings (primarily qualitative) that demonstrate low satisfaction rates with pharmacological PLP management, with individuals often doubting its efficacy or simply preferring not to develop long-term dependence on pharmaceuticals (Collins et al., 2021; Horne & Paul, 2019; Kern et al., 2012; Rich et al., 2023; Trevelyan et al., 2016). Indeed, there are often long-term adverse effects to routine use of pharmacological interventions (such as opioids), including addiction, dizziness, and drowsiness/fatigue (Quintero et al., 2017; Volkow et al., 2018). While medication may be a convenient treatment for PLP, it is not demonstrated to be preferred or efficacious, necessitating inquiry into nonpharmacological alternatives.

Nonpharmacological Interventions

Nonpharmacological interventions are proposed to work through cognitive mechanisms that trigger neural rewiring in the sensorimotor and associated cortical regions to reduce PLP

(Foell et al., 2014; MacIver et al., 2008). For example, cognitive and affective reactions to nociception— such as catastrophizing and distress— have been implicated in the cortisol release theorized to modulate pain perception (Angrilli & Köster, 2000; Melzack, 2001; Moseley et al., 2012). Numerous case series and clinical trials demonstrate preliminary effectiveness of therapies that promote effective stress regulation and reduce emotional/cognitive reactivity to modify the maladaptive pain neurosignature, such as eye movement desensitization and reprocessing therapy, biofeedback, hypnosis, and cognitive behaviour therapies (Niraj & Niraj, 2014). However, researchers seem to have shifted away from affective PLP intervention in recent years, as reflected in a recent meta-analysis that excluded them from consideration (Wang et al., 2023). Contemporary research has instead favoured the evaluation of how proprioception may be targeted in the treatment of PLP. A recent review by Fuchs et al. (2018) summarized a wealth of literature that indicates there is a significant negative correlation between one's ability to mentally rotate their phantom limb and PLP intensity. This cognitive mechanism for PLP relief is corroborated by additional studies that show short-term PLP reduction is significantly associated with increased phantom limb control (Osumi et al., 2014; 2017; 2019). People with PLP may suffer from a cognitively dissonant body representation (i.e., body schema) following limb loss, in which they implicitly expect sensory input from their missing limb and experience pain as a result (Fuchs et al., 2018; Osumi et al., 2014). Recent nonpharmacological interventions attempt to correct this maladaptive body schema to reduce PLP.

Limb Simulation Through Mirror Therapy and Mental Imagery.

Both mirror therapy and mental imagery have been used across healthcare disciplines to treat PLP by increasing phantom limb control. Mental imagery (typically facilitated by mental health specialists such as clinical psychologists) involves the deliberate visualization of phantom

limb movement and has demonstrated efficacy for PLP reduction through both self-report measures and neuroimaging (Brunelli et al., 2015; MacIver et al., 2008). Meanwhile, mirror therapy is a unilateral (i.e., where there is one amputated limb) PLP treatment typically administered by physiotherapists that provides visual feedback of phantom limb control by reflecting the existing limb in a mirror box (Gautam et al., 2023). The patient then performs a series of exercises in front of the mirror to create the illusion that both limbs are still present and moving symmetrically. A recent meta-analysis demonstrates mirror therapy is significantly more efficacious than a placebo (such as a covered mirror or sensorimotor therapy) to treat PLP (Wang et al., 2023). Both mental imagery and mirror therapy have successfully been used to treat PLP, theoretically by correcting maladaptive body schemas through phantom limb control.

To ascertain how effective mirror therapy is at generating the illusion of control over the phantom limb, researchers often measure agency, which is the degree to which one feels their phantom limb is responsible for the mirrored (i.e., virtual) limb movements (Roth & Latoschik, 2020). Virtual limb agency has been shown to be related to PLP reduction, both through self-report (Cole et al., 2009; Imaizumi et al., 2017) and functional magnetic resonance imaging (Foell et al., 2014). Agency should be distinguished from ownership, which is the degree to which one feels the virtual limb is their own (Roth & Latoschik, 2020). Despite being similar constructs, agency and ownership do not always correlate; nonetheless, both agency and ownership over virtual and prosthetic limbs, respectively, have been associated with PLP reduction (Bekrater-Bodman et al., 2021; Imaizumi et al., 2017). This evidence suggests agency and ownership in the virtual limb might be necessary conditions to reduce PLP through mirror therapy.

Graded Motor Imagery (GMI).

While mental imagery and mirror therapy have both been shown to reduce PLP independently (Brunelli et al., 2015; Wang et al., 2023), further studies suggest their treatment efficacy can be enhanced when they are combined in a single treatment regime (Brunelli et al., 2023; Wang et al., 2023). The pioneers of this line of scientific inquiry were Moseley et al. (2012), the researchers who developed GMI for PLP. GMI involves the stepwise visualization of one's phantom limb through three sequential tasks. The first exercise is left/right discrimination (also known as implicit motor imagery), which entails quickly sorting images of left and right limbs. The second exercise is explicit motor imagery (another term to describe phantom motor imagery), while the third and final task is mirror therapy. Research suggests the GMI treatment components might be ineffective or even increase PLP (termed a "flare-up" by GMI specialists) if they are administered out of order or too quickly (Mibu et al., 2016; Moseley et al., 2005). A flare-up occurs when phantom limb movement has become associated with PLP, which is the result of neurons responsible for the amputated limb in the sensorimotor cortex becoming sensitized to neighbouring neural activity (Moseley et al., 2012). GMI allows the patient to reduce sensitization by activating the prefrontal cortex first (through left/right discrimination) before activating the sensorimotor cortex (through explicit motor imagery) and related cortical regions, such as the visual cortex (through mirror therapy), in a stepwise manner. To mitigate the risk of flare-ups, GMI has traditionally been administered by highly trained physiotherapists to guide patients through the treatment process (Moseley et al., 2012). GMI has been demonstrated to be one of the most promising evidence-based PLP interventions to date (Limakatso et al., 2023).

VR.

VR (i.e., a computer-generated three-dimensional simulated environment in which a user may be immersed with the use of a mounted headset) has also shown preliminary efficacy as a PLP treatment through a variety of different interfaces (Cheung et al., 2023). For example, VR has been used to simulate virtual visual feedback similar to mirror therapy (Mercier & Sirigu, 2009; Murray et al., 2007; Rey et al., 2022). A study by Diers et al. (2015) suggests virtual visual feedback produces significantly higher activation in the contralateral sensorimotor cortex during mirrored movements compared to traditional mirror therapy, highlighting the novelty and, potentially, increased effectiveness offered by VR by facilitating presence (i.e., focused attention through immersion; Berkman & Catak et al., 2021) in the treatment task (Spiegel et al., 2019). VR has also been used to gamify treatment, allowing phantom motor imagery and execution to be administered through platforming games (Ambron et al., 2021; Ortiz-Catalan et al., 2014; 2016), physical exercises (Annapureddy et al., 2023; Rutledge et al., 2019), and interactions with the natural world (Cole et al., 2009). Oftentimes, this gamification is adapted for people with upper limb amputations, rather than LLA (Cheung et al., 2023), representing a gap in the literature. VR is another example of a nonpharmacological treatment that could be invaluable to people with PLP, particularly those with LLAs.

Preventative PLP Interventions

While most treatments are administered over three months after PLP first occurs (i.e., following PLP onset), researchers have also successfully prevented PLP by administering pharmacological or nonpharmacological treatments during the perioperative period of amputation. For example, both epidural and systemic analgesia (i.e., morphine and ketamine) administered before, during, and after major limb amputation have been shown to reduce PLP

incidence compared to a control group up to one year and six months following the procedure, respectively (Valero et al., 2023). Similarly, surgical intervention geared towards neuroma prevention (such as targeted muscle reinnervation) employed at the same time as major limb amputation has demonstrated significant PLP reduction compared to a control group at three-month follow-up (Valerio et al., 2019). Within the last few years, researchers have even begun to investigate the prophylactic effects of nonpharmacological PLP interventions. A study conducted in India by Purushothaman et al. (2023) found that traditional mirror therapy administered for 14 days immediately following LLA significantly reduced PLP incidence (11.7%) and severity as far as 6-month follow-up compared to treatment as usual (28.3%). Likewise, Agostinho et al. (2023) demonstrated that acute PLP treatment (< two months since major limb amputation) through a combination of mirror therapy and neuromodulation results in a PLP reduction twice as large as that seen in people who were treated for PLP when their amputation was over three months ago. Recent preliminary evidence highly suggests the effectiveness of early PLP intervention to reduce both PLP intensity (amongst those who develop PLP) and PLP incidence.

The Problem

The feasibility of implementing nonpharmacological PLP interventions on a national scale is limited by systemic and individual barriers to accessing care in the Canadian healthcare system. These limitations can be classified according to the Theoretical Domains Framework, a model validated through systematic review and consensus that identifies fourteen barriers to behavioural change (Cane et al., 2012). The Theoretical Domains Framework can be simplified by mapping each domain onto the Behaviour Change Wheel, which specifies behavioural change is affected by an individual's capability, opportunity, and motivation for the desired behaviour (Michie et al., 2011). Canadian healthcare access for nonpharmacological PLP intervention is

influenced by a complex intersection of individual barriers (i.e., capability and motivation) and systemic barriers (i.e., opportunity).

Personal characteristics and perceived competencies affect an individual's ability to access nonpharmacological PLP treatment in Canada. Qualitative research suggests many patients do not realize PLP interventions exist beyond the medication prescribed by their physicians, despite expressing a desire for alternatives (Collins et al., 2021; Horne & Paul, 2019; Trevelyan et al., 2016). A nationwide survey conducted in Germany by Kern et al. (2012) demonstrated that 42% of patients with LLAs were not even informed by healthcare staff before their LLAs that they would likely develop PLP, let alone how they might treat it. Qualitative research has corroborated this startling lack of knowledge mobilization about PLP to patients within the Canadian healthcare system (Trevelyan et al., 2016). Additional qualitative investigations also indicate confusion as to how to navigate ambiguous bureaucratic pathways to receive public healthcare, such as completing lengthy, confusing paperwork (MacKay et al., 2022; Radenovic et al., 2022). According to the Theoretical Domains Framework, patients lack the psychological capability to pursue nonpharmacological PLP treatment either because they are unaware of its existence or they lack the skills and knowledge to approach it successfully (Cane et al., 2012).

Beyond capability, an individual's motivation to pursue nonpharmacological PLP intervention is impacted by an array of psychological factors. For example, people who perceive their PLP to disrupt their quality of life seem to be more motivated to seek intervention, self-administered or otherwise (Crooks et al., 2025; Trevelyan et al., 2016). However, many people feel hopeless about their PLP due to receiving ineffective pharmacological interventions, often believing they must learn to endure and accept their pain rather than seek treatment (Horne &

Paul, 2019; Kern et al., 2012; Trevelyan et al., 2016). Additionally, many patients report being so overwhelmed by their LLA and its associated challenges (e.g., limited mobility, physical rehabilitation to enable prosthetic use) that they simply do not have the time, energy, or attention to dedicate to prioritizing PLP treatment (Crooks et al., 2025; Radenovic et al., 2022). These data suggest an individual's motivation to seek and engage with PLP treatment may be influenced by depressive (i.e., helplessness) and anxious symptomatology (i.e., overwhelm). For GMI specifically, motivation to pursue and sustain treatment is highly impacted by buy-in (i.e., whether an individual believes the intervention is effective and worth their time; Bakshi et al., 2021; Crooks et al., 2025; Moseley et al., 2012). In conjunction with whether an individual is capable of pursuing PLP intervention, motivation is a critical consideration when addressing low PLP treatment access in Canada.

Lastly, systemic barriers to Canadian healthcare access disproportionately deter vulnerable groups from pursuing nonpharmacological PLP intervention. People from neighbourhoods with low socioeconomic status (SES; including individuals from the lowest quintile of total household income and people who achieved less than a high school education) are three to four times more likely to develop LLAs due to diabetic indications compared to their higher SES counterparts (Canadian Institute for Health Information, 2024). As such, an abundance of qualitative research suggests finances are a severe stressor following LLA due to reduced capacity to sustain employment, as well as an inability to afford accessible housing, transportation to healthcare appointments, or a prosthetic leg, among other miscellaneous expenses (Collins et al., 2021; Crooks et al., 2025; MacKay et al., 2022; Radenovic et al., 2022). Moreover, people living in rural areas are 1.6 times more likely to develop a diabetic LLA compared to individuals living in urban centres, and yet they are disproportionately unable to

access healthcare due to limited mobility and a lack of healthcare providers living in their community (Canadian Institute for Health Information, 2024; Radenovic et al., 2022; van der Schans et al., 2002). Among rural inhabitants, Indigenous peoples are at an even higher risk to develop diabetic LLA and encounter additional social barriers to access due to a history of colonialist policies and discrimination in Canada, leading to a mistrust of healthcare providers (Blanchette et al., 2023). Even in urban areas, there is a dearth of physiotherapists available that are essential to the feasible administration of traditional GMI (Johnson et al., 2012; Moseley et al., 2012). A recent study evaluating public pain clinics across Canada reported minimum wait times of six months to access outpatient healthcare (Liddy et al., 2024). These environmental contexts, resources, and social influences are identified in the Theoretical Domains Framework as key domains that may affect an individual's opportunity to pursue nonpharmacological PLP intervention in Canada (Cane et al., 2012).

The Solution

To address current barriers to PLP care, our multidisciplinary research team (consisting of clinical psychologists, physiotherapists, physiatrists, anesthesiologists, surgeons, and engineers) developed a novel VR program that allows people with LLAs to self-administer GMI treatment. In line with its capacity for gamification, research suggests VR is more motivating and usable than two-dimensional treatment administration modalities (Spiegel et al., 2019). The novelty offered by VR will be invaluable to administer GMI psychoeducation and tasks in a gamified manner to increase patient buy-in and knowledge (Bakshi et al., 2021). Thus, according to the Theoretical Domains Framework, the VR GMI program may be able to combat the hopelessness and limited psychological capacity surrounding nonpharmacological PLP treatment commonly reported by people with LLAs (Crooks et al., 2025; Cane et al., 2012; Kern et al.,

2012; Radenovic et al., 2022). Moreover, all GMI psychoeducation and treatment tasks are embedded on the device, bypassing systemic barriers by eliminating the need to wait for and travel to a physiotherapist (Cane et al., 2012). Lastly, visual feedback may be of particular benefit to people with LLA. Research suggests lower limb movements are more natural when performed asymmetrically (such as pedalling or walking); therefore, VR (through its capacity for asymmetrical movement) may produce more favourable outcomes for people with LLA compared to traditional mirror therapy by generating a higher sense of agency (Henriksen et al., 2018). To bypass these barriers, our research team specifically designed the VR GMI program to be administered in the postoperative acute care setting immediately following LLA, when intervention is suggested to be the most effective (Agostinho et al., 2023). Additionally, patients have endorsed significant boredom the postoperative period (Crooks et al., 2025), suggesting VR GMI may also represent a welcome distraction from the monotony of the hospital setting. See Figure 1 for an overview of the five stages in the VR program: psychoeducation, left/right discrimination, explicit motor imagery, limb simulation without leg tracking, and limb simulation with leg tracking.

VR Implementation Barriers

VR PLP (without embedded GMI) treatment has previously been self-administered by participants with LLAs and has produced promising feasibility outcomes (Annapureddy et al., 2023; Annaswamy et al., 2022; Lendaro et al., 2020). However, notable implementation barriers have been reported, including difficulties with technical setup, scheduling conflicts, RLP, feeling unchallenged by the intervention, and low PLP. Barriers to medical VR application appear more pronounced in hospital settings (Crooks et al., 2025; Mosadeghi et al., 2016; Roznik et al., in progress). A large feasibility study conducted by Mosadeghi et al. (2016) suggests that of 510

inpatients assessed, 83% were ineligible to participate due to cognitive impairment (with limited capacity to consent), critical illness, and proneness to nausea or vomiting. Of the 87 inpatients approached, 66% refused due to anxiety associated with the headset, not understanding the medical application of VR, fatigue/sickness, fear of losing control, not wanting to be experimented on, and a general lack of interest in VR. Findings from phases 2 and 3 of VR GMI development corroborate these barriers to inpatient VR use in the postoperative period, adding physical pain, limited perceived benefit, and competing priorities beyond PLP management as additional reasons for refusal (Crooks et al., 2025; Roznik et al., in progress). Older adults were significantly more likely to decline participation, reflecting age-related differences in technological self-efficacy that may affect acceptability (Mosadeghi et al., 2016). These findings highlight the importance of assessing the feasibility of VR interventions to improve their fidelity prior to conducting larger clinical trials.

Purpose and Rationale

The purpose of the current study was to evaluate the feasibility and pilot preliminary outcomes of the VR GMI program to prevent PLP in the postoperative acute care setting (i.e., inpatient and early outpatient and home settings) immediately following LLA. This inquiry fits the criteria of a VR2 study in the Virtual Reality Clinical Outcomes Research Experts (VR-CORE) model developed by Birckhead et al. (2019). The VR-CORE outlines the phases of patient-centered development a medical VR program should undergo prior to assessing its efficacy in a randomized controlled trial in order to maximize its chances of implementation.

