Designing Passive Haptic Simulators for Injury Assessment Training

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

The research presented in this thesis is the result of a collaborative effort involving myself, my supervisors, Dr. Mark Hancock and Dr. Oliver Schneider, and Robert Burns, a clinician from our university whose expertise and feedback strongly informed the design of the technologies presented in chapters 3, 4, and 5 of this thesis. All of them are also co-authors on the publications associated with those chapters. While the first-person singular "I" is used throughout this thesis, the work presented is a collaborative effort with them.

Chapter 3 Publication: Moran-Ledesma, M., Burns, R., Hancock, M., & Schneider, O. (2025). TRAIN-KNEE: Developing a Haptic Manikin for Knee Injury Assessment Training. IEEE Transactions on Medical Robotics and Bionics, 7(4), 1777–1788.
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Abstract

In kinesiology and health sciences, practitioners rely heavily on repeated practice to master manual musculoskeletal (physical) assessments. This exposes them to realistic scenarios and helps them refine judgment and adapt to variability. However, providing structured, safe, and repeatable opportunities for this training remains a challenge. Haptic simulators for medical education are a promising approach because they enable safe, repeatable, and controlled practice environments for clinical skill development. While significant progress has been made in areas such as surgical training, minimally invasive procedures, and rehabilitation, relatively little attention has been given to using haptic technologies for training physical assessments. This dissertation addresses this gap through the design, development, and evaluation of passive haptic simulators for training in the physical examination of joint injuries, with a focus on the Valgus stress test used to detect damage to the medial collateral ligament (MCL) of the knee.

First, I introduce ***TRAIN-KNEE***, a high-fidelity passive haptic simulator designed to 1) reproduce MCL injuries and 2) enable realistic Valgus stress testing. TRAIN-KNEE was developed collaboratively with a certified clinician and evaluated in three stages: a calibration using a psychophysics method to configure four MCL injury conditions; a study where six certified clinicians rated each condition for consistency; and a technical evaluation measuring valgus motion in two conditions. Results show that TRAIN-KNEE reliably represents healthy and injured MCLs, with sensitivity values close to those in the literature.

I then present ***Flex-Knee***, a cheaper and easy-to-build passive haptic simulator that provides the same functionality as TRAIN-KNEE. I evaluated Flex-Knee in three stages: a

calibration with our collaborating clinician to configure it for the four MCL conditions using a psychophysics method; an acceptance test with 6 additional clinicians; and a showcase with students in a kinesiology class. Clinicians distinguished healthy, partially torn, and fully torn MCLs in Flex-Knee; students also recognized these differences.

Finally, I present a modular **template system** for designing passive haptic simulators for training physical assessment of hinge joints. The system consists of reusable design templates that can be adapted to different joints and injury types. I demonstrate its application in three simulators targeting the MCL and anterior cruciate ligament (ACL) in the knee, and the ulnar collateral ligament (UCL) in the elbow. Calibration using a psychophysics-based method for two simulators, along with a preliminary evaluation of the third, shows that all three achieve sufficient fidelity for the intended use cases.

These three contributions establish a progression from a high-fidelity, task-specific simulator to a low-cost and scalable simulator, and finally to a generalized template for designing passive haptic simulators for manual physical assessment. Across these stages, this work demonstrates how clinically relevant tactile experiences of joint injury assessment can be reproduced using passive systems, while progressively improving affordability, modularity, and adaptability. More broadly, the dissertation advances the design space of haptic training tools for kinesiology and health sciences, and provides a foundation for developing future systems that support safe, repeatable, and effective training of novice practitioners in manual musculoskeletal assessment.

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I would like to thank all the little people who made this thesis possible.

I first want to thank my family: my mom, my dad, and my siblings. Thank you for your unconditional love, support, and patience throughout this journey. Thank you as well for listening to every rant, frustration, setback, and moment of self-doubt that inevitably came with pursuing a PhD. Whether you realized it or not, those conversations often helped me more than you know. To my mom in particular, thank you for being the greatest cheerleader I could ever ask for. You never stopped believing in me, praying for my success, and, perhaps just as importantly, praying for my sanity. Although we were separated by distance, I carried you with me every day. Your presence was a constant source of strength throughout this journey, and you were always close by, even here in my office. If there is any credit to be given for this degree, a large part of it belongs to you. You believed in this moment for longer and way more faithfully than I ever did. Truthfully, I think you are even more excited than I am to finally cross the finish line.

Second, I must thank my supervisors, Dr. Mark Hancock and Dr. Oliver Schneider, for their unwavering advice, availability, guidance, mentorship, and financial support throughout my graduate studies. I have been incredibly fortunate to learn under their mentorship. I am especially grateful for their patience and encouragement. Research has never come naturally to me, and it is not something I ever really saw myself pursuing as a career. I began graduate studies without many of the skills and experiences that are often expected at this level. Despite this, they consistently met me where I was, providing guidance at every stage and helping me develop as a researcher. Their willingness to explain even the most

fundamental concepts, often more than once, made challenges feel manageable and created an environment where I could continue growing. Other supervisors likely would have shown me the door. I am also thankful for the trust and independence they gave me throughout this work, something I have witnessed is not always the case in other supervisor-student relationships on campus. They encouraged me to pursue ideas that interested me and supported my decisions regarding the direction of the research, including publishing in smaller and less well-known venues where I felt our work was genuinely valued. Their confidence in my judgment allowed me to shape this research in a way that remained meaningful to me. I will always hold respect and appreciation for them and their work.

Third, I would like to express my deepest gratitude to my collaborating clinician, Robert Burns. This work began when he approached my supervisors and me with a challenge that had become particularly pressing during the COVID-19 pandemic: how to effectively teach physical examination skills to kinesiology and health sciences students when access to traditional hands-on instruction was severely limited by remote delivery of classes. That conversation kicked off the research presented in this dissertation. Throughout this journey, Rob was an invaluable collaborator and unwavering supporter. He generously shared his expertise, participated in countless discussions and feedback sessions, and played a central role in the validation of the simulators developed in this dissertation. He was also the first point of contact for recruiting participants and helped spread awareness of the project among practitioners and students. His enthusiasm, encouragement, and willingness to invest his time were instrumental every step of the way. In a few words, this dissertation does not get accomplished without his involvement.

I am very grateful to my examination committee members as well, Dr. David Wang, Dr. Jennifer Howcroft, and Dr. Shi Cao. They were incredibly generous during my comprehensive exam in May 2024, and played a crucial role in helping me reshape and refine my research agenda. Dr. Howcroft, I am especially grateful for the thoughtful words you have shared in every encounter we have had since then; they continued to guide my thinking. I would also like to sincerely thank my external examiner, Dr. Jeremy Brown from Johns Hopkins University. I had the pleasure of meeting him briefly at the 2026 Haptics Symposium, where I was impressed by his work, his students' work, and his energy. I also appreciated his unique, firm fist bumps.

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Dedication

To the woman of my life whom I have yet to meet.

I hold onto the belief that my full authentic self will be enough when our paths cross.

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Chapter 1

Introduction

1.1 Motivation

In many professional domains, expertise depends not only on theoretical knowledge but also on the development of embodied skills through direct interaction with physical systems and environments (Yardley et al., 2012). These skills often require individuals to interpret sensory information, coordinate fine motor actions, and make decisions under uncertain or variable conditions (Wolpert et al., 2011). Unlike purely conceptual learning, such competencies are acquired through repeated experiential practice, where learners gradually refine perception, judgment, and motor control through exposure to realistic scenarios. However, reproducing these experiences in ways that are safe, structured, repeatable, and broadly accessible remains a persistent challenge across professional education.

This challenge becomes particularly significant in healthcare (Henriksen et al., 2018), where many clinical competencies rely heavily on perceptual and hands-on skills developed through interaction with the human body (Chacon et al., 2019; Lelevé et al., 2020). For example, a paramedic performing cardiopulmonary resuscitation (CPR) should rapidly detect and respond to subtle physiological cues (Thielen et al., 2017). Although the theoretical principles underlying these tasks can be taught through lectures, textbooks, or demonstrations, opportunities to develop practical expertise are inherently constrained. Learning often depends on access to patients or volunteers, exposure to sufficiently diverse conditions, and supervised repetition in realistic contexts. As a result, acquiring proficiency can be difficult, particularly when conditions are rare, variable, or ethically challenging to reproduce.

Haptics (Kim and Schneider, 2020) has introduced new teaching methods in medical education through the development of *simulators* designed to improve clinical skill acquisition (Pacheco-Barrios et al., 2024), naturally enabling opportunities for repeated hands-on skill development while allowing practitioners to develop medical competency without fear of harming real patients (Beyea and Kobokovich, 2004). For example, through the use of CPR simulators, healthcare personnel can physically perform the procedure while experiencing realistic haptic feedback associated with chest compressions and patient interaction, enabling repeated, risk-free practice in conditions that resemble real clinical scenarios.

Within kinesiology and health sciences, developing proficiency in musculoskeletal injury assessment requires extensive hands-on practice. When an individual sustains trauma to a joint such as the knee or elbow, clinicians and certified kinesiologists perform standardized manual physical examinations to evaluate structural integrity and determine the presence

of injury (Petty and Ryder, 2018). These examinations rely extensively on tactile perception and fine motor interaction, as practitioners interpret variations in joint motion, soft tissue resistance, laxity (Neumann, 2016), and patient feedback to identify abnormalities (Clarkson, 2022). However, acquiring proficiency in these examination techniques presents a significant challenge. Training typically occurs on peers or volunteers, who are usually healthy, which limits exposure to relevant conditions. Without access to a diverse range of injuries, it becomes difficult to fully understand how these conditions present in practice. Even when an injured individual is available, it represents only a single instance within a broad range of conditions, and additional constraints such as liability further restrict learning opportunities.

Haptic simulation has been widely adopted in multiple medical domains such as surgery, rehabilitation, and minimally invasive procedures, and it has been shown to improve skill acquisition and clinical competency (Escobar-Castillejos et al., 2016; Pacheco-Barrios et al., 2024). However, several challenges remain regarding its incorporation into kinesiology and health sciences, particularly for training in manual musculoskeletal assessments—manual physical tests to examine the physical conditions of human joints and to determine the presence of injuries (Clarkson, 2022).

First, comparatively less attention has been devoted to simulators intended for training manual physical examinations, despite the central role that tactile interpretation and physical manipulation play in these practices. Existing work has largely focused on procedural and instrument-mediated tasks, leaving diagnostic assessments of musculoskeletal injuries relatively underexplored (Escobar-Castillejos et al., 2016; Syamlan et al., 2022). As a result, less is known about how to effectively design haptic simulators that reproduce

the perceptual and biomechanical cues practitioners rely on during manual assessment, such as joint laxity, soft tissue resistance, or abnormal motion. This lack of prior work also limits the availability of established design principles, evaluation methods, and implementation approaches that could inform the development of new systems for musculoskeletal assessment training.

Second, access to haptic simulators is often limited to well-resourced institutions such as hospitals, research centers, and universities due to the high cost of hardware and software, as well as the infrastructure, technical expertise, and maintenance required to support these systems (Coles et al., 2011; Gunabushanam et al., 2019). As a result, these systems are typically deployed in controlled simulation spaces rather than being widely accessible for individual or distributed use. This limitation can restrict the frequency and flexibility of practice, particularly for students and trainees who may benefit from more continuous and self-directed learning opportunities.

Third, many existing solutions are designed around a single, well-defined task and therefore offer limited flexibility to adapt to additional use cases (Moran-Ledesma et al., 2026a). For example, a simulator developed for one specific physical assessment may not easily generalize to different injuries or anatomical regions without substantial redesign. In clinical practice, however, healthcare professionals must perform a wide range of assessments across multiple joints and conditions. This highlights the need for scalable and adaptable haptic simulation systems capable of supporting diverse training scenarios within a shared platform.

This dissertation aims to help address these gaps by investigating the design, implementation, and evaluation of haptic simulators specifically intended to support training in manual musculoskeletal physical examination, while also contributing design knowledge and implementation approaches to inform future work in this relatively underexplored area.

1.2 Scope

The specific research area of this dissertation is *haptic simulators for training in physical examination of human joint injuries*, with a focus on the knee joint. Traumatic injuries in the knee are commonplace and account for a large number of emergency room visits every year (Branch et al., 2017), making it a common site for clinical assessment and a critical target for training. Correct evaluation of knee injuries relies heavily on manual physical examination skills, where healthcare professionals interpret tactile and mechanical cues such as abnormal joint motion, limb instability and misalignment, and altered soft tissue resistance during manipulation (Lubowitz et al., 2008).

Within this context, this work lies at the intersection of multiple research areas, as illustrated in Figure 1.1. At its core, it builds on advances in haptic devices for educational purposes, focusing on the design of systems that enable realistic tactile interaction. It is further situated within the context of medical simulation, where such technologies support the development of clinical skills. In addition, this dissertation draws on contributions from human–computer interaction (HCI) and research on prototyping toolkits and frameworks, particularly in the design of tools for creating interactive haptic systems that are both affordable and scalable.