This thesis represents the final stage of a four-phase patient-centered prototype development protocol outlined by El-Gabalawy et al. (2025). Phase 1 entailed consultation with physiotherapists, people with lived experience of LLAs, and research literature to produce a low

fidelity prototype and treatment plan in collaboration with engineers at the National Research Council. In the second phase, for the purposes of my undergraduate thesis, I aimed to conduct a VR1 study to evaluate how practical and engaging the initial VR GMI prototype was perceived to be by people with lived experience of LLAs ($n = 12$) in a single, intensive community session. Using a multi-methods approach, I explored anticipated barriers and facilitators to VR GMI use in the postoperative period, including technological self-efficacy, treatment priorities beyond PLP, as well as the perceived benefit and convenience of intervention use (Crooks et al., 2025). In phase 3, we conducted a small VR2 study through a descriptive case series ($n = 6$) designed to evaluate preliminary recruitment trends and patient satisfaction with the VR GMI program in the acute inpatient setting immediately following LLA (Roznik et al., in progress). A larger scale feasibility study of this nature is the ideal next step to further validate the VR GMI program in accordance with the VR-CORE model, thereby taking a patient-centered approach.

Design and Objectives

The current thesis builds on previous work and employed a one-group multi-method design to assess the feasibility and pilot preliminary outcomes of a novel VR program to prevent PLP in inpatient rehabilitation settings immediately following LLA. Specifically, approximately one VR stage was administered to people with LLAs daily for up to 17 days in the acute postoperative stage (i.e., within two months following amputation; Agostinho et al., 2023) to evaluate feasibility outcomes through self-report data and recruitment trends. Pilot outcomes were assessed at one-month follow-up through self-report measures. Reasons for ineligibility, disinterest, early participation withdrawal/session discontinuation, and missed sessions were recorded and analyzed through qualitative descriptive analysis to supplement the results.

In accordance with feasibility study guidelines (Birckhead et al., 2019; Orsmond & Cohn, 2015), the present research investigated five objectives and hypotheses.

1. *Procedural Feasibility.* I assessed the effectiveness of the employed recruitment strategies and study procedures. Recruitment and study pathways were iteratively developed over time with a multidisciplinary healthcare team at the Health Sciences Centre (HSC), a public inpatient hospital located in Winnipeg, Canada, in addition to the literature (Griffin et al., 2017; Purushothaman et al., 2023). Therefore, I hypothesized the current recruitment strategies would be effective, and produce sufficient eligibility, interest, retention, and follow-up rates.
2. *Intervention Feasibility.* I evaluated the acceptability and tolerability of, as well as engagement with, the VR program immediately following LLA in the postoperative acute care setting. I predicted participants would rate the VR program favourably for each component, in line with the feasibility of previous VR PLP interventions using quantitative measures (Annaswamy et al., 2022; Rutledge et al., 2019).
3. *Pilot Outcomes.* I planned to conduct a preliminary exploration into the treatment effect that the length of VR program engagement had on PLP incidence, intensity, and interference. I hypothesized higher levels of program engagement would lead to lower levels of PLP incidence, intensity, and interference, in line with previous research investigating prophylactic PLP treatment through mirror therapy in the postoperative period (Purushothaman et al., 2023).
4. *Exploratory Analyses.* I also planned to explore how sample characteristics (such as pre-amputation pain, amputation indication, embodiment, presence, anxious/depressive symptomatology, and age) affected VR program acceptability, engagement, and pain

outcomes, which have all been implicated in treatment engagement or PLP onset (Foell et al., 2014; Mioton et al., 2020; Srifuengfung et al., 2023; Tashjian et al., 2017).

5. *Reasons for Disengagement.* I explored reasons patients disengaged from the study at various stages, including participation refusal, early session discontinuation, and study withdrawal. I hypothesized reasons for disengagement would reflect that of previous feasibility studies assessing VR interventions in the home setting, as well as anticipated barriers that participants identified in previous phases of VR GMI program development (Crooks et al., 2025; Lendaro et al., 2020; Mosadeghi et al., 2016; Roznik et al., in progress).

Chapter II: Method

Participants

Eligibility Criteria

I aimed to recruit thirty participants (*n = 30*), in line with the 80% power required to accurately detect the desired eligibility criterion and an additional five participants to account for attrition (Lewis et al., 2021; Young et al., 2019). Potential participants were approached if they met the following inclusion criteria: if they underwent or were about to undergo a unilateral or bilateral major LLA (hip, below-knee, above-knee, or foot) within the last two months (the period in which prophylactic PLP treatment have previously been seen to be efficacious, according to Agostinho et al., 2023); if they were currently receiving inpatient treatment at the Health Sciences Centre (HSC) in Winnipeg, Canada; and if they could speak/read English fluently. Potential participants were removed from consideration if they met the following exclusion criteria: any visual, hearing, motor, or cognitive impairment that would affect

engaging with a head-mounted VR headset or hand controls, as judged by research or nursing personnel; and anyone younger or older than eighteen and eighty years old, respectively.

Anticipated Participant Characteristics

A sociodemographic and participant characteristic self-report questionnaire was verbally administered to assess age, gender, ethnicity, the chronicity of pre-amputation lower limb pain, education, occupation, and marital status, as well as current/historical mental healthcare utilization and behavioural pain management. Each of these variables has been associated with PLP onset or adverse postoperative outcomes that may affect engagement (Blanchette et al., 2023; Boomgaardt et al., 2022; Canadian Institute for Health Information, 2024; Fuchs et al., 2018; Mioton et al., 2020). I also collected information regarding amputation etiology, whether that be atraumatic (e.g., cancer, diabetes; planned amputations) or traumatic (e.g., car accident; unplanned amputations) indications (the literature is mixed as to which indication is more strongly associated with PLP, warranting investigation; Mioton et al., 2020; Limakatso et al., 2020). Given that traumatic limb loss is, by definition, the result of abrupt accidents that require intensive care (compared to planned surgeries), I anticipated there would be a higher proportion of people with atraumatic amputations who met the eligibility criteria. Specifically, I anticipated a particularly high proportion of diabetic amputations, given their prevalence in Canada (67.8% of total amputations in 2011; Imam et al., 2017). Since Indigenous peoples are disproportionately affected by diabetic LLA (Blanchette et al., 2023), the sample characteristics should reflect this ethnic diversity.

Recruitment

Recruitment strategies were established iteratively throughout phase 3 in collaboration with HSC stakeholders (Roznik et al., in progress). Potential participants were screened from the

following avenues: the preanesthesia clinic (in charge of presurgical visits between anesthesiologists and patients prior to LLA); the operating room slates (which contain the information of every patient about to undergo an LLA); vascular and orthopedic surgeons; physiotherapists working with potential participants in the inpatient rehabilitative setting; and weekly correspondence with charge nurses on select vascular, orthopaedic, general/plastic surgery, and rehabilitation inpatient units.

Once potential participants were identified, healthcare professionals in their circle of care approached them to ascertain their interest in hearing more about the study from research personnel. Purposive sampling was utilized to maximize study enrollment. In other words, every individual who met the eligibility criteria after in-person or phone screening by research personnel and provided written informed consent was recruited. Following consent, every participant received a $25 gift card to express gratitude for their time. If an individual was ineligible or declined to participate, their reason for refusal was recorded.

Ethical approval for the present study was obtained from Bannatyne Research Ethics Board at the University of Manitoba (B2022107) and Shared Health (SH2022254).

Outcome Measures

Theoretical Framework of Acceptability Questionnaire (TFAQ)

The TFAQ consists of seven statements that gauge the acceptability of a healthcare intervention (Sekhon et al., 2022). Each statement is rated on a five-point Likert scale, with qualitative anchors that differ by question (with one referring to the lowest rating of acceptability on that item). The TFAQ has excellent content validity informed by a preexisting theoretical framework (Sekhon et al., 2017), as well as coded feedback from experts and stakeholders (Sekhon et al., 2022). Nonetheless, the questionnaire is still considered to be in the pre-

implementation phase and therefore has not been assessed for other forms of validity or internal reliability. However, all other acceptability measures in the literature are either too burdensome or too vague to administer at each VR stage (Mettert et al., 2020). Given that acceptability can vary across the implementation process (Proctor et al., 2011), the TFAQ was considered to align with the feasibility aims of the current study for the purposes of stage-specific evaluation. The TFAQ was administered verbally or in writing after participants completed each VR GMI stage for the first time. See Appendix A for how the TFAQ was tailored for the current research.

Numerical Rating Scale (NRS) for PLP, RLP, and nausea

The NRS is a verbally administered 11-point unidimensional measure that has sufficient criterion validity for both pain (Lee et al., 2021) and nausea (Wikström et al., 2019). While both pain and nausea are anchored with zero referring to *no [insert construct],* ten refers to *worst pain imaginable* and *severe,* respectively. Currently, there are no measures validated specifically for PLP; therefore, researchers have often generalized the utility of the NRS as a scale to measure PLP (Purushothaman et al., 2023; Rothgangel et al., 2018). The NRS was administered to measure state levels of PLP, RLP, and nausea before and after each VR session as an operationalization of tolerability.

Brief Pain Inventory (BPI)—Pain Intensity

The BPI—Pain Intensity consists of four items that inquire into the respondent's worst, least, and average pain in the last week, as well as their current pain. Each item consists of an eleven-point Likert scale that ranges from zero (*no pain*) to ten (*pain as bad as you can imagine*). It is scored by taking the average of the four items. The questionnaire has strong construct validity and internal consistency ($\alpha = .85$) amongst people with chronic non-malignant pain (Tan et al., 2004). Similar to the NRS, the BPI is often used to measure PLP intensity in the literature

(Brunelli et al., 2023; Limakatso et al., 2020; Segal et al., 2021), so it was employed to measure PLP intensity at one-month follow-up.

Patient-Reported Outcome Measurement Information System (PROMIS) Pain Interference Scale—8a

The PROMIS Pain Interference Scale consists of eight items that gauge how much the respondent's pain interfered with their daily functioning in the past seven days (Amtmann et al., 2010). Each item is rated on a five-point Likert scale of one (meaning *not at all*) to five (meaning *very much*). I scored it by entering deidentified summed raw scores from participants into the *HealthMeasures Scoring Service* to generate T-scores using the default item-level calibration sample. The measure demonstrates excellent internal consistency (α = .96), as well as adequate criterion and construct validity, in veterans who recently underwent orthopedic surgery (Hadlandsmyth et al., 2020). It was administered to measure PLP interference at one-month follow-up.

Exploratory Outcome Measures

A variety of validated and reliable measures were used to explore how length of program engagement, acceptance, and PLP intensity/interference at one-month follow-up may be affected by heterogenous participant characteristics and experiences. The Patient Health Questionnaire (PHQ-9) measured depressive symptoms (α = .87; Kocalevent et al., 2013; Kroenke et al., 2001), while the Generalized Anxiety Disorder (GAD-7) measured anxiety symptoms (α = .89; Löwe et al., 2008). A cut-off score equal to or greater than 10 was used to denote clinically significant symptomatology, in line with previous validation studies (Kroenke et al., 2001; Löwe et al., 2008). Meanwhile, the Virtual Embodiment Questionnaire (VEQ) measured the agency, ownership, and changes in body schema facilitated by the VR (i.e., embodiment; α = .78, .76,

and .76, respectively; Roth & Latoschik, 2020), and the iGroup Presence Questionnaire (IPQ) measured the degree to which one was immersed in the VR (α = .77, .68, and .65 for spatial presence, involvement, and realism subscales, respectively; Berkman & Catak, 2021). Depression, anxiety, embodiment, and presence have all been implicated in the etiology, maintenance, or recovery of postoperative pain (Foell et al., 2014; Srifuengfung et al., 2023; Tashjian et al., 2017).

Intervention

The VR program operates on an Oculus Meta Quest 2, a head-mounted VR hardware system (El-Gabalawy et al., 2025). The VR software consists of five stages: 1) psychoeducation (i.e., the participant watches a video explaining the GMI theory behind the VR program, which has been suggested to be crucial for treatment buy-in; Moseley et al., 2012); 2) the left/right discrimination task (i.e., the participant sorts images of left and right feet); 3) the explicit motor imagery task (i.e., the participant engages with guided mindfulness exercises that facilitate phantom limb focus and imagery); 4) the limb simulation task without leg trackers (i.e., an adapted and enhanced mirror therapy task, where the VR creates the illusion that the participant still has and can move both legs asymmetrically); and 5) the limb simulation task with leg trackers (in which participants wear leg trackers to have more immediate control over their virtual leg movements in limb simulation). See Figure 1 for an overview of the VR GMI stages.

Procedures

Participants were asked to engage in one VR session per day from the inpatient orthopedic, vascular, general/plastic surgery, or rehabilitation wards. At the beginning of the first VR session, after informed consent was obtained and the honorarium was given to the participant, I administered the sociodemographic and patient characteristics questionnaire, PHQ-

9, and GAD-7. Either a research assistant or I then showed the participant a brief video via laptop that introduced them to the VR program, including how to operate the controls and put on the headset. The video also included instructions about study procedures to standardize expectations across participants. Following that and at the beginning of each subsequent VR session, research personnel verbally administered the NRS for PLP, RLP, and nausea and asked if they wanted to engage with the VR program that day. If they did not (or they could not be found on their inpatient unit by research personnel), their reason for declining the VR session was recorded. If the participant was interested, they engaged in one of the VR GMI stages. All participants began in the psychoeducation stage and were only permitted to engage in one VR GMI stage per day. After their session, the research personnel verbally readministered the NRSs for PLP, RLP, and nausea, as well as the stage specific TFAQ, and (in the case of the limb simulation stage) the IPQ and VEQ. The TFAQ, IPQ, and VEQ were only administered once the first time the participant completed the stage being assessed.

Participants were only permitted to move onto the next VR stage if their RLP, PLP, or nausea NRS scores did not increase by more than three points during or in the time since their previous session (given that treatment can sometimes exacerbate pain or nausea; Mibu et al., 2016; Mosadeghi et al., 2016; Moseley et al., 2012). The participants were also asked to verbally indicate whether any NRS increase, no matter the size, was distressing enough to deter use (e.g., leading to a discontinued or declined VR session). Such instances of distress were coded as adverse events and were considered as a measure of tolerability. Each adverse event was recorded and would result in an adjusted treatment plan in line with patient interests (e.g., lower amount of time spent in the VR GMI program during the next session or moving back to a previous VR GMI stage).

Participants were asked to engage in the VR GMI program daily for twenty minutes (excluding weekends) until they engaged in fourteen limb simulation sessions, with or without leg tracking. Previous literature assessing traditional mirror therapy as a PLP intervention (prophylactic or otherwise) has suggested this to be a sufficient dose to see a treatment effect (Griffin et al., 2017; Segal et al., 2021; Purushothaman et al., 2023). However, results from phase 3 suggested participants would be discharged from the hospital before the ideal dose could be administered (Roznik et al., in progress). Therefore, during the treatment period, participants were anticipated to transition from the inpatient to the home setting with the VR GMI program. At each transition, I contacted participants over the phone or in-person (if still inpatient) to inquire as to whether they would be interested in continuing to participate in the intervention for the duration of the sessions they had remaining. If they wished to continue (and they remained in Winnipeg), their treatment continued at home via regular visits by research team members. If their treatment did not continue in Winnipeg, their treatment was discontinued.

One month after the participant's last VR session, I contacted them via phone to verbally administer the BPI Pain Intensity and PROMIS Pain Interference questionnaires as they pertain to their PLP. If the participant had not yet experienced PLP onset, this was recorded.

Operational Hypotheses

Corresponding to the aforementioned objectives, I assessed the following hypotheses.

1) *Procedural Feasibility.* I assessed this objective through a priori eligibility, recruitment, retention, and attrition rate criteria, as systematically developed by Young et al. (2019) in collaboration with clinicians and patients to evaluate whether a RCT should proceed to evaluate a healthcare intervention.

a. If the recruitment strategies and study procedures were appropriate and feasible, at least 50% of screened patients should have been eligible to participate in the study. Moreover, at least 50% of the eligible patients should have expressed an interest and consented to participate in the study.
b. If the proposed treatment dosage was feasible, at least 70% of the participants should have participated in fourteen sessions of limb simulation, representing completion of the VR GMI program.
c. If the follow-up period was feasible, at least 80% of participants should have responded to the one-month follow-up interview.