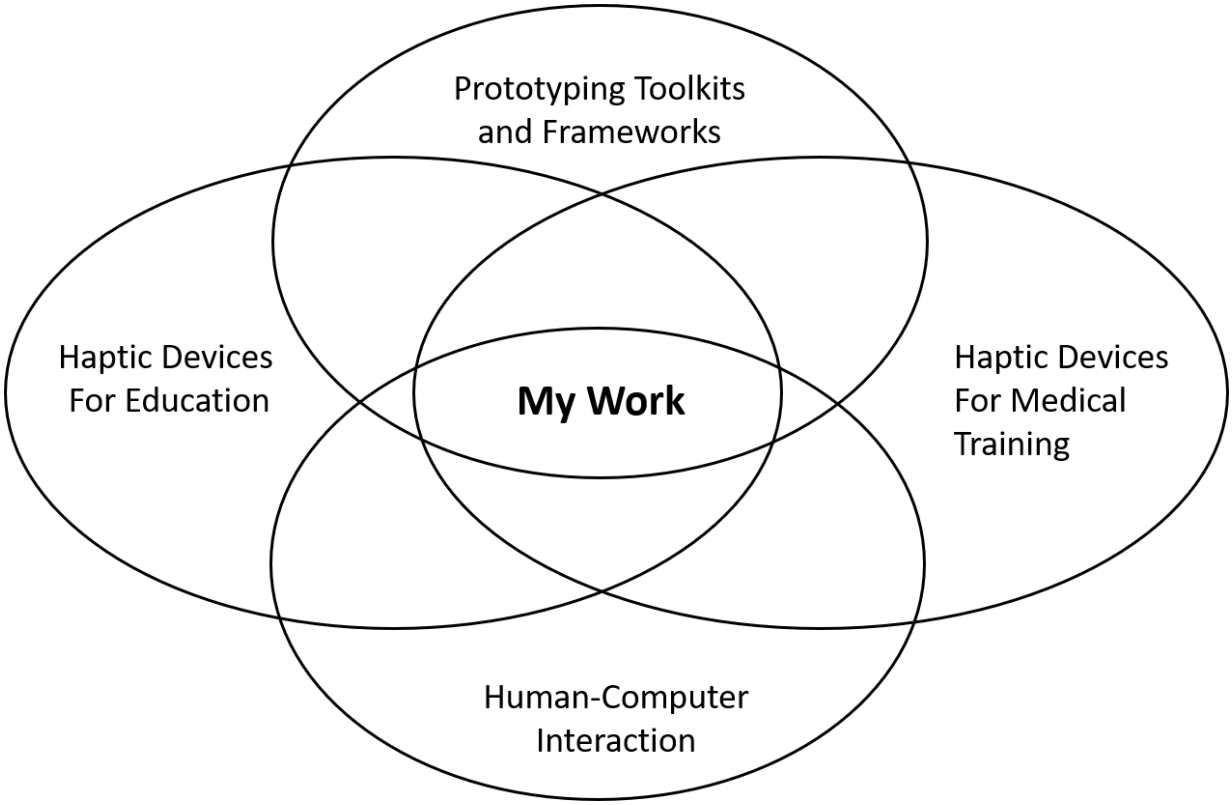


Figure 1.1: Scope of this dissertation.

1.3 Approach and Contributions

In this research, I take the following approach to address the aforementioned issues:

First, I investigate how to create a simulator capable of supporting novice practitioners in training for manual musculoskeletal physical examination. To address this problem, I co-design a system with an expert clinician while adopting a primarily engineering-driven approach informed by existing work in robotics, haptics, soft interface design, and digi-

tal fabrication. Given the limited availability of established design principles, evaluation methods, and implementation approaches for systems tailored for musculoskeletal assessment training, I place particular emphasis on achieving realistic tactile and mechanical behaviour, as well as anatomical accuracy, in the simulator design. I also incorporate validation with experts in the field.

Following this approach, I present the first contribution (**C1**) of this dissertation in **chapter 3**: the development of *TRAIN-KNEE* (Moran-Ledesma et al., 2025), a high-fidelity haptic knee simulator designed to support training in the *Valgus* Stress Test (Aronson et al., 2010). This test evaluates the integrity of the medial collateral ligament (MCL), a commonly injured knee ligament (Fetto and Marshall, 1978; Sawant et al., 2004). Co-designed and calibrated with a certified clinician using a psychophysics method (Cornsweet, 1962) and then evaluated with six additional certified physiotherapists and athletic therapists from our university campus, TRAIN-KNEE physically incorporates anatomical structures and soft tissue components to generate realistic mechanical resistance during manipulation. It is capable of reproducing healthy and injured MCL conditions and establishes the feasibility of achieving clinically meaningful tactile realism of a musculoskeletal injury in a purely passive simulator.

After this, I investigate how to create a simulator that supports training in musculoskeletal physical examination while retaining or improving the benefits of TRAIN-KNEE at a lower cost. Although highly realistic systems such as TRAIN-KNEE can provide meaningful training experiences, they are also more difficult to manufacture and less accessible for large-scale deployment. I envision these technologies reaching classrooms and laboratories at universities and colleges. Building on the findings from TRAIN-KNEE, I

therefore investigate approaches to reduce manufacturing complexity and cost while also expanding the capabilities of the simulator. In particular, while TRAIN-KNEE was only able to reproduce healthy and injured MCL conditions, in the next stage of this work I explore designs that can represent a wider range of MCL injuries.

Building on these insights, I present the second contribution (**C2**) of this dissertation in **chapter 4**: the development of *Flex-Knee* (Moran-Ledesma et al., 2026b), a low-cost, scalable, and modular knee simulator that reduces manufacturing complexity while expanding the range of simulated MCL injury conditions. The system uses widely available hardware components, 3D-printed parts, and a metamaterial-inspired (Ion et al., 2016) approach to injury representation. With Flex-Knee, I demonstrate that clinically relevant tactile experiences of MCL injuries can be achieved without relying on expensive fabrication methods. Evaluations with six new certified professionals and sixteen students from our university campus show that Flex-Knee not only preserves the core capabilities of TRAIN-KNEE but also extends them by enabling the simulation of multiple MCL injury conditions, including healthy, partially torn, and fully torn states.

Finally, I investigate how to abstract Flex-Knee's design so that the same underlying system can support multiple training scenarios. Developing a dedicated simulator for a single injury or assessment test limits scalability and reduces the broader educational impact of the technology. In practice, healthcare practitioners may encounter a wide range of conditions, including MCL injuries, ACL injuries, elbow injuries, or concurrent injuries affecting multiple structures. Creating separate systems for every condition quickly becomes impractical in terms of cost, fabrication, and deployment in educational settings. Following the development of Flex-Knee, I therefore explore approaches for creating mod-

ular and reusable parts where shared mechanical and structural elements can be adapted to represent different joints, injuries, and examination procedures. This approach increases accessibility, reduces fabrication redundancy, and expands the range of clinical experiences available to novice practitioners.