2) *Intervention Feasibility.*
   a. If the VR GMI program was acceptable, median TFAQ scores at each VR stage were predicted to be higher than three (which indicates a more favourable acceptability rating than *no opinion*; Sekhon et al., 2022) for each of the seven questions in each administration setting.
   b. If the VR GMI program was tolerable, at least 70% of participants should not have reported any adverse events in the VR GMI program (in line with the acceptability criterion outlined by Young et al., 2019).
   c. If the VR GMI program was engaging, median length of program engagement at each VR stage and administration setting was predicted to be equal to or longer than 20 minutes (administered to find a treatment effect after fourteen sessions of limb simulation by Griffin et al., 2017; Purushothaman et al., 2023).
3) *Pilot Outcomes.* If the VR GMI program demonstrated a preliminary treatment effect, participants who spent more time in the VR program (e.g., fourteen sessions in limb

simulation) were predicted to report lower BPI and PROMIS Pain Interference scores at one-month follow-up compared to participants who spent less time in the VR program (e.g., one session in the program; in line with dose effect demonstrated by Griffin et al., 2017). On average, participants who spent more time in the VR program were predicted to report lower PLP incidence compared to people who spent less time in the VR program (in line with Purushothaman et al., 2023).

4) *Exploratory Outcomes.* I planned to explore whether PHQ-9, GAD-7, VEQ, IPQ, and sociodemographic/background information affected VR program acceptability, length of engagement, or PLP incidence, intensity, and interference at one-month follow-up.
    a. Research suggests embodiment and presence are the cognitive mechanisms through which PLP reduction occurs (Cheung et al., 2023; Spiegel et al., 2019); therefore, I predicted VEQ and IPQ scores in the limb simulation stage of the VR GMI program would be negatively associated with PLP incidence, intensity, and interference.
    b. I predicted depressive/anxious symptomatology would be negatively associated with average length of engagement, as it would minimize motivation to engage in the program (Canadian Institute for Health Information, 2024; Crooks et al., 2025; Kern et al., 2012; Radenovic et al., 2022; Trevelyan et al., 2016).
    c. I also hypothesized older age would negatively affect technological literacy, which would, in turn, be associated with decreased average TFAQ scores and length of engagement (Canadian Institute for Health Information, 2024; Mosadeghi et al., 2016).

   d. Lastly, I predicted the chronicity of pre-amputation pain would demonstrate a positive relationship with PLP incidence, intensity, and/or interference at one-month follow-up, while amputation indication (whether diabetic or nondiabetic) would demonstrate a positive or negative relationship with these variables (Limakatso et al., 2020; Mioton et al., 2020).

5) *Reasons for Disengagement.* I explored reasons for participation refusal, early session discontinuation, and study withdrawal, which I predicted to include: lack of perceived benefit of VR, anxiety about using VR, feeling too tired/ill to use VR, concerns about "losing control" in VR, not wanting to be "experimented on", lack of interest in VR, feeling frustrated with VR (or treatment in general), other life priorities, and other (Crooks et al., 2025; Lendaro et al., 2020; Mosadeghi et al., 2016; Roznik et al., in progress).

Data Analysis

Quantitative Analysis

Objectives 1 and 2 were analyzed through nonparametric descriptive statistics (including median and interquartile range; IQR) in Excel to suit the small, skewed sample, and figures were generated in RStudio. For objective 1, eligibility, interest, retention, and follow-up rates were analyzed by frequency count to assess whether progression criteria prespecified by Young et al. (2019) were met. Objective 2 was analyzed through descriptive comparisons of the median item-level and total TFAQ scores, using qualitative descriptors embedded in the literature to ground reporting. TFAQ scores were further explored by assessing the frequency of cases who rated the VR GMI program as acceptable (TFAQ median > 3) or unacceptable (TFAQ median < 3) on each item at each stage.

For objectives 3 and 4, I planned to conduct Spearman correlation coefficients and their corresponding p-values to explore associations between the number of VR sessions completed and BPI/PROMIS Pain Interference at one-month follow-up (Objective 3), as well as associations between exploratory variables—such as IPQ, VEQ, GAD-7, PHQ-9, and others—and both engagement with the VR program and pain outcomes (Objective 4). Descriptive results for BPI, PROMIS Pain Interference, IPQ, and VEQ were reported.

Qualitative Analysis

Qualitative Descriptive Design.

For objective 5, I employed a qualitative descriptive design to categorize reasons for participation and session refusal, early session discontinuation, and study withdrawal (Doyle et al., 2020). Grounded in a naturalistic and relativistic paradigm, qualitative descriptive analysis is commonly used in health behavioural intervention development and entails researchers immersing themselves in the environment of inquiry to engage in summarization of participant experiences according to manifest content and low-level inference (Bradshaw et al., 2017). Rather than emphasizing specific methodological stages to follow, proponents of qualitative description instead emphasize flexibility to explore and provide clear descriptions of the phenomena of interest (Doyle et al., 2020).

Methodological Considerations.

Rigor in qualitative description research is enhanced by prioritizing credibility (i.e., engaging with participants in the long-term to encourage openness with the research team), confirmability/dependability (i.e., being transparent about how results were generated, such as by keeping a research journal), and transferability (i.e., providing enough details of analytic methods and results to facilitate replication; Bradshaw et al., 2017). In line with this

methodological approach, research personnel established long-term relationships with participants and prioritized rapport by asking about life beyond research matters. Brief field notes were maintained throughout the study to document contextual observations and informal insights during participant and staff interactions. The two coders then independently categorized reasons for refusing participation in Excel following data collection, in accordance with iterative procedures outlined by Vears & Gillam (2022) and guided by qualitative descriptive methodology (Bradshaw et al., 2017; Doyle et al., 2020). Afterwards, the coders met to collaboratively develop categories until interpretations aligned. The results of these analyses are reported under objectives 1-4 to contextualize patterns in recruitment, adherence, and retention.

Reflexivity Statements.

To engage in manifest coding and low-level inference, another research personnel and I exercised reflexivity, which can be defined as critical appraisal of how one's personal and professional experiences interact with that of participants to bias data collection, coding, and interpretation (Braund et al., 2024). As such, the other research personnel and I reflected on our unique positionalities to enhance the transparency and dependability of our categorical interpretations, and in turn, qualitative rigor.

Megan Crooks. As a nondisabled, White, young individual in graduate school to become a clinical psychologist and researcher, my attitudes and appearance likely contributed to Indigenous participants and individuals with lower educational attainment perceiving me as untrustworthy due to my privilege and colonialist policies in Canada. To compensate for this, I often found myself exerting additional effort to establish rapport with participants who seemed skeptical or annoyed with me or the VR GMI program, which likely affected their response and my interpretations. I also initially approached data collection from a postpositivist lens, aiming to

identify clear reasons for participation refusal to facilitate the initially proposed deductive analytic plan. This limited my early inquiry and understanding of nuanced qualitative recording. As the study progressed, I became more aware of these biases and sought to remain open to complex participant experiences while remaining grounded in a qualitative descriptive framework.

Hilary Johnson. As a white, educated woman, I recognize the potential for disconnect between myself and participants whose lived experiences differ from my own, particularly those facing structural disadvantage or limited access to essential resources such as housing, food, and healthcare. My background as a trained physical therapist with both institutional and clinical experience influenced how I interacted with research collaborators, participants, and hospital staff. I acknowledge that these positionalities shaped my perspectives and the research process. With this awareness, I strived to approach each participant with openness and humility and remain mindful of implicit bias during data collection and analysis.

Chapter III: Results

Sample Characteristics

By the end of the nine-month recruitment period (conducted from July 2024 to April 2025), I recruited 17 participants. I recruited an average of 2-3 participants per month ($M = 2.43$, $SD = 1.09$) from a variety of HSC acute surgical wards, including the vascular (A3; $n = 3$, 17.65%), orthopaedic (D2; $n = 4$, 23.53%), general (H3; $n = 3$, 17.65%), and plastic (H5; $n = 4$, 23.53%) wards, in addition to a few participants from the rehabilitation unit (R5/R6; $n = 3$, 17.65%). Due to early participant disengagement, select sociodemographic and baseline characteristics were missing for one participant, while PHQ-9 and GAD-7 scores were missing for three participants.

Most participants reported being male (*n = 11*; 64.71%), single (*n = 7*; 41.18%), White (*n = 11*; 64.71%), urban (*n = 12*; 70.59%), between the ages of 50-69 years old (*n = 12*; 70.59%) and an education level of high school equivalence or lower (*n = 11*; 64.71%). Only two participants had bilateral amputations, while the rest had unilateral amputations (*n = 15*; 88.24%). Most participants reported having pain in their lower limb before it was amputated (*n = 11*; 64.71%) due to both diabetic (*n = 9*; 52.94%) and nondiabetic ischemic (*n = 7*; 41.18%) indications, and only one participant underwent a traumatic amputation (*n = 1*; 5.88%). Only two participants endorsed previous use of VR, mental health services, or behavioural pain management (11.76%). According to the PHQ-9 and GAD-7, six (*n = 6*; 35.2%) and four participants (*n = 4*; 23.53%) expressed clinically significant depressive and/or anxiety symptoms during the postoperative period, respectively. Nine participants reported experiencing PLP within two months following their LLA (*n = 9*; 52.94%). Please see Table 1 for an overview of the sample characteristics.

Objective 1: Procedural Feasibility

A total of 111 inpatients at the HSC were identified as potential participants during the recruitment period. The highest number of potential participants were identified consecutively in July/August 2024 (*n = 30*, 27.03%), September 2024 (*n = 17*, 15.32%), and October 2024 (*n = 16*, 14.41%), with a downward trend in November 2024 (*n = 7*, 6.31%). Recruitment escalated again in January 2025 (*n = 12*, 10.81%) and February 2025 (*n = 15*, 13.51%) before dipping in March (*n = 7*, 6.31%) and April (*n = 7*, 6.31%) 2025. Patients were primarily identified through weekly correspondence with charge nurses on inpatient surgical units (*n = 95*, 85.59%), while the remaining patients were identified through the pre-anesthesia clinic (*n = 14*, 12.16%) and

clinician referral (*n = 2*, 1.80%). See Figure 2 for a diagram that depicts recruitment flow, including screening, eligibility, interest, retention, and follow-up rates.

Eligibility and Interest Progression Criteria

Of the 111 potential participants identified, 90 proceeded to screening (81.08%). Among the 21 patients excluded from screening, 16 patients were discharged before they could be approached (76.19%), while another five patients could not be found after identification, precluding participation (23.81%). As such, these patients (18.9%) were excluded for reasons unrelated to ineligibility for or disinterest in the VR GMI program.

Out of the 90 remaining patients screened, 29 patients were deemed ineligible after discussion with their healthcare staff, before research personnel could gauge their interest (32.22%). Eight patients were excluded due to cognitive impairment (such as postoperative delirium, confusion, or dementia; 23.53%), while another three were excluded due to motor, hearing, and/or visual impairment (8.82%) that healthcare staff believed would prevent VR engagement. An additional 12 patients were excluded based on age (> 80 years old; *n = 3*, 8.82%), undergoing LLA more than two months ago (*n = 6*, 17.65%), non-English fluency (*n = 2*, 5.88%), and having a bilateral amputation before September 2024 (when study approval was extended to include people of this population; *n = 1*, 2.94%). The remaining five patients were unable to be screened by research or healthcare staff due to unanticipated criteria, including critical illness (such as end-of-life care; *n = 3*, 8.82%) and personal circumstances keeping patients off-unit for extended periods of time, thereby preventing approach (*n = 2*, 5.88%). One patient was not screened due to unknown reasons (*n = 1*, 2.94%).

61 patients were approached by research or healthcare staff to ascertain their interest in participating in the VR GMI program and confirm eligibility criteria. Of these individuals, one

patient could not be found after nursing staff gauged their interest (1.64%), yielding 60 patients screened. A total of 31 of these individuals communicated disinterest in participating in the VR GMI program (51.67%). Six of these patients declined due to concerns about study risks and procedures, such as the potential for adverse events (*n = 4*, 12.90%) and the length of the requested time commitment (*n = 2*, 6.45%). Four more patients declined because they indicated a lack of interest in research and VR (12.90%), while another two patients declined because they did not experience current PLP (6.45%). Three additional patients expressed frustration with their medical care that led to treatment refusal (such as feeling misunderstood due to non-English fluency or being denied certain privileges as they recovered; 9.68%). Two patients had personal circumstances that kept them off-unit for extended periods of time and prevented approach for consent (6.45%). The greatest proportion of patients expressed disinterest in the VR GMI program because they indicated they were overwhelmed and wanted to focus on their recovery (*n = 9*, 29.03%). Lastly, five patients indicated they were uninterested in participation but gave no rationale as to why (16.13%). In total, 29 of the 60 patients approached expressed an interest in participating in the VR GMI program (48.33%); therefore, my hypothesis that the interest rate would be greater than 50% was not supported (albeit by a slim margin). See Figure 3 for a pie chart illustrating reasons for lack of interest in VR GMI program participation.

Among the 29 interested patients, 17 individuals provided consent to participate, while 12 patients were excluded after being deemed ineligible by research personnel (41.38%). Five of these patients were discharged from the HSC within 2 days following indication of interest (41.67%), preventing their engagement. One patient indicated interest preoperatively but ultimately only required a minor LLA proximal to their ankle, excluding them from participation (8.33%). Similarly, two participants indicated interest but were discovered to have undergone a

LLA more than two months ago (16.67%). The remaining four participants presented with severe visual (e.g., diabetic retinopathy leading to blindness), hearing, and/or motor impairment that prevented engagement with a VR headset. In total, out of 90 potential participants that were identified, 29 were deemed ineligible at screening and 12 were determined to be ineligible immediately prior to consent (*n = 41*; 45.56%). Therefore, 49 patients were eligible to participate in the VR GMI program, yielding an eligibility rate of 54.44%. My hypothesis that the eligibility rate would be greater than 50% was supported. See Figure 4 for a pie chart depicting reasons for exclusion from the VR GMI program during screening and before consent.

Retention Criterion

To assess whether the prespecified retention criterion of 70% was met, I calculated the number of participants who engaged in the recommended dose of fourteen sessions of limb simulation (with or without leg trackers). Among 17 participants, six people did not engage in the limb simulation stage at all (35.29%). Five participants engaged in the limb simulation stage for less than or equal to three sessions (29.41%) and three participants engaged for six to eight sessions (17.65%). Only three participants engaged for the recommended 14 sessions in the limb simulation stage, yielding a retention rate of 17.65%. Therefore, my prediction that the retention rate would be greater than 70% was not supported.

Across the 14 participants who completed less than 14 limb simulation sessions, there were a variety of reasons for early study withdrawal. Two participants were transferred to a new hospital in Winnipeg, while another three were discharged to their rural community, precluding continued participation at home (*n = 5*, 35.71%). One participant was discharged home but did not continue participation due to lack of interest (i.e., finding the program boring and redundant; 7.14%). One participant expressed an interest in continuing the VR GMI program at his home in

Winnipeg following hospital discharge but was unable to do so due to unavailability of research personnel (7.14%). Only one participant continued to use the VR GMI program at home but eventually withdrew due to physical pain and illness associated with their recovery (7.14%). Five other hospital-based participants withdrew for similar reasons (35.71%). The final participant left against medical advice from the HSC and did not have (or chose not to disclose) contact information for follow-up (7.14%).

Follow-Up Criterion

All 17 participants were contacted for an interview one-month following their final session with the VR GMI program, among which nine responded. In total, the follow-up rate was 52.94%. Therefore, my prediction that the follow-up rate would be greater than 80% was not supported.

See Table 2 for examples of how the reasons for disinterest and ineligibility were qualitatively coded.

Objective 2: Intervention Feasibility

Acceptability

Out of 17 participants, 16 completed or partially completed the TFAQs at each VR GMI stage, including psychoeducation *(n = 14)*, left/right discrimination *(n = 15)*, explicit motor imagery *(n = 15)*, limb simulation *(n = 10)*, and limb simulation with leg trackers *(n = 4)*. One participant only partially completed the TFAQ for every stage they trialled (up to and including limb simulation) due to frustration with being asked to quantify their experience; another participant missed an item within the explicit motor imagery TFAQ after they completed the questionnaire by hand. Within specific VR GMI stages, two psychoeducation TFAQs were not

administered due to miscommunication amongst research personnel; one left/right discrimination TFAQ was not administered due to participant disinterest; and one limb simulation TFAQ was not completed due to a participant's psychological distress (unrelated to the study). All other uncompleted TFAQs can be attributed to participants not engaging in certain VR GMI stages before study withdrawal.

I calculated the median and IQR for each TFAQ item associated with the five VR GMI stages to evaluate participant acceptability across different dimensions of the intervention. Participants tended to rate the program as acceptable to completely acceptable, with low to high variability (median range: 4 – 5; IQR: 0 – 2.25), and rated the program to require little to no effort (median range: 1 – 2; IQR: 0 – 1). Overall, my hypothesis that participants would rate the VR GMI program as acceptable at each stage was supported. See Figures 5 and 6 for a series of boxplots illustrating the median and IQR of participant scores on each TFAQ item at each VR GMI stage.