Following this direction, I present the third contribution (**C3**) of this dissertation in **chapter 5**: a generalized template system for implementing passive haptic musculoskeletal injury simulators (Moran-Ledesma et al., 2026a). Rather than developing one simulator per joint injury, I propose a shared hardware framework built around an abstract mechanical joint with tunable parameters, limb-like soft structures with variable material composition, and silicone-based skin layers. I demonstrate this approach through multiple prototypes that support knee and elbow valgus assessments as well as anterior cruciate ligament evaluation through the Lachman test. Preliminary calibration and evaluation with a certified clinical instructor from our university campus illustrate how a common baseline design can be adapted to support different injury conditions and examination scenarios.

Taken together, these contributions establish a research trajectory: from a high-fidelity, task-specific prototype to a cost-effective, modular system, and finally to a generalized template system to make passive haptic simulators for manual musculoskeletal assessment. This dissertation advances the design space of passive haptic training platforms, and establishes a foundation for future systems designed to deliver realistic, safe, and repeatable training experiences that enable health practitioners to further develop and refine their clinical skills.

Chapter 2

Related Work

This chapter provides the background needed to situate this work within prior research. First, I review haptic simulators for medical training, highlighting the relative abundance of systems for procedural and surgical practice compared to the more limited focus on supporting diagnostic skill development. Second, I discuss haptic devices for learning and training to position this work within broader efforts to support skill acquisition through interactive haptic systems. Third, I examine soft surface design for haptic simulators, focusing on approaches that approximate the compliance and deformation of objects. Fourth, I review methods for customizing the mechanical behaviour of 3D-printed objects, which inform techniques for producing tailored motions and interactions. Fifth, I explore multi-purpose passive haptic devices, emphasizing strategies that enable reuse and adaptability across different scenarios. Finally, I discuss haptic fidelity, framing the trade-offs between realism, cost, and accessibility that inform the design choices in this work.

2.1 Haptic Simulators for Medical Training

Haptic technology has transformed interactions between humans and both physical and virtual environments, enhancing the way we perceive, manipulate, and learn from tangible and digital systems (Shaikh et al., 2017); as a result, its application in the medical sector has emerged as a natural progression, where the sense of touch plays a critical role in patient care.

Haptic simulators for medical training have emerged as a means to support the development of procedural skills (Coles et al., 2011) and improve clinical competence (Pacheco-Barrios et al., 2024). In medical practice, touch is not only complementary but fundamental (Lelevé et al., 2020), as tasks like surgical procedures or physical examinations often rely on the ability to interpret forces, stiffness, and subtle variations in tissue response. Developing these skills requires hands-on experience, which cannot be fully achieved through passive learning methods such as lectures or demonstrations (Escobar-Castillejos et al., 2016).

However, acquiring hands-on experience in real clinical settings is often constrained. Allowing novices to practice directly on patients raises ethical, safety, and liability concerns (Shi et al., 2021), as errors may result in discomfort or harm. Furthermore, exposure to specific conditions is unpredictable (Coles et al., 2011; Riener et al., 2004; Shi et al., 2021), meaning that learners may need to wait until encountering particular cases in practice to fully understand them. This is especially limiting for conditions that are rare or require repeated interaction to develop proficiency.

Haptic simulators help address these challenges by providing controlled and repeatable environments for hands-on practice. These systems enable learners to develop tactile and

procedural skills in a safe setting by reproducing conditions and responses encountered in medical environments. In doing so, they help bridge the gap between theoretical knowledge and practical application, offering a more accessible and effective pathway for clinical skill development (Pacheco-Barrios et al., 2024). Building on this idea, the work presented in this dissertation extends the application of haptic simulators to other areas of medical education, specifically health sciences and kinesiology. The following subsections (subsection 2.1.1 to subsection 2.1.3) review existing work across multiple medical domains, which highlights that health sciences and kinesiology have received comparatively less attention.

2.1.1 Surgical Procedures

One area that has received considerable attention is surgical procedures and skills, where researchers have devoted substantial time and effort to developing training systems (Coles et al., 2011; Morgan et al., 2017; Thomas et al., 2014) for novice surgeons. Some of the most popular include dental procedures (Bandiaky et al., 2024), suturing procedures (Marshall et al., 2006), minimally invasive procedures such as endoscopy (Delorme et al., 2012), punctures (Felten et al., 2025), laparoscopy (Park et al., 2013), and orthopedic procedures such as arthroscopy (Heng et al., 2004; Morgan et al., 2017). Across these domains, a common approach is the use of force-feedback haptic devices in combination with a visual interface such as virtual reality, augmented reality, or a conventional screen. In these systems, the user typically interacts through a handheld device, such as a stylus or instrumented tool, which reproduces forces, resistance, and tissue-like interactions encountered during procedures. This coupling of visual and haptic feedback allows novice practition-

ers to practice and refine motor skills in a controlled environment that approximates real surgical manipulation.

2.1.2 Organ Exploration

More recently, haptics has been integrated with mixed reality systems to recreate the tangible properties of organs for preoperative exploration and planning (Reinschluessel et al., 2019, 2021, 2023). Research in anatomy education suggests that firsthand experience of anatomical structures improves learning outcomes (Johnson, 2002), which in turn indicates that presenting information in a realistic physical form may also benefit surgical outcomes. Reinschluessel et al. (2019) combine 3D-printed organ models with a VR environment to enable interactive exploration of medical imaging data. The authors converted medical scans into digital 3D models, which are then physically fabricated and linked to their virtual counterparts. Interaction with the tangible models is reflected in VR, allowing users to simultaneously benefit from physical manipulation and immersive visual feedback. Later, Reinschluessel et al. (2021) conducted a study investigating how the size of tangible, 3D-printed liver models affects interaction with medical data in VR. The authors fabricated multiple liver replicas in different scales using nylon and paired them with corresponding virtual representations of medical imaging data. These physical models were used as handheld controllers within a VR environment, allowing 14 surgeons to manipulate and explore the associated anatomical information.

2.1.3 Rehabilitation

Haptics for rehabilitation has also seen significant development (Pacheco-Barrios et al., 2024), particularly through robotic platforms and exoskeleton-based systems (Ai et al., 2018; Kong et al., 2021; Rätz et al., 2024). Kong et al. (2021) developed a realistic 6-DOF upper-limb simulator intended to train therapists in rehabilitation maneuvers for conditions such as spasticity, characterized by involuntary muscle stiffness, tightness, and spasms resulting from nerve damage. Ai et al. (2018) introduced a haptic interface integrated into a robotic ankle rehabilitation platform, providing force feedback and sensing capabilities to enable controlled interaction during therapeutic exercises. Similarly, Rätz et al. (2024) presented a post-stroke rehabilitation system that engages the full hand in upper-limb therapy through distributed force feedback, simulating contact with physical objects to support functional hand movement training. In a related approach, Lai et al. (2023) proposed a soft robotic glove for hand rehabilitation, featuring bidirectional actuation and sensing to both assist and resist finger movements, thereby enabling controlled, guided rehabilitation exercises in a wearable form factor. Pinto et al. (2019) presented a preliminary haptic surface for hand rehabilitation and sensory re-education, consisting of an interactive interface that users manipulate through hand movements during training exercises aimed at improving functional motor control.