To elucidate the high variability in IQR observed across median TFAQ scores, I calculated the frequency at which individual participants rated the VR GMI stages favourably (TFAQ median > 3), neutrally (TFAQ median = 3), or unfavourably (TFAQ median < 3) on each of the seven items. The effort required to participate was rated low by 78.57% to 100.00% of participants across stages, consistent with the median values previously described. On the other TFAQ items, between 70% - 100% of participants favourably rated the acceptability of the psychoeducation stage and limb simulation stages (with and without leg trackers) on each item. The left/right discrimination stage was similarly rated favourably by 80.00% to 92.86% of participants on each item except the one that inquired into whether it was clear to them how the stage is meant to prevent/improve their PLP. Out of the fifteen participants who responded to this

item, 60.00% provided a favourable rating (*n = 9*), 13.33% provided a neutral rating (*n = 2*), and 26.67% provided an unfavourable rating (*n = 4*). Lastly, the explicit motor imagery stage was rated as less acceptable than the other stages, only garnering 60.00% to 85.71% favourable ratings across each item. Overall, 100% of respondents indicated they found the psychoeducation stage (*n = 14*) and limb simulation stage (with leg trackers; *n = 4*) acceptable, 92.86% found the left/right discrimination stage acceptable (*n = 14*), and 77.77% rated the limb simulation stage (without leg trackers) as acceptable (*n = 7*), while the remaining 22.22% were neutral (*n = 2*). The explicit motor imagery was rated as acceptable by 71.43% of participants (*n = 10*), rated neutral by 7.14% of participants (*n = 1*), and rated as unacceptable by the remaining 21.43% (*n = 3*). See Figures 7 and 8 for a series of bar graphs displaying the number of participants who favourably or unfavourably rated each TFAQ item at each VR GMI stage.

Tolerability

To assess tolerability, I calculated the number of participants who experienced an increase in PLP, RLP, or nausea during or outside of a VR session that they attributed to the VR GMI program and considered distressing. While research personnel attempted to collect NRS scores for PLP, RLP, and nausea before and after each session, fluctuations were often too transient to capture (e.g., acute, temporary PLP 'shocks') because they returned to baseline before the VR headset was removed. Therefore, adverse events were instead identified by whether PLP, RLP, or nausea increases were of sufficient magnitude to discontinue or miss a VR GMI session.

Among the 16 participants who trialled the VR GMI program, eight reported at least one adverse event (50.00%). One participant stopped left/right discrimination early due to dizziness, representing the only adverse event reported during that stage (6.25%). In the explicit motor

imagery stage, one participant stopped performing the exercises after growing anxious the VR GMI program was hypnotizing them. They expressed consent to trial the same stage again the following session but stopped after experiencing a PLP flare-up (6.25%). Limb simulation (both with and without leg tracking) led to mixed PLP and RLP flare-ups for five other participants, leading to early session discontinuation (31.25%). One more participant experienced distress upon viewing his virtual leg in limb simulation for the first time and thus concluded his session early (6.25%). As an operationalization of tolerability, I predicted less than 30% of participants would endorse symptoms consistent with an adverse event; however, my hypothesis was not supported.

Length of Engagement

I assessed length of engagement by calculating the median amount of time spent in each VR GMI stage. The psychoeducation stage entailed discrete content played for a predetermined amount of time (approximately six minutes) and was completed by all 16 participants who engaged in the VR GMI program; therefore, it was removed from the median calculation. 16 participants trialled the left/right discrimination stage for one session, where they spent a median of 13.50 minutes (IQR = 9.50). Meanwhile, among 15 participants who tried the explicit motor imagery task for one to two sessions, the median length of engagement was 20 minutes (IQR = 2.5). Eight participants completed the recommended exercises (20 minutes), three participants completed one additional exercise (30 minutes), and four participants chose to conclude their time in the task early (10 – 15 minutes). Lastly, across a total of 69 limb simulation sessions (both with and without leg trackers), eleven participants engaged for a median of 20 minutes (IQR = 6.50) in the limb simulation stage. Therefore, my prediction that the average length of engagement in each stage would be 20 minutes or higher was partially supported.

Reasons for Early Session Discontinuation

Participant rationale for concluding a session before 20 minutes had passed were evaluated and categorized across all 54 incomplete VR GMI sessions. Thirty-two sessions were concluded early due to adverse events (*n = 19*, 35.19%), technical issues (*n = 6*, 11.11%), and physical pain or fatigue unrelated to the VR GMI program (*n = 7*, 12.96%). Less commonly, participants concluded a session early if they did not like the stage in question (specifically, the explicit motor imagery stage; *n = 3*, 5.56%) or if the session was interrupted by their medical team (*n = 3*, 5.56%). A large proportion of sessions were concluded early due to a desire for novelty after extended periods of time in a stage (particularly limb simulation) was indicated to have become repetitive or boring (*n = 16*, 29.63%). See Figure 9 for a pie chart illustrating the reasons for early session discontinuation.

Reasons for Missed Sessions

There was a total of 142 VR GMI sessions missed across 16 participants. 42 sessions were missed due to research staff being unavailable to administer a session (*n = 35*, 24.65%) and miscommunication with hospital staff during unit transfer that delayed relocation of participants (*n = 7*, 4.93%). A large proportion of other sessions were missed due to medical reasons (*n = 46*, 32.39%), including nausea associated with dialysis (*n = 10*, 7.04%), fatigue (*n = 8*, 5.63%), bodily pain (*n = 5*, 3.52%), RLP (*n = 7*, 4.93%), RLP/PLP (*n = 8*, 5.63%), other medical symptoms (e.g., hospital-based infection symptoms; *n = 4*, 2.82%), or a combination of two or more of the aforementioned conditions (*n = 4*, 2.82%). Nine participants (6.34%) also missed sessions due to low mood associated with being in the hospital for an extended period (*n = 6*, 4.23%), often in conjunction with bothersome medical symptoms (*n = 3*, 2.11%). Lastly, another large proportion of sessions were missed because the participant was busy (*n = 47*, 33.10%) due

to personal commitments (e.g., visiting family; *n = 8*, 5.63%), medical appointments (*n = 26,* 18.31%), or other reasons unknown to the research team (*n = 8*, 5.63%).

See Figure 10 for a pie chart displaying the different reasons participants missed a VR GMI session. See Table 3 for examples of qualitative codes contributing to reasons for missed and early session discontinuation.

Objectives 3 & 4: Pilot Outcomes

Due to the low follow-up rate, Spearman correlation coefficients for objectives 3 and 4 were not calculated. As noted in prior literature, the final sample size was insufficient to yield statistically reliable or practically meaningful estimates (Hertzog, 2008). Furthermore, all participants reported some degree of phantom limb pain at follow-up, while only four endorsed any PLP-related interference, resulting in limited variability and reducing the value of further analysis. As such, only descriptive statistics are reported for the BPI, PROMIS Pain Interference, and VEQ measures; no inferential analyses were conducted.

PLP Incidence, Intensity, and Interference

All nine participants who responded at one-month follow-up were verbally administered the BPI Pain Intensity and PROMIS Pain Interference measures. There were no missing data except the last item on the PROMIS Pain Interference measure for two participants. One of these missing items reflected researcher oversight, while the other participant ended their follow-up interview early due to extreme distress at being asked to describe the effect their pain had on their life.

Across the nine respondents, the median BPI score was 1.88, with a high degree of variability (IQR = 2.38). Only five participants indicated their PLP interfered with their daily functioning and completed the PROMIS Pain Interference measure (55.56%). As per PROMIS

procedures, raw pain interference scores were entered into the *HealthMeasures Scoring Service* to generate T-scores for reporting purposes (HealthMeasures, 2021). The average PROMIS Pain Interference T-score was equal to 54.45 (SD = 3.82), reflecting pain interference approximately 0.42 standard deviations above the population mean of the PROMIS comparison sample.

Presence

Early participant feedback indicated that lengthy self-report questionnaires were frustrating to complete and often required verbal administration, deviating from protocol. To reduce participant burden, the IPQ was excluded from data collection.

Embodiment

Eight participants completed the VEQ after trialling the limb simulation stage without leg trackers. Three participants who engaged in the limb simulation stage did not complete the VEQ due to early study withdrawal. The median score on the agency subscale was 6.00 (IQR = .88), reflecting that participants agree that they could cause or control the movements of the virtual body in the limb simulation stage. The median score on the ownership scale was slightly lower (median = 5.75, IQR = 1.31) and suggests participants only somewhat agree that the virtual body felt like their body during limb simulation. Lastly, the median score on the body change scale was 4.75 (IQR = .88), which suggests participants tend to be neutral or somewhat agree that the limb simulation stage made them feel like their body had changed.

All three participants who trialled the limb simulation with leg trackers completed an additional VEQ on their experience. According to the qualitative descriptors associated with the VEQ scale, participants reported a slight median increase in sense of agency (median = 6.50, IQR = .75*)* and ownership (M = 6.00, IQR = 1.25*)* with the addition of leg trackers to the limb

simulation stage. The body change subscale showed a small median decrease (median = 4.50, IQR = 2.38).

Chapter IV: Discussion

Overview

The present thesis represents the first multi-method investigation on the feasibility of a VR PLP intervention administered to people recovering from LLA in the postoperative acute care setting. The current literature consists of a disproportionate number of case series investigating short-term effectiveness of VR interventions on PLP (Cheung et al., 2023), with little research comprehensively investigating the feasibility of these programs. By investigating feasibility, successful implementation of the VR GMI program becomes much more probable (Birckhead et al., 2019; El-Gabalawy et al., 2025). The investigations conducted in this thesis were essential to identify further developments required of the VR GMI program from a patient-centered approach, and, in turn, improve the quality of life for people living with LLA upon implementation.

The sample characteristics are important to consider when contextualizing the feasibility results. The sample primarily included older, urban, White men with lower educational attainment who underwent LLA due to diabetic and nondiabetic ischemic indications, aligning with Canadian trends (Canadian Institute for Health Information, 2024; Imam et al., 2017) Individuals from rural or Indigenous communities—who experience disproportionately high rates of diabetic LLA—were underrepresented (Blanchette et al., 2023; Canadian Institute for Health Information, 2024). Rates of depression/anxiety within two months following LLA were

lower than previously reported, while the PLP rate fell within the expected range (2.2%-72%; Pedras et al., 2018; Stankevicius et al., 2021).

Within this sample, the findings indicate the employed recruitment, follow-up, and VR GMI administration procedures were not feasible for a future randomized controlled trial, nor implementation. Intervention feasibility was more promising, with inpatient participants generally rating each VR GMI stage as acceptable for use in the postoperative period and engaging for the recommended period. However, future VR GMI development should prioritize decreasing the frequency of adverse events. Only once the barriers to procedural and intervention feasibility are addressed can a more robust sample be generated and allow pilot outcomes to be elucidated.

Adaptations to Improve Procedural Feasibility

Overall, integrated qualitative and quantitative data suggest procedural feasibility is limited by systemic and individual barriers prevalent within two months following LLA. Most patient attrition throughout recruitment, retention, and follow-up can be attributed to the prioritization of critical illness in the acute inpatient setting, such as cognitive, motor, visual, or hearing impairment associated and physical pain/fatigue leading to early intervention withdrawal, in line with early findings from VR GMI development (Crooks et al., 2025). According to the Theoretical Domains Framework, these characteristics should be conceptualized as barriers of opportunity, rather than motivation or capability (Cane et al., 2012). In other words, the unique environmental context and resources in the postoperative period primarily limit current feasibility, rather than the intervention itself. Even tolerability—a construct initially intended as a measure of intervention feasibility—seems to be more reflective of preexisting physical pain/fatigue associated with the postoperative period. Moving beyond the

perioperative period, addressing early hospital discharge, and implementing evidence-based follow-up procedures should be prioritized to address systemic barriers to VR GMI program use.

Address Early Hospital Discharge

Many patients were lost at the screening, consent, and retention stages of participation due to early hospital discharge or severe medical comorbidities that warranted tertiary care. Patients were often discharged home within one week following their LLA, before they could be screened or consented. Meanwhile, many participants stayed at the HSC for over a week before being transferred to another hospital, precluding home use for all but one participant and severely affecting the retention rate. These differential trends in discharge location according to length of stay are corroborated by the literature. According to a report by the Canadian Institute for Health Information (2024), the median length of hospital stay for people undergoing LLA in Canada between 2021 and 2023 was 19 days, and two-thirds of these patients were transferred to another hospital to receive specialized support. In contrast, those undergoing ankle or foot amputations had a median stay of 8 days, and most were discharged directly home. This variability in length of stay likely contributed to our recruitment strategy capturing only patients with lengthy hospital stays who were more often transferred than discharged home, limiting our ability to recruit participants who could trial the VR GMI program at home post-discharge. It also implies we recruited patients with impaired functional independence at admission that warranted extended hospitalization, as found by Karmarkar et al. (2014), which could include acute physical pain and nausea, as well as comorbid cognitive, motor, visual, and hearing impairment. Recruiting patients with shorter hospital stays for home administration of the VR GMI program may have resulted in higher eligibility, interest, and retention rates, as well as a lower frequency of missed sessions. Increasing the feasibility of the study procedures should

therefore entail modified recruitment strategies to optimize our ability to screen patients with lower medical acuity.

To ensure future recruitment and administration strategies capture a representative sample of people with LLAs who can trial the VR GMI program for a longer period, three adaptations should be applied to current procedures. First, research personnel should be deployed more strategically to optimize use of inpatient time. Approximately one quarter of VR GMI sessions were missed due to unavailability of research personnel, and one participant was unable to continue the intervention at home despite being willing for the same reason. The limited evidence base detailing research assistants' perspectives on clinical research suggests efficiency might be improved through more tactical scheduling and training on how to navigate variable participant availability in the hospital setting (Cambron & Evans, 2003). Having standardized training on how to identify the best time to recruit or conduct VR GMI sessions across different inpatient units may improve the efficiency of research personnel.

The second and most evident procedural improvement is to increase the frequency at which charge nurses are consulted for screening from once a week to twice a week, given this method contributed the highest proportion of potential participants. This would likely also facilitate preoperative recruitment, for which ethical approval was received, but research personnel were often too late to capitalize on. However, stakeholders suggest care must be taken to avoid overburdening the nursing staff involved in screening. In line with this feedback, an integrative review indicates lack of time, leadership, and heavy workload may be barriers to nurse engagement in external organizational projects (Alexander et al., 2022). The authors suggest one way to mitigate these barriers is to facilitate leadership by identifying a volunteer senior nurse on each relevant unit to champion VR GMI participation across other nursing staff.

Such a champion on each inpatient unit could be recruited to the research team to promote a culture of participation in the VR GMI project and facilitate communication across team members.

In addition to establishing stronger relationships with nursing staff, the recruitment strategies could be improved by enabling access to hospital databases. One reason recruitment from the pre-anesthesia clinic was relatively low was because patients could not be identified on inpatient units after they were referred. These patients could not be located independently in the HSC electronic patient record because such access to confidential personal health information was not deemed necessary during initial ethical approval. Moreover, unlike other Canadian provinces such as Alberta and Quebec, Manitoba lacks a provincial electronic system that allows identification of patients by reason for admission (i.e., LLA) which further limited recruitment effectiveness. In fact, according to eChart Manitoba, the province's electronic medical record system "is not to be used for research study purposes" (2022, p. 6), highlighting a gap between research practice and policy. The results of the current study may justify the use of the electronic patient record for future recruitment (subject to provincial regulation) and more frequent correspondence with nursing staff.

Move Beyond the Postoperative Period

The eligibility, interest, and retention rates (54.44%, 48.33%, and 17.65%, respectively) could be improved further by recruiting patients in a less acute care setting. As reported in phase 3 of VR GMI program development, adaptations to the VR GMI interface could facilitate engagement for people with cognitive, hearing, visual, or motor impairment (El-Gabalawy et al., 2025; Rich et al., 2022). In fact, the eligibility criteria of the current study were expanded to include patients with bilateral amputations to increase accessibility (Roznik et al., in progress).

However, these developments cannot address the acute impairments and barriers characteristic of the inpatient setting, such as postoperative delirium, progressive diabetic retinopathy/neuropathy, and other critical illnesses or medical procedures that contribute to sickness, fatigue, and pain.

This acuity presented several barriers to the study protocol, from recruitment to withdrawal. One third of screened participants rejected participation due to preferring to focus on other aspects of their recovery, and one third of missed sessions were attributed to medical causes. Mosadeghi et al. (2016) reported similar eligibility and interest rates and reasons for VR treatment refusal among hospitalized patients in the USA, corroborating the accessibility issues common in this population. However, their research does not reflect the high prevalence of adverse events in our study population (approximately half). This distinction further highlights that the VR GMI program may be better suited for administration in an outpatient or inpatient rehabilitation setting, when patients are fitted for their prosthetics. Prosthetic rehabilitation in Canada typically entails at least 4–6 weeks of physiotherapy, during which time people with LLAs have expressed strong motivation to increase their mobility through alternative interventions (Crooks et al., 2025; Imam et al., 2019). This period may be ideal for administering the VR GMI program in future studies. Approximately 53% of people with LLAs walk with prosthetics at four months post-amputation (Webster et al., 2012), suggesting most could still self-administer the VR GMI program within six months to benefit from PLP intervention (Purushothaman et al., 2023). However, a recent epidemiological analysis demonstrates only 18% of Canadians who undergo LLA receive inpatient rehabilitation at sites like the HSC (Imam et al., 2025). This low prevalence implies the individual and systemic barriers previously described in this thesis may disproportionately select for the few individuals who can navigate and access public rehabilitation services (e.g., Liddy et al., 2024; Radenovic et al., 2022).

Moreover, administering the VR GMI program during prosthetic rehabilitation may be less effective than within the intended two-month window, as central sensitization may have progressed further (Agostinho et al., 2023; Moseley et al., 2012). Nonetheless, recruitment and VR GMI program administration would likely be more feasible in rehabilitation settings, rather than the postoperative period.

Implement Evidence-Based Follow-Up Procedures

Lastly, specific consideration needs to be given to improving the follow-up rate to assess the efficacy of the VR GMI program in a future randomized controlled trial. While specific reasons for attrition at follow-up are unknown, they may be speculated. One third of participants withdrew early due to physical pain and illness associated with their recovery, and other participants were transferred to another hospital for specialized long-term care, such as dialysis. Findings from earlier phases of VR GMI development suggest participants may have been too overwhelmed with their recovery to respond (Crooks et al., 2025; Roznik et al., in progress). In contrast, previous clinical trials on PLP intervention have demonstrated follow-up rates greater than 50% consistently after one, three, and six months (Ambron et al., 2021; Brunelli et al., 2015; Lendaro et al., 2025; Limakatso et al., 2020; Moseley, 2006), even within two months following LLA (Purushothaman et al., 2023; Segal et al., 2021). However, a previous study suggests individuals who have not completed high school are less likely to respond at one-month follow-up due to the burden of other life demands and reduced health literacy (Leak et al., 2015). Given the high prevalence of participants with relatively low education in the sample, concentrated effort should be dedicated to improving follow-up in this population. A systematic review of evidence-based follow-up procedures suggests small financial incentives and multimodal reminders (e.g., email, mail, and phone) are effective ways to improve response rates

(Gillies et al., 2021). Scheduling the follow-up date and time in advance, rather than just calling the participant outright, would likely amplify the follow-up rates as well. These procedural adjustments and considerations should bolster the follow-up rates in future VR GMI clinical trials.

Adaptations to Improve Intervention Feasibility

Procedural feasibility remains the primary barrier to VR GMI utilization in the postoperative setting, given high ratings of acceptability that suggest the intervention itself is feasible. Individual motivation and capability present significant barriers to VR GMI engagement and should be targeted to improve retention, in line with the Theoretical Domains Framework (Cane et al., 2012). Findings from the current study demonstrate the need to address stage-specific barriers to motivation and capability through additional prototype development to enhance intervention feasibility.

Promote Mental Effort through Spaced Psychoeducation and Limb Simulation Gamification

Each VR GMI stage was rated to require little to no effort from the user, suggesting cognitive engagement needs to be carefully defined and optimized in future development. The authors behind the TFAQ conceptualized mental effort through the lens of burden, and hypothesized an intervention perceived to require too much cognitive engagement would be considered unacceptable by users (Sekhon et al., 2017; 2022). Such consideration is particularly relevant given the critical illness prevalent in the inpatient setting that deter participation in novel interventions (Mosadeghi et al., 2016; Roznik et al., in progress). In contrast, the pioneers behind GMI suggest mental effort should be encouraged to promote the neuroplastic modifications to the sensorimotor cortex that are necessary for PLP reduction (Moseley et al., 2012). These differing perspectives are reconciled through the arousal theory of behavioural motivation, which

posits moderate mental effort (rather than high or low) is required to achieve the level of arousal that facilitates motivation and optimal performance (Ningjian, 2024). The arousal theory of behavioural motivation has been supported for generalization to VR applications in neurorehabilitation (Lewis & Rosie, 2012). To improve motivation for and cognitive engagement in the VR GMI program, the psychoeducation and limb simulation stages should be improved in accordance with arousal theory.

One way to optimize the mental effort entailed in VR GMI participation is to introduce gamification in the limb simulation stages (both with and without leg trackers). While self-report ratings indicated limb simulation was the most acceptable of all the VR GMI stages, additional consideration should be given to increasing length of engagement and retention. One third of all VR GMI sessions that were ended early were due to a desire for novelty in the limb simulation stage, and one participant even withdrew from the study for this reason. In accordance with this feedback, arousal theory posits that repeated administration of a therapeutic task decreases arousal and in turn, cognitive engagement (Ningjian, 2024). Previous medical VR applications have embedded gamification to increase novelty and sense of challenge with repeated use (Lewis & Rosie, 2012). The VR GMI program presents with a lack of gamification compared to other VR PLP interventions, which frequently include novel activities such as car racing, drumming, bicycle riding, and ball bouncing, among many others (Cheung et al., 2023). We initially chose to forgo gamification in favour of strict adherence to GMI protocol. However, future development of the VR GMI program should instead prioritize embedding gamified tasks to improve length of engagement and cognitive engagement. This could include bouncing a ball on the virtual legs during leg tracking, or daily goals to complete 10–20-minute exercise sets without leg tracking. These considerations are important to motivate goal-oriented participants,

as described by Lendaro et al. (2020), to self-administer the VR GMI program upon eventual implementation. While simple, such developments should significantly improve motivation to engage in the limb simulation stage for at least fourteen sessions.

Improvements to the psychoeducation stage would also likely increase cognitive investments in the VR GMI program. Moseley et al. (2012) emphasize thorough neuroscience psychoeducation as theoretically essential for patient motivation to engage in biopsychosocial pain treatments mediated by central sensitization. Therefore, a brief psychoeducation stage was embedded in the VR GMI program after phase 3 of development to improve patient buy-in without burdening participants in the postoperative period with too many details (Roznik et al., in progress). To facilitate increased cognitive engagement throughout the rest of the VR GMI program, the psychoeducation stage could be optimized in two ways. First, psychoeducation could be administered through multiple brief interactive videos delivered across sessions as opposed to a single, passive video delivered at the beginning of participation. This altered administration style would facilitate spacing, a psychological study technique that has been shown to increase learning retention by allowing time for memory consolidation between psychoeducation blocks (Carpenter et al., 2022). Brief psychoeducation pertaining to each stage could be administered immediately before their administration to capitalize on the spacing principle and emphasize the importance of cognitive engagement in the therapeutic tasks. Second, psychoeducation content could contain multiple learning modalities. Nijs et al. (2011) developed a series of practice guidelines to facilitate effective neuroscience psychoeducation for pain involving central sensitization, consisting of two guided 30-minute sessions with a teacher (involving both oral and visual elements) separated by assigned independent reading and a validated knowledge retention test. While such extensive psychoeducation would likely be too

burdensome for administration in the postoperative period, the visual and rehearsal learning techniques could be integrated into the VR GMI program using diagrams or single questions to evaluate knowledge retention and clarify any misunderstandings. By embedding spacing and multimodal learning techniques, psychoeducation could increase cognitive engagement throughout the VR GMI program.

Make Left/Right Discrimination Optional

The integration of stage-specific psychoeducation reminders would be particularly relevant for the left/right discrimination stage, which demonstrated relatively low TFAQ scores for the item pertaining to treatment understanding. On the other hand, given the weaker buy-in for the left/right discrimination stage and the limited time patients are available prior to hospital discharge following LLA, the most feasible option may be to make this stage optional, even though this would depart from traditional GMI principles (Moseley et al., 2012). Many VR PLP treatments have historically mimicked evidence-based treatments such as mirror therapy with gamified modification (Cheung et al., 2023) yet still demonstrate promising effectiveness outcomes. Moreover, contemporary randomized controlled trials suggest a combination of phantom limb exercises and mental imagery techniques (such as progressive muscle relaxation and explicit motor imagery) with mirror therapy is a more effective PLP intervention than placebo or mirror therapy alone (Brunelli et al., 2015; 2023; Lendaro et al., 2025; Wang et al., 2023). The VR GMI program could instead administer graded exposure, an evidence-based approach that would still target the central sensitization implicated in PLP but affords more flexibility to skip left/right discrimination (Nijs et al., 2011). The lack of PLP flare-ups experienced in the left/right discrimination stage further draws into question whether central sensitization has progressed enough in the postoperative acute care period for it to be necessary.

Nonetheless, the stage could still be kept in the VR GMI program for participants to use should they present with a PLP flare-up in the explicit motor imagery stage, indicative of early central sensitization that warrants more gradual motor exposure (Mibu et al., 2016). Making the left/right discrimination stage optional would likely improve the feasibility of the VR GMI program in the acute inpatient setting without sacrificing effectiveness.

Introduce Visuals in Explicit Motor Imagery

Lastly, improvements should be applied to the explicit motor imagery stage to increase intervention feasibility. Three participants (20.00%) disliked to strongly disliked the explicit motor imagery stage. Qualitative descriptive analysis of reasons for early withdrawal indicated that dissatisfaction with this stage stemmed from it being perceived as boring, stilted (i.e., overly formal or "pretentious"), unbeneficial, and/or stifling (i.e., the headset grew too hot after extended use). In addition to incorporating brief psychoeducation immediately before this stage as previously discussed, relaxing visuals could be embedded to promote cognitive engagement. An abundance of literature supports the effectiveness of mental imagery coupled with progressive muscle relaxation to reduce PLP (Brunelli et al., 2015; MacIver et al., 2008). Similarly, relaxation techniques have often been integrated in VR PLP interventions to promote cortical reorganization during motor imagery training (Cheung et al., 2023). When rerecording audio to accompany these visuals, patients with lived experience of LLAs should be consulted to ensure the content is delivered without being perceived as condescending or patronizing (Birckhead et al., 2019). The audio may also be adapted for administration without the headset to improve comfort, in line with an accessible approach to GMI treatment (Rich et al., 2022). Given its precedent in the literature, the VR GMI program should embed relaxing natural visuals and

audio developed through a patient-centered approach to induce mindfulness of the phantom limb while simultaneously increasing buy-in.

The Role of Embodiment

The current findings suggest the limb simulation stage generated high perceived embodiment even without leg trackers, with a slight improvement observed among the four participants who trialled the stage with leg trackers. These data suggest the current customization options in the limb simulation stage (e.g., skin colour, height, and leg/foot sizing) are sufficient to produce a sense of ownership over the virtual legs, and that the visuomotor synchrony between actual and virtual movements produces an adequate sense of agency, even in the absence of leg tracking (Roth & Latoschik, 2020). However, prior studies of similar VR interventions without leg trackers reported lower ownership relative to agency (Imaizumi & Asai, 2015; Prahm et al., 2025), and unpublished data from phase 2 of VR GMI development among community-dwelling individuals with LLAs also identified this discrepancy (Crooks et al., 2025; Sano et al., 2016; see Table 4). Several explanations may account for this divergence from previous research. The VEQ may have presented with a ceiling effect or lacked sensitivity to detect nuanced differences between the two subscales, and a larger sample size may have revealed greater divergence between agency and ownership. Alternatively, the absence of an agency-ownership discrepancy in the present sample could reflect the relatively early stage of recovery following LLA, during which the maladaptive body schema hypothesized to contribute to PLP may not yet have fully developed (Fuchs et al., 2018; Moseley & Brugger, 2009). An increase in the body change VEQ subscale would have suggested that distorted phantom limb representations—such as clenched or telescoped limbs—were being corrected toward typical proportions (Ortiz-Catalan et al., 2014; 2016). However, the subscale decreased slightly with the

introduction of leg trackers, occurring alongside the observed improvement in agency and ownership. These preliminary findings suggest that distinct cognitive mechanisms may underlie prophylactic versus standard GMI interventions for PLP, particularly in terms of the timing and nature of body schema engagement.

Strengths and Limitations

The current study design presents with many significant strengths. The multi-method design enabled a detailed analysis of the reasons for deflated eligibility, interest, retention, and follow-up rates, which allowed for a critical appraisal of how the study procedures and VR GMI program might be improved. Such methodologies are highly recommended in research assessing the feasibility of novel medical VR interventions (Birckhead et al., 2019; Orsmond & Cohn, 2015). Moreover, the predefined progression criteria were chosen based on expert and patient consensus, rather than the arbitrary conditions subject to researcher bias that are typical in these studies (Young et al., 2019). Lastly, this is one of the first VR PLP interventions to be measured longitudinally in the postoperative setting, which necessitated intensive administration and data collection. The low retention rate was only able to be discovered through this careful and ambitious design. As the final step in a four-phase patient-oriented developmental protocol for the VR GMI prototype, these data will be invaluable for the finalization of the program.

There were also three notable methodological limitations of the current research. First, most participants were White and urban residents, directly contradicting population-based studies suggesting Indigenous people and individuals living in rural communities are disproportionately affected by diabetic LLA (Blanchette et al., 2023; Canadian Institute for Health Information, 2024). To promote equitable healthcare access, the VR GMI program should be developed in consultation with Indigenous community partners and Elders to encourage more

representative VR GMI utilization. Second, the research was only conducted at a single site in Manitoba, one of the only Canadians provinces that lacks access to electronic medical records for the purposes of research (eChart Manitoba, 2022). This unique characteristic severely limits the generalizability of the current findings, particularly as they pertain to recruitment feasibility. A third notable limitation of the current thesis was the validity of the self-report measures. Unfortunately, quantitative ratings seemed to overestimate acceptability and PLP compared to unstructured verbal feedback and field observation. These discrepancies reflect demonstrator and acquiescence bias, in that participants did not want to rate the VR GMI program unfavourably or simply reported the highest score if they did not understand the items. For example, participants would indicate understanding the purpose of a given stage on the TFAQ yet were unable to explain their understanding. Demonstrator and acquiescence biases were likely worsened by visual, cognitive, and motor impairments necessitating verbal self-report measure administration for most participants.

Future clinical trials on the VR GMI program should improve measurement validity. First, chart information should be collected instead of participant account whenever possible to minimize self-report bias, as cognitive impairment and poor health literacy are significantly more prevalent among people with diabetic LLAs compared to the general population and other orthopaedic patients, respectively (Coffey et al., 2012; Hadden et al., 2019). For similar reasons, intervention acceptability should be measured through semi-structured interviews that are then deductively coded into favourable, neutral, and unfavourable feedback and assessed for interrater reliability, in line with previous studies assessing VR acceptability (Keller et al., 2017; Mosadeghi et al., 2016). Lastly, despite previous clinical trials using the BPI as their primary outcome measure for PLP, participants often expressed frustration at being asked to quantify

their PLP intensity (Brunelli et al., 2015; Limakatso et al., 2020). This is because PLP is often confused (and correlated) with RLP (Limakatso et al., 2020). A systematic review published in 2025 concluded there were no standardized questionnaires in the literature that capture the multidimensional characteristics of PLP while providing differentiation from RLP (Jenson et al., 2025). These results highlight the critical need to develop a sensitive PLP measure. These three considerations are essential to mitigate future acquiescence and demonstrator bias that may have affected self-report ratings of acceptability and PLP in the current study.

Implications and Future Directions

Findings from the current thesis will directly inform further VR GMI prototype development and the methodological pathway through which its feasibility and efficacy will continue to be evaluated. As intended in the original VR GMI development protocol (El-Gabalawy et al., 2025), recommended intervention improvements from the current phase (including promoting cognitive engagement through spaced psychoeducation and limb simulation gamification, making the left/right discrimination optional, and introducing visuals into the explicit motor imagery stage) will be embedded into the prototype before final evaluation through a series of focus groups consisting of participants from the present sample. Following that, an additional feasibility study will be conducted to assess new recruitment, administration, and data collection procedures in line with recommendations from the current thesis. Simultaneously or through a distinct study, the optimal frequency and duration of VR GMI delivery to observe a clinically significant effect should be established in the community to ascertain minimum retention targets (Czajkowski et al., 2015). A randomized controlled trial preceded by a vanguard study to assess the feasibility of randomization procedures will then be conducted to assess the efficacy of the final VR GMI program in the target administration setting

(to be determined following stakeholder and collaborator consultation). Once feasibility and efficacy are supported, the VR GMI program will be implemented and evaluated at multiple Canadian sites to improve quality of life for Canadians living with LLAs.