2.1.4 Physical Assessment Maneuvers

A limited number of systems provide training for novice practitioners and opportunities to learn manual physical assessment of injured limbs without involving real patients.

A notable example of haptic interfaces for physical assessment is *SpinalLog* (Chacon et al., 2019), which is a tangible spine model equipped with sensors to help medical students receive real-time feedback on spinal mobilization through passive haptic sensations and visual feedback. However, SpinalLog's sensors are foam-based and may degrade under prolonged and repeated deformation. In addition, the system does not include soft-tissue emulation of the back. Without a compliant layer above the vertebrae, the simulator lacks the fidelity required to closely reproduce the feel of a real human back. These limitations reduce SpinalLog's ability to provide a fully immersive and realistic training experience. Earlier lower-limb approaches include a simulator that records limb manipulation motions and uses computational models to estimate joint forces, which are then conveyed to users through a haptic device (Giles et al., 2018). While this system provided compelling feedback, its reliance on an active mechanism increased cost and made the haptic experience less natural. Another physical system reconstructed the anatomy and ligament structures of the knee joint to support teaching of ligament function and manual instability testing (Wirz and Jakob, 1999). This simulator employed fiberglass-reinforced plastic for the limb and steel wires to represent ligaments; however, it lacked soft tissue coverage, resulting in limited tactile realism and reduced haptic fidelity. More recently, Tatsuzawa et al. (2025) presented *vARtebrae*, a tangible user interface (TUI) that incorporates 3D-printed metamaterials and a silicone layer to replicate the physical fidelity of the human lower back anatomy. vARtebrae features a magnetometer-based sensor system capable of accurately measuring deformation and providing objective visual feedback via an extended reality (XR) app. The vARtebrae system has the potential to improve spinal mobilization training, yet it is primarily demonstrated as a compact prototype, with evaluation focused on

feasibility and interaction rather than clinical validation or comprehensive biomechanical realism of spinal motion.

My work aims to extend this body of research by focusing on manual physical assessment of injured joints. As discussed above, prior work has explored human back assessment through systems such as SpinalLog and vARtebrae, while knee assessment has received some attention, primarily in earlier high-cost simulator platforms. Unlike SpinalLog and vARtebrae, which focus on guiding user movements and teaching procedural techniques, the work presented throughout this dissertation emphasizes the simulation of haptic and visual cues that practitioners rely on during diagnostic examination. In particular, it prioritizes realistic soft-tissue representation and biomechanical behaviour, ensuring that the perceived joint response closely reflects both normal and abnormal conditions. Furthermore, similar to SpinalLog and vARtebrae, domain experts, including students and instructors, were actively involved in the design process to inform the development of the technology presented in this dissertation.

2.2 Haptic Devices for Learning and Training

Low-cost, interactive, and modular haptic devices have gained attention as accessible solutions for education and training (Minaker et al., 2016), particularly in Science, Technology, Engineering, and Math (STEM) education. I discuss some below. Within this context, my work builds on these efforts by developing interactive, touch-based systems that support skill development through physically grounded experiences. The goal is to bridge theoretical knowledge and hands-on practice while maintaining accessibility and scalability.

Haptic paddles have been widely adopted for teaching a variety of lessons, as their simple, one-degree-of-freedom design enables them to be easily programmed by students to create haptic virtual environments. *Hapkit* (Martinez et al., 2016, 2020; Morimoto et al., 2020) is a low-cost, 1-DOF kinesthetic feedback device that provides haptic feedback through a handheld handle, allowing users to physically interact with and experience fundamental concepts in math, physics, and dynamics. The modularity of Hapkit has enabled the creation of more complex configurations, such as pantograph and serial mechanisms. *Graphkit* (Martinez et al., 2017) is a 2-DOF pantograph-like kinesthetic haptic feedback device. It is similarly used in science courses, allowing students to physically explore concepts across mathematics, physics, and engineering with more nuanced feedback. *Haplink* (Martinez et al., 2017) is another kinesthetic haptic device that can operate as either a 1-DOF or 2-DOF device, offering greater flexibility than Hapkit or Graphkit. These three devices are open-source and can be assembled by students (i.e., end users). *The Haply Development Platform* (Ding and Gallacher, 2018; MacLean et al., 2021) is another multi-degree-of-freedom pantograph that enables developers to leverage the same hardware and software architecture to implement force-feedback and vibrational haptic interactions ranging from 1 to 4 degrees of freedom. These systems have largely maintained a grounded design, requiring attachment to a fixed surface such as a table to ensure stable force feedback during interaction.

Alternatively, work in the wearable devices domain has explored approaches that offer greater mobility compared to grounded paddle-based designs. In addition, wearables can be simple, portable, and cost-friendly. Systems like the *TESLAGLOVE* (Fouad et al., 2023) and the *Immersion CyberGrasp* glove (Liu et al., 2017) have been used for educational

purposes. The *Hand-Held Haptic Kit* (H^3Kit) (Bloom et al., 2024) is a body-grounded, kinesthetic feedback device for STEM education that generates force feedback through a paddle and simulates environments such as virtual springs, walls, and viscous damping forces. Furthermore, *Snaptics* (Zook et al., 2021) is a collection of actuation modules, namely "Stretch," "Twist," and "Vibration," developed to enable rapid prototyping of fully wearable multi-sensory haptic devices. This teaching tool has been used to teach concepts in dynamic systems, control systems, mechatronics, and haptics.

My work extends this line of research to disciplines beyond STEM education. It inherits the emphasis on low-cost, physically grounded, and easily accessible interaction for learning, as well as a focus on modularity. In particular, in chapter 4 and chapter 5, I further investigate scalability and modularity, demonstrating how these design principles enable flexible adaptation across different training scenarios and support broader deployment in educational settings.

2.3 Soft Surface Design for Haptic Simulators

In physical examinations, healthcare practitioners often must place their hands on a patient's skin surface. These interactions suggest an opportunity to leverage existing approaches for customizing the softness of objects and surfaces, as explored in areas such as soft robotics, in order to allow for a more realistic feeling of skin and tissue.