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Table 1

Sample characteristics (n = 17)

Variable	**n (%)**
Age	
40-49 years old	2 (11.76)
50-59 years old	6 (35.29)
60-69 years old	6 (35.29)
70-79 years old	2 (11.76)
Missing	1 (5.88)
Gender	
Men	11(64.71)
Women	6 (35.29)
Ethnicity	
Indigenous	6 (35.29)
White	11 (64.71)
Education	
Less than high school or GED	6 (35.29)
High school or GED	5 (29.41)
Undergraduate degree or higher	4 (23.53)
College or trade	1 (5.88)
Missing	1 (5.88)
Marital Status	
Single	7 (41.18)

Divorced or separated	3 (17.65)
Married	4 (23.53)
Widowed	2 (11.76)
Missing	1 (5.88)
Occupation	
Full-time	6 (35.29)
Retired	5 (29.41)
Unemployed	5 (29.41)
Missing	1 (5.88)
Residence	
Winnipeg (urban)	12 (70.59)
Rural road access	5 (23.53)
Rural fly-in	1 (5.88)
Amputation Indication	
Nondiabetic ischemia	7 (41.18)
Diabetic	9 (52.94)
Traumatic	1 (5.88)
Amputation Type	
Unilateral	15 (88.24)
Bilateral	2 (11.76)
PLP < 2 months after LLA	
Yes	9 (52.94)
No	7 (41.18)

Missing	1 (5.88)
Pre-Amputation Pain	
None	6 (35.29)
< 6 months	4 (23.53)
6 months – 1 year	4 (23.53)
1 year +	3 (17.65)
Previous VR Use	
Yes	2 (11.76)
No	14 (82.24)
Missing	1 (5.88)
Previous Mental Health Service Use	
Yes	1 (5.88)
No	15 (88.24)
Missing	1 (5.88)
Previous Behavioural Pain Treatment	
Yes	1 (5.88)
No	15 (88.24)
Missing	1 (5.88)
PHQ-9	
> 10 (probable depressive symptoms)	6 (35.2)
< 10	8 (47.06)
Missing	3 (17.65)
GAD-7	

> 10 (probable anxiety symptoms)	4 (23.53)
< 10	10 (58.82)
Missing	3 (17.65)
Inpatient Unit of Consent	
Vascular (A3)	3 (17.65)
Orthopaedic (D2)	4 (23.53)
Medicine (H3/H5)	7 (41.18)
Rehabilitation (R5/R6)	3 (17.65)

Note. This table describes the sample characteristics. PLP = Phantom Limb Pain; LLA = Lower Limb Amputation; PHQ-9 = Patient Health Questionnaire 9; GAD-7 = Generalized Anxiety Disorder 7.

Table 2

Inductive Codes and Categories on Reasons for Study Ineligibility and Disinterest

(a) Reasons for Ineligibility (n = 41)

Category	Raw Responses
Cognitive impairment (n = 8)	• Confused and agitated • Confused after surgery • Dementia • The rest were recorded as "Cognitive impairment"
Motor, hearing, and/or visual impairment (n = 7)	• Paraplegia and severe neuropathy in hands • Feels like visual and hearing impairment would affect participation • Severe diabetic retinopathy resulting in blindness • Severe diabetic retinopathy prevents vision • Visual impairment, hearing impairment • Hearing impairment • Bilateral blindness, muscle weakness
Age > 80 (n = 3)	• All recorded as "> 80 years old"
LLA > 2 months ago (n = 8)	• All recorded as "LLA > 2 months ago"

Non-English fluency (n = 2)	• Nurses asked but does not understand English well • Non-English fluency
Bilateral LLA (n = 1)	• Bilateral LLA (before amendment)
Critical illness (n = 3)	• Catatonic • Too overwhelmed with pain • End of life, nurse deemed inappropriate
Busy/off-unit (n = 2)	• Very rarely on unit, and when he is, in too much pain or fatigue to talk. • Leaves hospital room too often
Discharged before consent (n = 5)	• Discharged from the hospital early due to behavioural issues, such as throwing food trays at nurses • The rest were recorded as “Discharged before consent”
Minor LLA (n = 1)	• Ended up only needing toe amp
Unknown reason (n = 1)	• No reason given
(b) Reasons for Disinterest (n = 31)	

Focused on recovery (n = 9)	• Overwhelmed after surgery • Overwhelmed after surgery • Overwhelmed with recovery • Feels too sick • Overwhelmed, because they just had a bilateral amp • Said they're not here for a long time so they see no point • "I can't even move!" • Wants to pursue standard treatment • "Too much" with everything else going on
Uninterested (unknown) (n = 5)	• No explicit reason given. She asked if she would be interviewed-- when I said yes, she declined participation • The rest were recorded as “No reason given”
Concerned about adverse events (n = 4)	• Prolonged screen time hurts eyes • Worried about being in too much pain, being discharged soon • Concerned about potential pain increase • Concerned about potential pain and nausea from VR

Frustrated with medical care (n = 3)	• Was going to say yes, then nurse told him he could not go outside • Frustrated that people can't understand his English, does not want to speak more than necessary • Pattern of refusing medical treatment
Concerned about time commitment (n = 2)	• One-month follow-up is too long • Concerned about 17 days of time commitment
Off-unit for personal reasons (n = 2)	• Off-unit for extended periods of time, which prevented approach
Uninterested (VR) (n = 2)	• Uninterested in VR, thought this would just be an interview • Feels he is too old to participate in VR
Uninterested (research) (n = 2)	• Uninterested in research • Prompted to provide reason, seemed despondent he was "already in study"
No PLP (n = 2)	• All recorded as “No PLP”

Note. This table provides a breakdown of reasons why participants were either ineligible for or uninterested in the VR GMI program, as coded through qualitative descriptive analysis. LLA = Lower Limb Amputation; PLP = Phantom Limb Pain; VR = Virtual Reality; GMI = Graded Motor Imagery.

Table 3

Inductive Codes and Categories on Reasons for Missed Sessions or Early Session Discontinuation

(a) Reasons for Missed VR GMI Sessions (n = 142)	
Category	**Raw Responses (Examples)**
Busy – Appointment (n = 26)	• Appointment with social work to find housing • Gone for dialysis • At occupational therapy or physiotherapy • Medical tests
Busy – Personal (n = 13)	• Visiting with family or friends • Not in room, nurses said they were going for food • Waiting for revision surgery, prefers not to start VR until then • Being discharged home soon
Busy – Unknown (n = 8)	• Off-unit for unknown reasons • Not enough time for session, did not disclose why
Medical cause – Nausea due to dialysis (n = 10)	• Vomiting • Sick • Dizzy

Medical cause – Fatigue (n = 8)	• Tired • Exhausted after medical tests • Fast asleep upon approach
Medical cause – Physical pain (n = 5)	• Hip pain • In a lot of physical pain after fall, being in bed so much
Medical cause – RLP (n = 7)	• Intense pain at amputation site • Open sore on leg, possible infection • Wants to wait until bandages are removed • Issue with pump on leg, needs a new one
Medical cause – Combined RLP and PLP (n = 8)	• Intense pain at amputation site *and* in phantom limb
Medical cause – Other symptoms (n = 4)	• Flu symptoms • Low blood count • Confusion • Claustrophobia in previous VR session
Medical cause – Multiple symptoms (n = 4)	• Fatigue and PLP • Physical pain + nausea
Low mood only (n = 6)	• Tired, just wants to go home • Overwhelmed with hospital appointments • Frustration about length of stay

	• Feeling low, too much time with thoughts, past trauma • Disappointed after seeing social worker
Low mood with medical symptoms (n = 3)	• Pain + emotional distress • Discouraged due to symptoms
RA unavailable (n = 35)	• RA unavailable due to sickness or schedule conflict
Miscommunication with hospital staff (n = 7)	• Could not find patient after they moved units
(b) Reasons for Early Session Discontinuation (n = 54)	
Adverse events (n = 19)	• Started to feel dizzy • Began feeling anxious • PLP Flare-up • RLP/tiredness • Seeing virtual leg is a shock, need time to adjust • Leg trackers rubbing against residual limbs
Technical issues (n = 6)	• RA stopped due to fine motor difficulties preventing engagement • Technical issues, then RA ran out of time to finish session

	• Bed frame prevented movement • Controls are jumpy, need to be fixed
Physical pain or fatigue from recovery (n = 7)	• Sleepy • No pain medication today • Wants to limit physical exertion in recovering leg • Got tired • Hip sore • Falling asleep
Disliked stage (n = 3)	• Explicit motor imagery – did not see the benefit, headset too hot, didn't like voice • Limb simulation—did not like leg trackers (ended session shortly after putting on)
Interrupted by medical team (n = 3)	• Medical staff came in during session • Physiotherapy appointment soon
Boredom/repetitiveness (n = 16)	• Left/right discrimination and limb simulation – completed all the exercises, did not want to repeat, getting monotonous/too easy

Note. This table summarizes inductive codes and categorized reasons for missed VR GMI sessions and early session discontinuation. Categories were derived from participant-reported explanations or staff notes recorded at the time of each missed or incomplete session. VR =

Virtual Reality; GMI = Graded Motor Imagery; PLP = Phantom Limb Pain; RLP = Residual Limb Pain; RA = Research Assistant.

Table 4

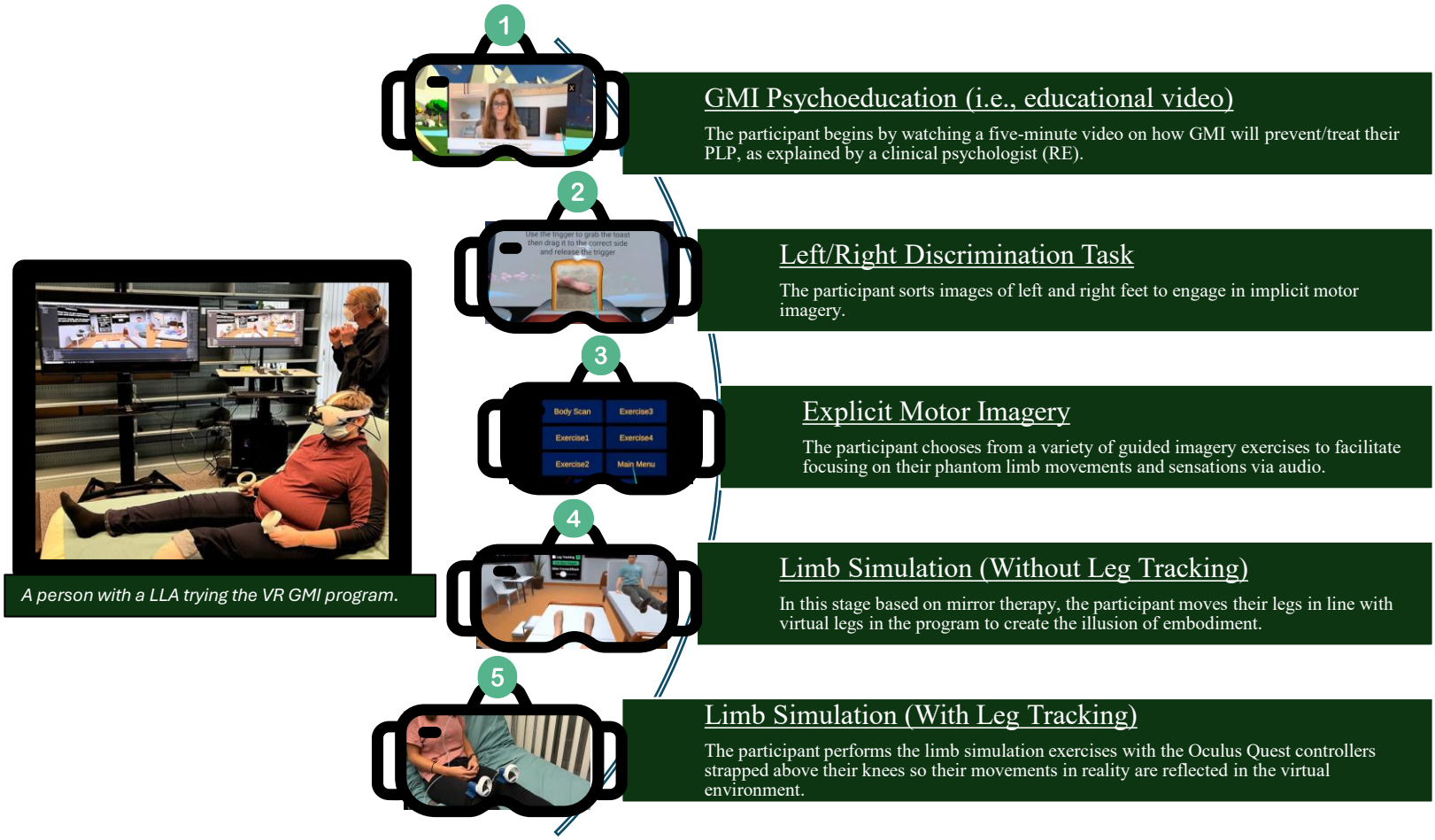
Unpublished Agency and Ownership Ratings for the Limb Simulation Stages from Phase 2

Participant #	Without Leg Tracking (agency/ownership)	With Leg Tracking (agency/ownership)
1	6/6	8/8
2	0/3	NA
3	0/7	9/9
4	4/8	9/9
5	1/5	8/5
6	3/4	9/6
7	4/3	NA
8	7/3	7/5
9	10/5	10/0
10	2/7	9/9
11	10/6	10/10
12	1/1	10/9

Note. The agency/ownership scales utilized in phase 2 of intervention development (Crooks et al., 2025) were adapted from Sano et al. (2016) and entail indicating one's level of agreement with two statements on a scale of one (indicating no agreement) through ten (indicating total agreement). These statements include "*I felt as if my virtual leg was my own leg*" (measuring ownership) and "*I felt as if I could control the movements of my virtual leg*" (measuring agency). These scales were administered at the end of each limb simulation stage to collect preliminary evidence of agency and ownership in the task.

Figure 1

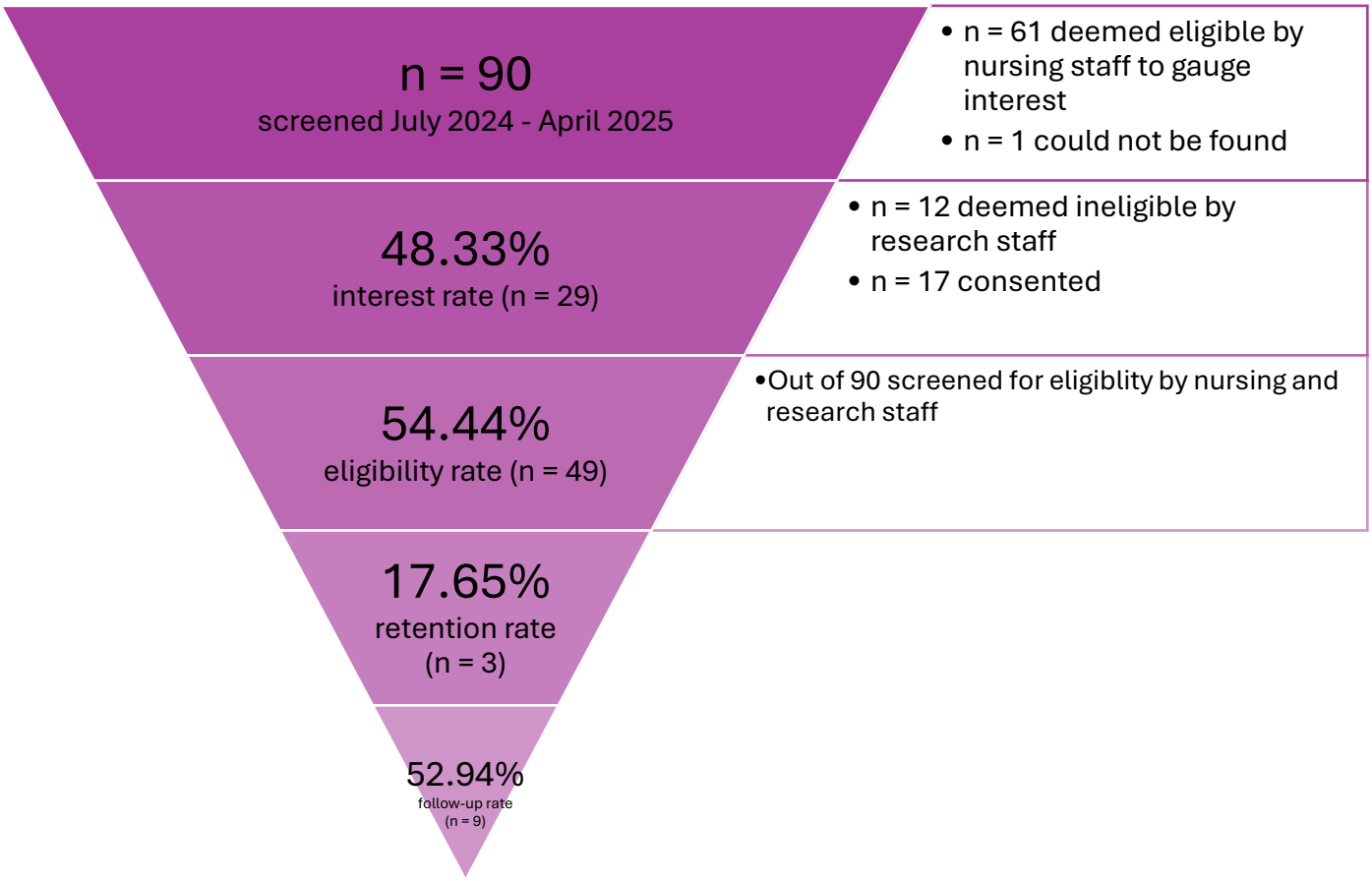
The Five Stages of the VR GMI Program



Note. This figure provides a visual overview and description of the five stages embedded in the VR GMI program. PLP = phantom limb pain; VR = virtual reality; GMI = graded motor imagery.

Figure 2

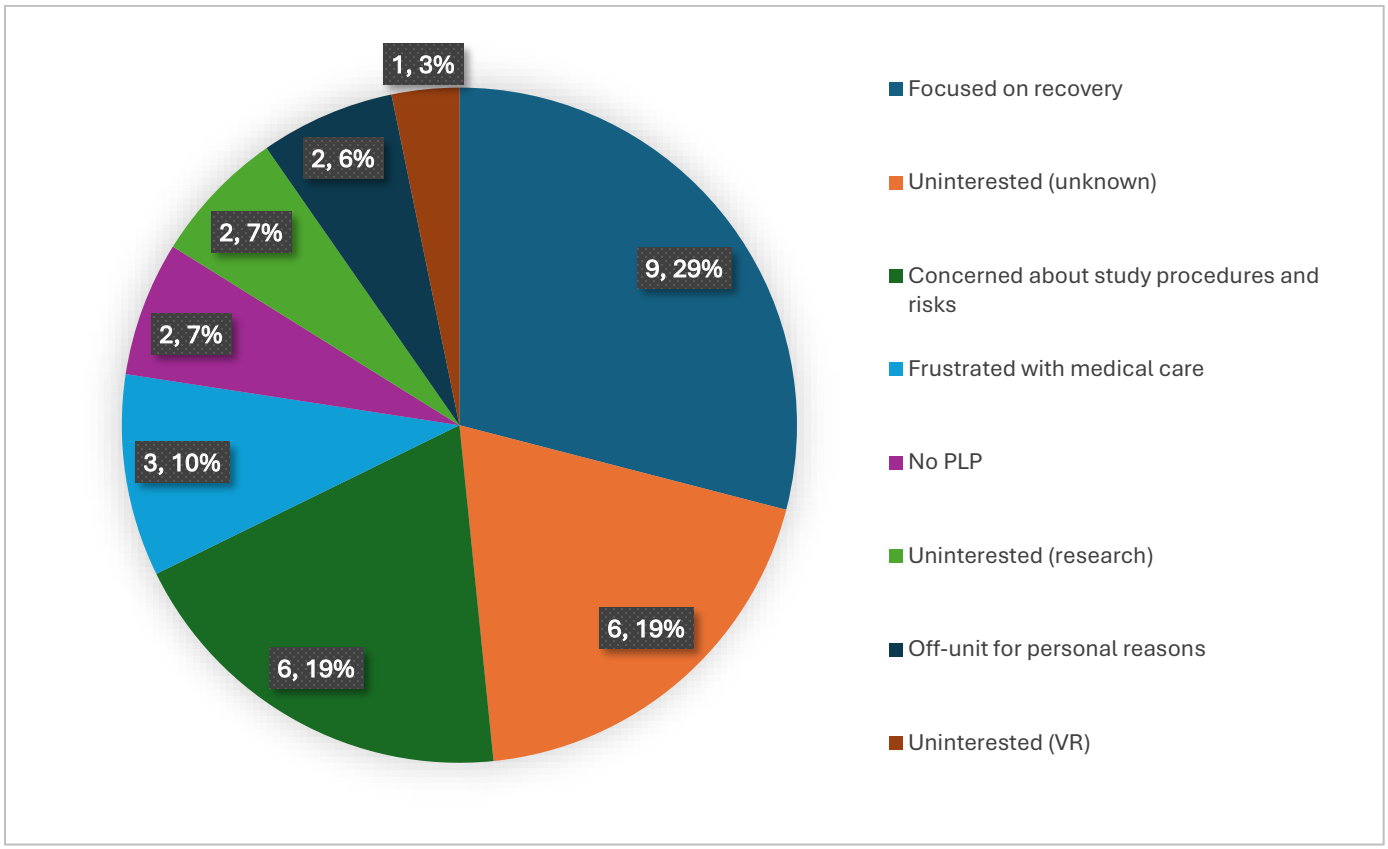
Procedural Feasibility Diagram



Note. A visual overview of the recruitment flow and the resulting interest, eligibility, retention, and follow-up rates.

Figure 3

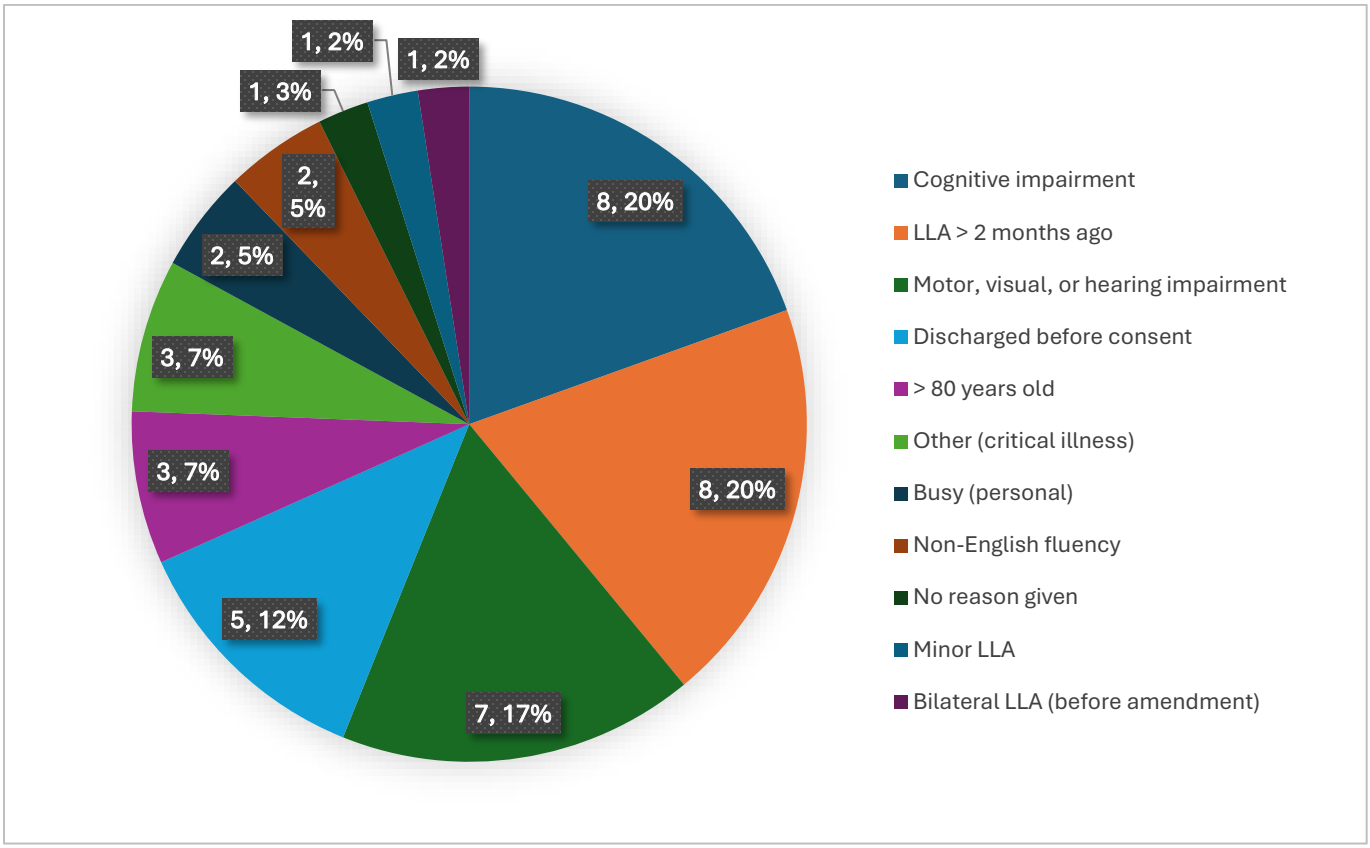
Reasons for Disinterest (n = 31)



Note. This figure displays a pie chart showing reasons patients were not interested in participating in the VR GMI program (n, %). VR = Virtual Reality; GMI = Graded Motor Imagery.

Figure 4

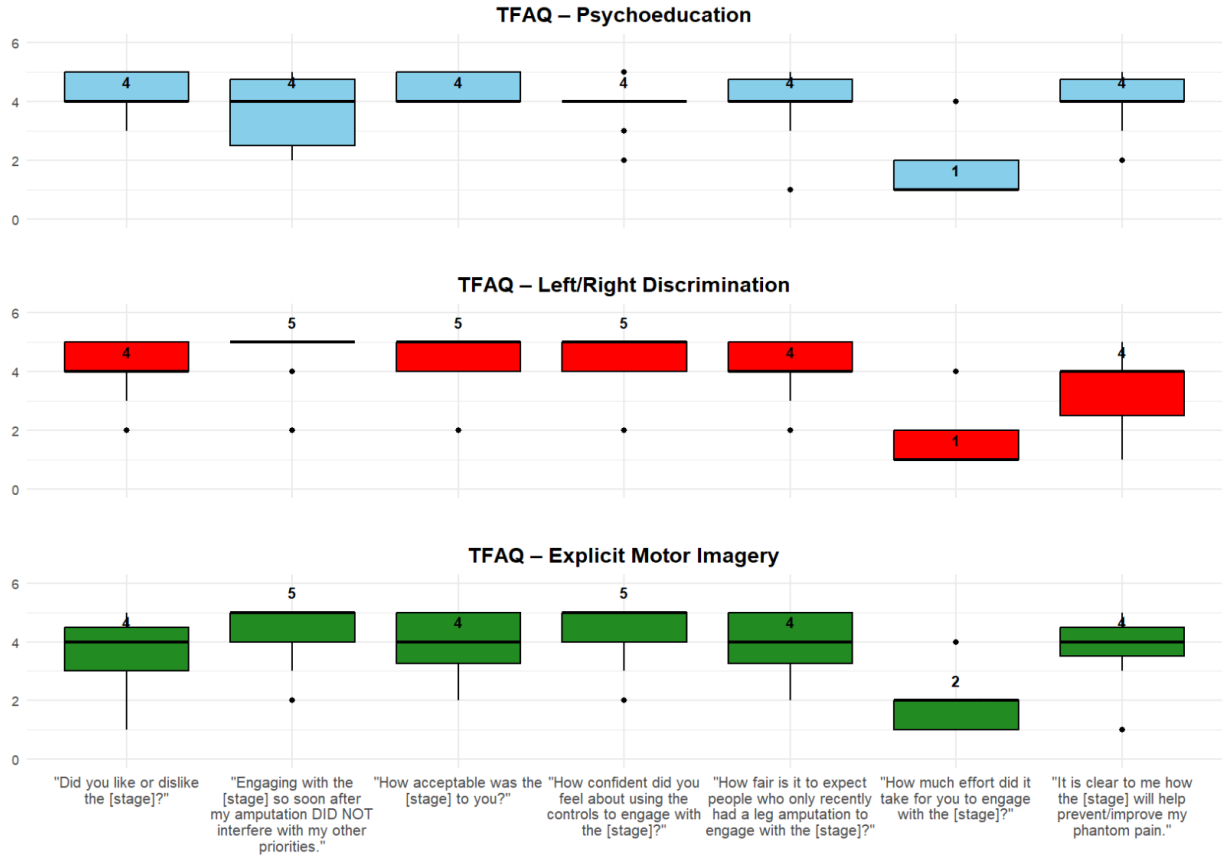
Reasons for Exclusion (n = 41)



Note. This figure displays a pie chart showing reasons patients were excluded from participating in the VR GMI program, both at screening and before consent (n, %). LLA = Lower Limb Amputation; VR GMI = Virtual Reality Graded Motor Imagery.

Figure 5

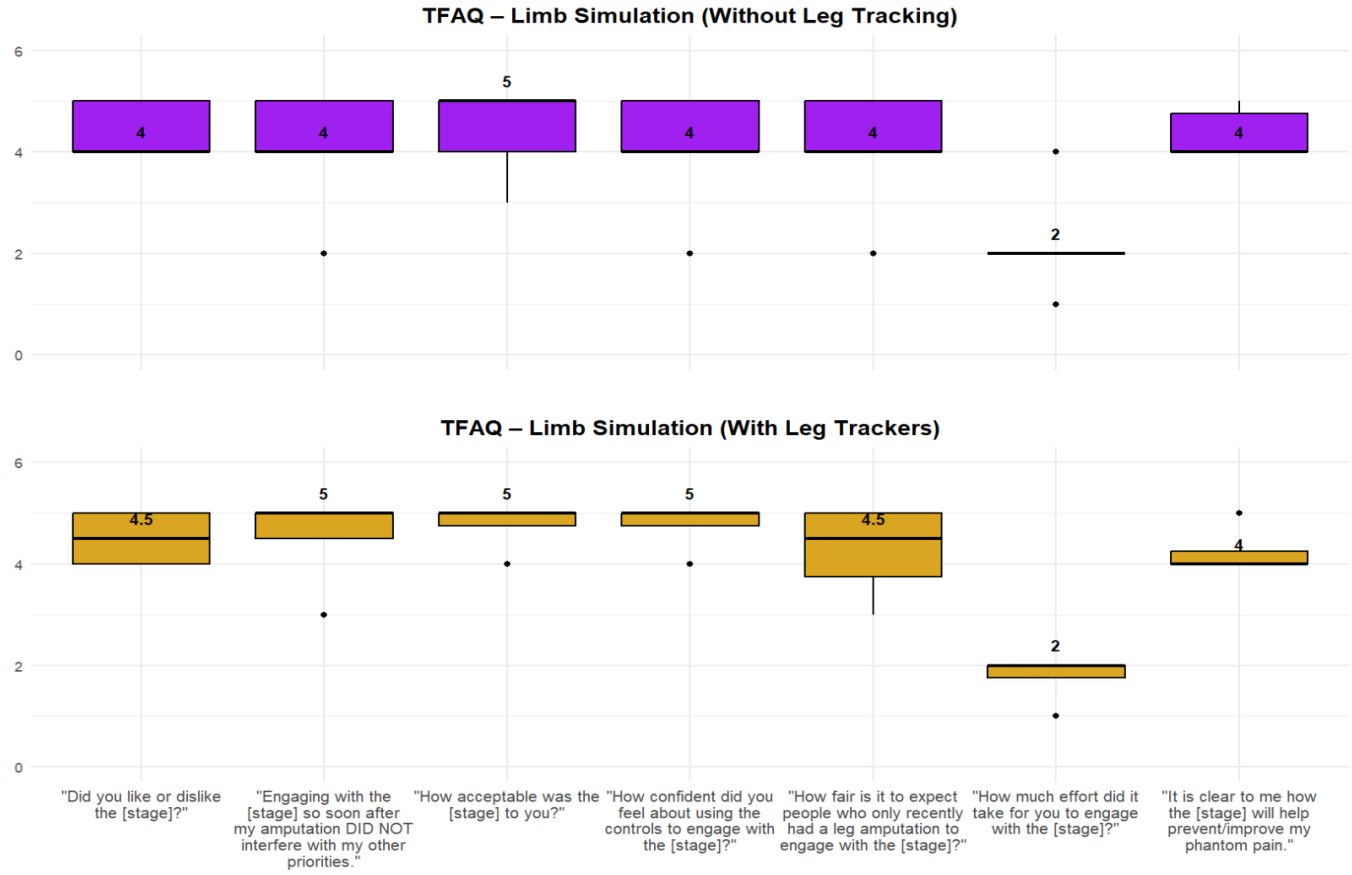
Boxplots displaying item-specific TFAQ scores for Psychoeducation, Left/Right Discrimination, and Explicit Motor Imagery



Note. This figure displays boxplots that depict item-specific TFAQ scores for the first three VR GMI stages, including psychoeducation, left/right discrimination, and explicit motor imagery. Higher scores reflect higher acceptability of the intervention. TFAQ = Theoretical Framework of Acceptability Questionnaire; VR GMI = Virtual Reality Graded Motor Imagery.