HapticPrint (Torres and Paulos, 2015) explores how 3D printing can be used to design not only the shape of objects but also their haptic properties. The approach includes an

external tool that transforms 2D texture images from a library into 2.5D patterns that can be fabricated on 3D-printed objects using desktop 3D printers, while still allowing users to adjust individual texture parameters such as size and spacing. It also introduces an internal tool that enables customization of properties such as weight and compliance by modifying infill patterns or filling internal regions of the model with liquid, paste-like materials. The authors demonstrate the ability to produce soft objects, compliant structures, and components with spatially varying mass distribution. There is value in using semi-automated tools to fabricate soft surfaces and objects. However, the approach presented by Torres and Paulos (2015) primarily produces standard geometric forms (e.g., cubes) and predefined shapes (e.g., a bunny model). While thin structures are relevant to my work, they need to be stretchable and conform to limb-like geometries. In addition, some fabrication steps require manual processes (e.g., pouring liquid materials), which makes the workflow slow and difficult to fully reproduce.

Skin-On is a much more promising approach. Teyssier et al. (2019) explore the design of interactive surfaces that resemble and behave like human skin, enabling more expressive and intuitive human–machine interaction. The work demonstrates a low-cost and simple fabrication approach for covering devices with a soft, skin-like layer embedded with sensing capabilities, allowing the surface to detect deformations such as pressing, stretching, and stroking. The authors use silicone-based materials to create artificial skin that provides a realistic appearance and tactile feel, and they apply it directly to everyday devices such as phones and watches. Subsequently, Teyssier et al. (2021b) expanded this concept by showcasing the broader potential of skin-like layers through flexible, multi-shape sensors integrated onto existing robotic platforms (e.g., the NAO robot). Moreover, they extended

this approach to enhance the anthropomorphism of ubiquitous sensing devices (e.g., webcams) in *Eyecam* (Teyssier et al., 2021a), with the goal of increasing users' awareness of their surroundings. This body of work highlights the potential of skin-like interfaces as a low-cost and scalable approach to enriching both physical interaction and anthropomorphic design. In this work, I directly adopt the same materials and fabrication steps. My focus is on providing healthcare practitioners with an experience that approximates the perception they obtain when placing their hands on a patient's skin, and the approaches presented by the authors align well with this objective. In addition, the low-cost and flexibility of this approach are consistent with the goals of my work.

2.4 Customized Mechanical Behaviour of 3D-Printed Objects

In physical examination maneuvers like the Valgus test or the Lachman test, healthcare practitioners rely on haptic and visual cues that may indicate abnormal joint motion. These interactions suggest an opportunity for existing approaches that customize the mechanical behaviour of fabricated objects to mimic such diagnostic phenomena. For example, varying material composition, stiffness, compliance, and geometry, particularly in flexible structures, can enable controlled compression, bending, or elongation to reproduce the exaggerated motions similar to those encountered in the Valgus and/or Lachman test.

Researchers exploring the customization of mechanical behavior in objects have investigated structural design strategies that modify the internal geometry of 3D-printed models.

One notable piece of work involved creating objects composed of many internal 3D cells arranged in a regular grid (Schumacher et al., 2015), in which each cell could be designed differently and thus produce many degrees of freedom. This led to the concept of *metamaterials* (Ion et al., 2016), artificial structures whose mechanical properties are determined not by the base material they are made of, but by their typically repetitive cellular patterns (Paulose et al., 2015). Based on this concept, researchers have created objects with unusual behaviours, such as metamaterials that collapse abruptly when compressed (Mullin et al., 2007), or objects that mix layers of soft and hard cells in order to emulate different material responses (Bickel et al., 2010).

While metamaterials are typically used for material properties, they can also be shown to function as machines by replicating mechanisms (Ion et al., 2016) through cellular structures where areas can either shear or remain rigid. This cellular structure can be adjusted to produce different effects. For example, Ion et al. (2016) illustrate this idea with a door latch implemented as a metamaterial mechanism, where a single block of material composed of a regular grid of cells integrates the handle, latch, and spring into one unified structure. More recently, this approach has been used to propagate digital signals through bistable springs (Ion et al., 2017), display tactile textures by buckling (Ion and Baudisch, 2019), alter hardness or roughness of structures upon compression (Feick et al., 2023), and enhance texture of objects in virtual reality (Degraen et al., 2019). Moreover, such methods show potential for serving as material descriptors in systems that translate texture images into stylized 3D models with corresponding tactile properties (Faruqi et al., 2025).

Building on this, my work is inspired by the concept of metamaterials to design and fabricate structures with engineered mechanical behavior that produce controlled move-

ments, which in this context resembling the biomechanics of a human limb in both healthy and injured conditions. This enables the reproduction of the exaggerated or restricted motions encountered in clinical examination maneuvers such as the Valgus and Lachman tests. In addition, I incorporate compliant regions to emulate soft-tissue behavior (e.g., a thigh or a calf area), supporting realistic deformation under applied loads and improving the fidelity of the simulated interaction. Importantly, and consistent with the approach introduced by Ion et al. (2016), I embed all of these behaviors within a single integrated structure, rather than being constructed from multiple separate components.

2.5 Multipurpose Haptic Devices

In clinical practice, healthcare practitioners often encounter varying severities of the same medical condition (e.g., grade 1, 2, or 3 MCL injuries). Beyond this variability, the range of cases they may face is extensive, as the human body contains roughly 350 joints (Neumann, 2016), each of which could present a different condition in a patient examination. Even among patients with clinically normal MCLs, the tactile response perceived by an examiner may vary (Deep, 2014). Designing a dedicated haptic device for every possible condition is therefore neither practical nor cost-effective.

Researchers have devoted considerable effort to developing haptic devices capable of supporting multiple use cases. Over time, this work has largely followed two broad research directions: active haptic feedback (AHF) and passive haptic feedback (PHF) systems. AHF devices employ powered actuators to generate haptic feedback, whereas PHF devices rely on physical structures, mechanical properties, or user-driven interactions to produce the

desired response (McClelland et al., 2017). Given the complexity, specialization, and often high cost associated with AHF systems, this dissertation explores PHF approaches exclusively. Within the PHF literature, several categories can be identified, including prototyping toolkits, grounded kinematic mechanisms, and ungrounded custom-made devices. These approaches are particularly relevant to this work because they emphasize modularity and reconfigurability, where a set of components can be rearranged to support multiple functions, use cases, or forms, or where a core design can be adapted and extended through add-ons.