Figure 6

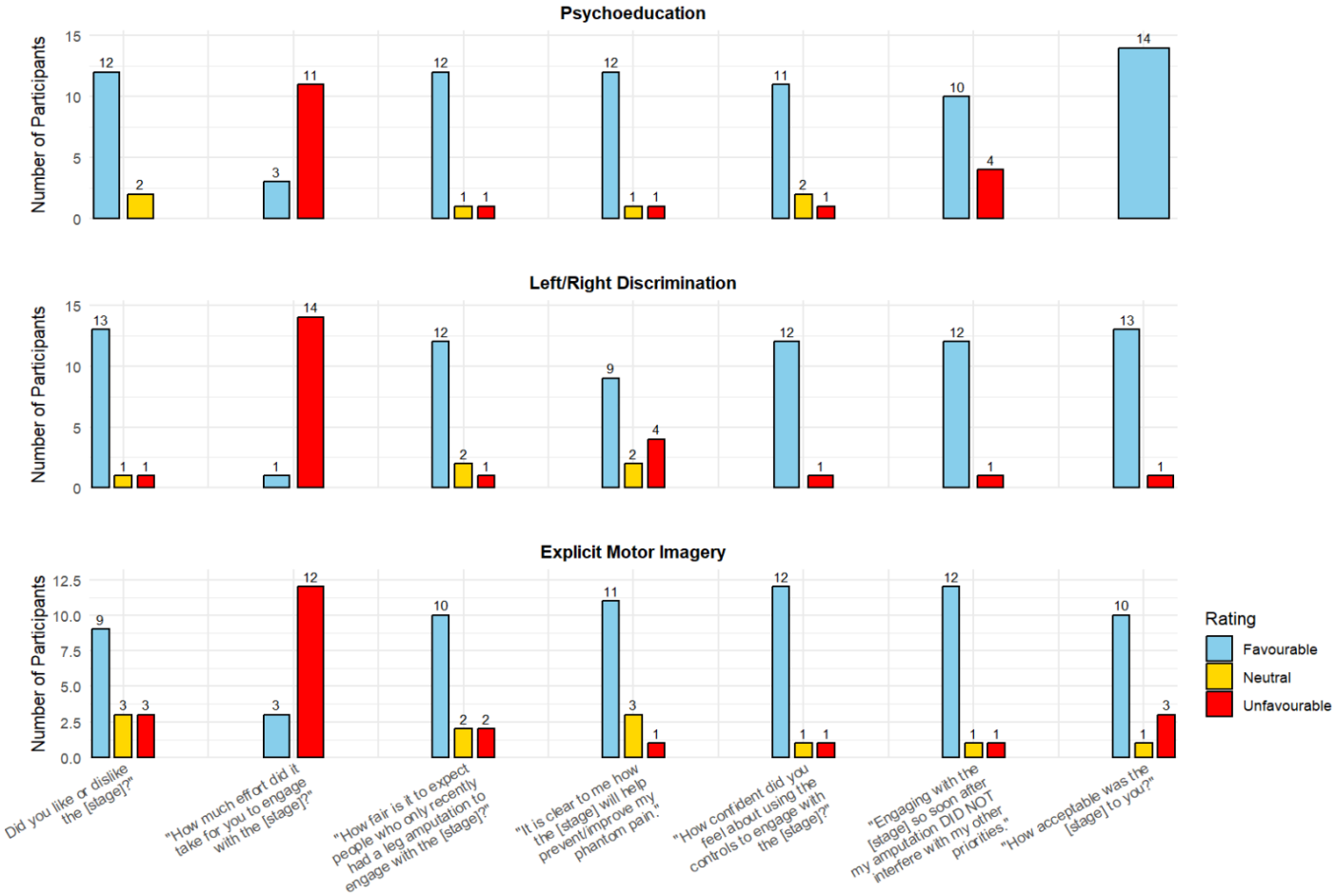
Boxplots displaying item-specific TFAQ scores for Limb Simulation (With and Without Leg Tracking)



Note. This figure displays boxplots that depict item-specific TFAQ scores for the limb simulation stages in the VR GMI program. Higher scores reflect higher acceptability of the intervention. TFAQ = Theoretical Framework of Acceptability Questionnaire; VR GMI = Virtual Reality Graded Motor Imagery.

Figure 7

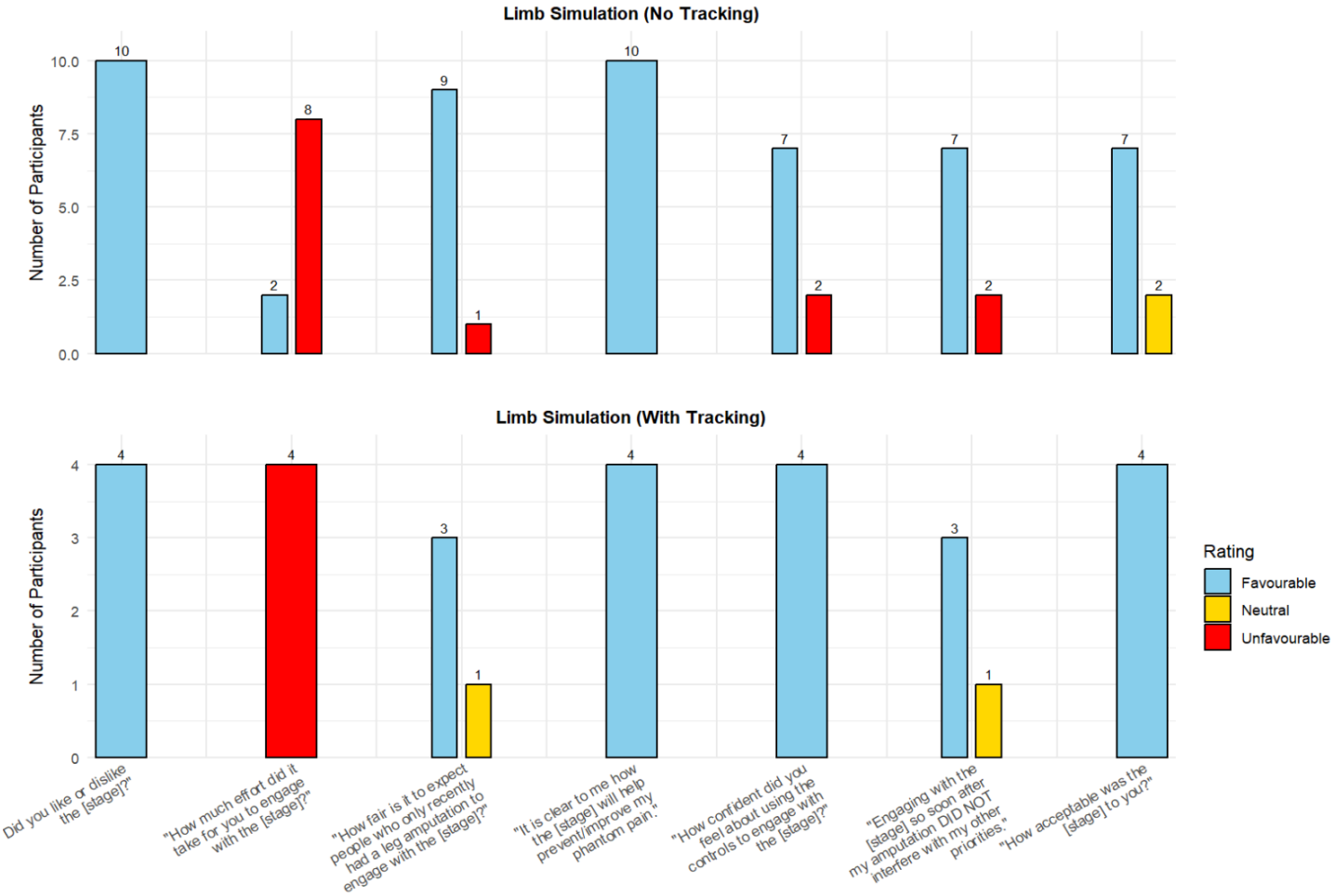
Frequency of Favourable, Neutral, and Unfavourable TFAQ Ratings – Psychoeducation, Left/Right Discrimination, and Explicit Motor Imagery



Note. Bar charts reflect the number of participants who rated each TFAQ item as Favourable (TFAQ > 3), Neutral (TFAQ = 3), or Unfavourable (TFAQ < 3) in the psychoeducation, left/right discrimination, and explicit motor imagery stages of the VR GMI program. TFAQ = Theoretical Framework of Acceptability Questionnaire; VR GMI = Virtual Reality Graded Motor Imagery.

Figure 8

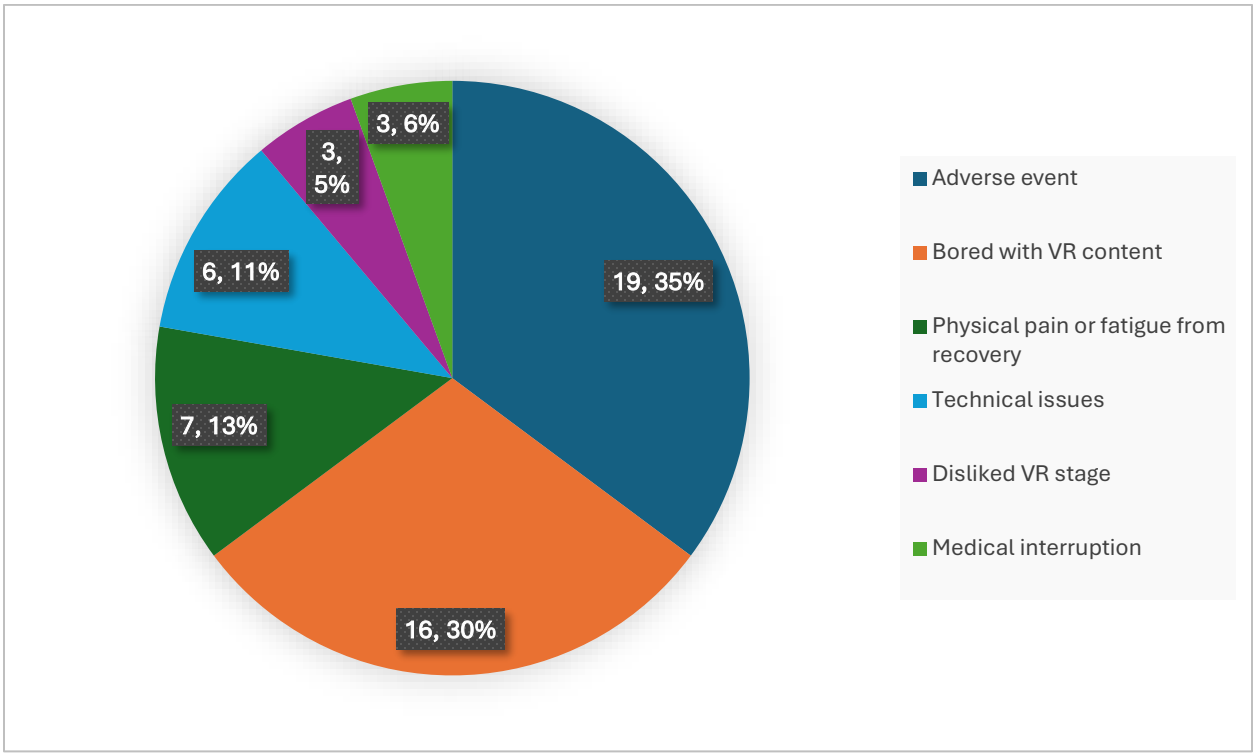
Frequency of Favourable, Neutral, and Unfavourable TFAQ Ratings – Limb Simulation (With and Without Leg Tracking)



Note. Bar charts reflect the number of participants who rated each TFAQ item as Favourable (TFAQ > 3), Neutral (TFAQ = 3), or Unfavourable (TFAQ < 3) in the Psychoeducation, limb simulation stages of the VR GMI program (with and without leg trackers). TFAQ = Theoretical Framework of Acceptability Questionnaire; VR GMI = Virtual Reality Graded Motor Imagery.

Figure 9

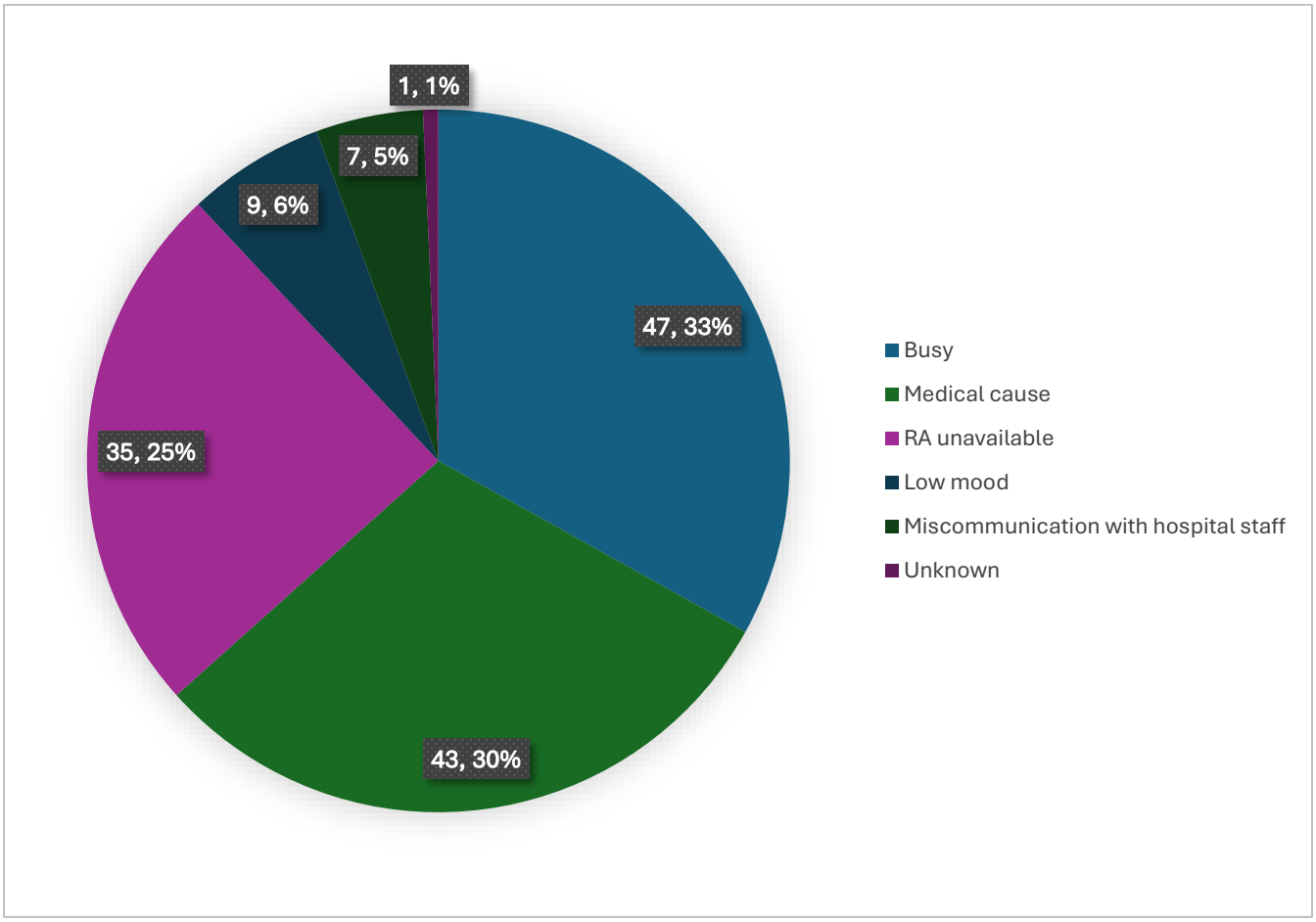
Reasons for Early VR GMI Session Discontinuation (n = 142)



Note. This pie chart illustrates the different reasons participants discontinued a VR GMI session earlier than the recommended twenty minutes (n, %). VR = Virtual Reality; GMI = Graded Motor Imagery.

Figure 10

Reasons for Missed VR GMI Sessions (n = 142)



Note. This pie chart illustrates the different reasons participant missed a VR GMI session (n, %).

RA = Research Assistant; VR GMI = Virtual Reality Graded Motor Imagery.

Appendix A

Theoretical Framework of Acceptability Questionnaire (TFAQ) Modified Questions

Each TFAQ administration will be preceded with: "When you answer the following questions, think about your experience with this stage specifically in [the hospital/this clinic/your home]."

1. Did you like or dislike the [educational video/insert stage]?

Strongly dislike	Dislike	No opinion	Like	Strongly like
1	**2**	**3**	**4**	**5**

2. How much effort did it take to [access/engage with] the [educational video/stage]?

No effort at all	A little effort	No opinion	A lot of effort	Huge effort
1	**2**	**3**	**4**	**5**

3. How fair is it to expect people who recently had a leg amputation to [watch/engage with] the [educational video/stage]?

Very unfair	Unfair	No opinion	Fair	Very fair
1	**2**	**3**	**4**	**5**

4. It is clear to me how using the [VR program/stage] early on in my recovery will prevent/improve my phantom pain.

Strongly disagree	Disagree	No opinion	Agree	Strongly agree
1	**2**	**3**	**4**	**5**

5. How confident did you feel about [accessing/engaging with] the [educational video/stage]?

Very unconfident	Unconfident	No opinion	Confident	Very confident
1	**2**	**3**	**4**	**5**

6. [Watching/engaging with] the [educational video/stage] so soon after my amputation interfered with my other priorities.

Strongly disagree	Disagree	No opinion	Agree	Strongly agree
1	**2**	**3**	**4**	**5**

7. How acceptable was the [educational video/stage] to you?

Completely unacceptable	Unacceptable	No opinion	Acceptable	Completely acceptable
1	**2**	**3**	**4**	**5**

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