2.5.1 Prototyping Toolkits

A method that has gained considerable interest is the use of *toolkits*, which consist of a collection of elements that enable the rapid generation of physical substitutes that emulate critical aspects of both the form and function of an object (Feick et al., 2020). Toolkits simplify authoring processes and enable creative exploration (Ledo et al., 2018). Feick et al. (2020) constructed *Tangi*, a toolkit that comprises four 3D printed *composable shape primitives*, including cubes, triangular prisms, half-spheres, and sticks, each available in three different sizes. While these shapes allow users to approximate several physical objects, some are more intricate, requiring stretching, folding, deforming, bending, and rotating, among other actions. To address this, the authors' toolkit also includes *manipulators*, which are modified versions of the cubes with internal sensors and circuitry that allow for these manipulations. Example applications and use cases of *Tangi* include a bunny toy, a catapult, a crossbow, and a robotic arm. Arora et al. (2019) utilized shapes based on

LEGO bricks in their work. *VirtualBricks* is a toolkit designed to facilitate the creation of a diverse range of controllers and props for VR. With *VirtualBricks*, users can experience the tactile sensation of manipulating various objects, including but not limited to weapons, slingshots, fishing rods, and even a DJ board. Additionally, this toolkit enables users to recreate previous haptic devices (Chang et al., 2017; McClelland et al., 2017). In more recent times, Feick et al. (2023) introduced *VoxelHap*, a toolkit that enables users to construct highly functional proxy objects using Voxels and Plates. Voxels are blocks with special functionalities that form the core structure of physical proxies. Plates, on the other hand, increase a proxy's haptic resolution, such as shape, texture, or weight. A use case of VoxelHap is a power drill, where the core pistol-like shape of the drill is implemented with voxels and textures are added by attaching 3D printed plates to some faces of the blocks. Other researchers have utilized compliant, planar, affordable, and easy-to-fabricate structures to develop toolkits. *FlexHaptics* (Lin et al., 2022) facilitates the creation of haptic inputs through 8 mechanical modules that provide reliable force-feedback with embedded beam structures. Each module generates a unique effect, such as resistance, detent, or bounce, while moving along a linear, rotary, or ortho-planar linear trajectory. Using this toolkit, users can resemble a bow for a shooting game. *Shape-Haptics* (Zheng et al., 2022) also includes planar structures for haptic feedback. Its elements consist of a sliding profile and a compliant side spring. During interaction, these two parts engage with each other and deliver variable force feedback. Haptic force feedback can be easily customized by shaping the contours of the sliding profile. Interactive applications of Shape-Haptics include augmented haptic effects on objects like pliers, pump bottles, and VR controllers. Finally, Muehlhaus et al. (2025) recently presented a toolkit designed to support rapid

prototyping and exploration of interaction techniques for arm-based exoskeleton systems. It provides modular hardware and software components that allow researchers to quickly configure and test different control strategies and interaction behaviours without building full custom systems from scratch. The toolkit aims to reduce development effort and accelerate iteration in the design of exoskeleton interfaces for rehabilitation and human assistance applications.

2.5.2 Kinematic Mechanisms

Kinematic mechanisms have been proposed as another method to efficiently design and generate a variety of object representations. *Woodenhaptics* (Forsslund et al., 2015) is a low-cost toolkit for building force-reflecting spatial haptic devices using readily available wooden and mechanical components. The kit is designed to enable rapid prototyping of haptic interfaces by providing a set of modular parts and design guidelines that can be assembled into functional force-feedback systems. *HapLinkage* (Li et al., 2020) is an electromechanical toolkit that facilitates proxy design and building of virtual hand tools. HapLinkage relies on templates of four-bar and six-bar linkages to produce circular, curved, linear, and complex motions, which are commonly associated with popular hand tools (e.g., scissors, pliers, and syringes). Moreover, the toolkit allows for the creation of five different force profiles that mimic the tactile feedback experienced when interacting with these tools. The toolkit has been demonstrated with a variety of applications, including a coffee grinder, fishing, a stick shift (found in vehicles), a syringe, a medicine roller, scissors, spring pliers, spray bottle, paper trimmer, and a saw. These applications showcase the versatility of

HapLinkage in creating haptic interactions for virtual hand tools across different domains. Yang et al. (2022) combines the benefits of compliant structures and tensioning cables to design multimodal reconfigurable kinematic mechanisms. *ReCompFig* includes rigid platforms (stages), flexible rods, sensing cables, and cables that are tightened by motors. The system can be used to create various input devices such as joysticks, sliders, and knobs for graphical user interfaces. It can also be used to develop wearable haptic proxies.

2.5.3 Custom-made Passive Haptics Devices

Finally, researchers have also constructed handheld reconfigurable systems that render a variety of objects and haptic sensations. However, these approaches are inaccessible to broad audiences. *HaptoBend* (McClelland et al., 2017) is a shape-changing prototype that provides haptic feedback for multiple objects. *HaptoBend* allows users to bend the device into 2D plane-like shapes (e.g., a phone or a tablet) and multi-surface 3D shapes (e.g., a flashlight or a hammer). Strasnick et al. (2018) introduced *Haptic Links*, a set of electromechanically actuated physical connections capable of rendering variable stiffness between two handheld virtual reality controllers. In this way, the system creates haptic rendering of diverse two-handed objects, such as a rifle, a bow, a trombone, and a couple of pistols. *Transcalibur* (Shigeyama et al., 2019) is a novel reconfigurable handheld controller that renders a 2D shape by by modifying its mass properties on a 2D planar area. Due to this feature, users can perceive various shapes in a virtual environment, for example, holding a sword, a gun, and a crossbow. Zenner and Krüger (2019) implemented *Drag:on*, a device whose appearance and performance are similar to Transcalibur's. The handheld controller

provides haptic feedback based on drag, i.e., air resistance and weight shift. By using *Drag:on*, users are able to experience the haptic sensation of manipulating a ratchet, a shovel, and a wagon. *HapTwist* (Zhu et al., 2019) is a twistable passive device made of Rubik's Twist to create haptic proxies for distinct hand-graspable VR objects, such as a ping-pong paddle, a steering wheel, a machine gun, and a fishing rod. Some researchers have introduced toolkits that utilize basic, abstract geometric shapes.

Taken together, these approaches highlight both the promise and the current limitations of modular and reconfigurable passive haptic design. Prototyping toolkits suggest a path toward generality, yet their application to the full complexity of the human body and its wide range of injury conditions remains an open challenge, as the literature does not yet provide solutions for individual cases (e.g., knee, elbow, shoulder). Kinematic mechanisms are flexible and expressive, but introduce substantial engineering complexity that can hinder accessibility and scalability. Moreover, custom-made passive haptic devices also tend to be highly specialized and difficult to manufacture. In response to these gaps, in chapter 5, I adopt a more practical direction: the development of a single passive joint design that can be structurally modified prior to fabrication. These design variations modify its mechanical properties and degrees of freedom, allowing the approach to balance adaptability with manufacturability while enabling a single base joint to support multiple use cases without requiring fully custom or highly complex systems.

2.6 Haptic Fidelity

A key consideration in my work is haptic fidelity. In the context of injury assessment training, the simulators I present in chapter 4 and chapter 5 intentionally trade some degree of realism for affordability and simplicity. These are designed to preserve the essential functional cues required for learning and practice, which enables broader adoption without the cost and complexity of highly specialized systems.

Efforts and attempts to define fidelity comprehensively have been unsuccessful (Schricker et al., 2001). Rehmann et al. (1995) investigated over 30 years of research on fidelity and found that there was no agreed-upon single definition for the term. In essence, fidelity can be understood as "how closely a simulation imitates reality" (Alessi, 1988). However, instead of a singular definition, researchers have developed multiple fidelity models in the last decades, each considering a variety of factors.

Vincenzi et al. (2009) compiled a list from research that has focused on structuring and defining various components of fidelity. In essence, this list can be divided into two categories: those that describe physical experiences and those that describe psychological or cognitive experiences. *Physical* fidelity refers to the extent to which a simulator mirrors the appearance, sound, and tactile sensations of a real environment, encompassing various aspects. This includes *visual and auditory* fidelity, which pertains to the level of detail presented by the simulator, as well as *equipment* fidelity, which denotes the simulator's ability to replicate the equipment found in the authentic setting, such as in a flight simulator. Additionally, *motion* fidelity measures the simulator's capacity to recreate the sensation of movement experienced by individuals in the real environment. *Psychological-cognitive*

fidelity, on the other hand, is the degree to which the user is psychologically and cognitively engaged in the same manner when compared to the degree to which a real environment would engage the user. Other facets of fidelity compiled in this list include *task* fidelity, which is the degree to which a simulator replicates the tasks involved in a realistic environment; and *functional* fidelity, which can be described as how the simulator reacts to the tasks and commands being executed by users.

More recently, Muender et al. (2022) proposed the *Haptic Fidelity Framework* as a means to comprehensively describe, understand, and compare haptic feedback systems. The framework locates a system in the spectrum of providing realistic or abstract haptic feedback using the *Fidelity* dimension. It comprises 14 criteria that describe *sensing*, *software*, and *hardware* factors. Within the sensing category, criteria include body location (involvement of specific body parts), body area (extent of body surface involved), stimuli (engagement of haptic receptors), magnitude (intensity and variation of stimuli), sensor integrity (matching of haptic stimuli with system intent), dependency (impact of missing dependent haptic stimuli), and distinguishability (effect of rendering physical properties on perception). Hardware criteria encompass degrees of freedom (capability to provide feedback in same dimensions), precision (detail in creating intended feedback), latency (impact of hardware delay on perception), side effects (creation of unintended stimuli), and constraints (limitation on user movement). Software criteria involve precision (detail in simulating intended feedback) and latency (impact of software delay on perception).

Although this dissertation does not investigate the intricacies of haptic fidelity directly, discussing its background and the various dimensions through which it has been characterized provides important context for understanding the design decisions made in this work,

particularly those aimed at improving the cost-effectiveness, accessibility, and ease of fabrication of haptic simulators for injury examination training. Furthermore, the simulators presented in this dissertation contribute to the emerging area of haptic systems for physical assessment training by introducing a new class of artifacts. As this area continues to develop, researchers and designers may benefit from systematic frameworks that describe the factors influencing haptic perception. Approaches such as the Haptic Fidelity Framework may help analyze simulators and identify opportunities for new designs. Formally classifying the simulators presented in this dissertation using such frameworks is beyond the scope of this work, but this possibility is briefly discussed as a direction for future research in chapter 6.

Chapter 3

TRAIN-KNEE: Developing a Haptic Simulator for Knee Injury Assessment Training

In this chapter, I present the first contribution (**C1**) of this dissertation, the TRAIN-KNEE simulator (Figure 3.1). I discuss its co-design and calibration, its evaluation with multiple clinicians, and the results demonstrating its effectiveness as a haptic training simulator for physical examination of a knee injury. This chapter establishes a foundational design and evaluation that inform the subsequent contributions in this dissertation, specifically in the development of a cheaper, less sophisticated design (C2). Additionally, this chapter also contributes to an emerging research direction, as haptic simulators for physical examination training have received very limited attention in the literature (subsection 2.1.4).

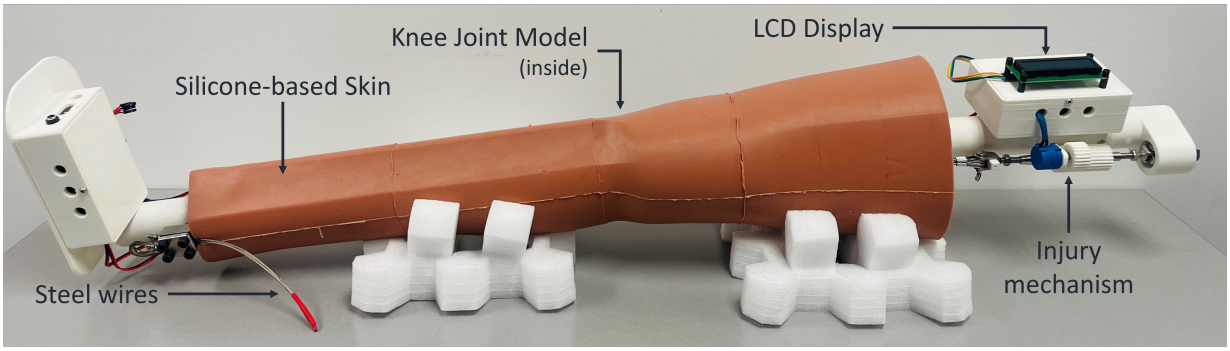


Figure 3.1: *TRAIN-KNEE*: a haptic simulator that uses silicone to mimic skin look and feel, a knee joint model to reproduce knee biomechanics, a tensioning mechanism with steel wires to simulate MCL injury conditions, and a user display for real-time visualization and control of the injury state.

3.1 Introduction

As discussed in chapter 1 and chapter 2, much of the existing work in haptic simulators for medical training has focused on other applications, such as surgical procedures (Coles et al., 2011; Thomas et al., 2014), organ examination (Reinschluessel et al., 2019, 2021), and rehabilitation (Pacheco-Barrios et al., 2024). Even within the musculoskeletal domain, research has largely centered on training interventions aimed at correcting or treating identified issues rather than supporting their detection (Morgan et al., 2017). Comparatively, little attention has been given to simulators designed specifically for musculoskeletal assessment, particularly those supporting the development of diagnostic skills through manual physical examination techniques.

To explore this gap, this chapter focuses on assessment of the medial collateral ligament (MCL) in the human knee. The knee joint comprises multiple structures that are suscep-

tible to injury, including several bones as well as key ligamentous components, namely the cruciate and collateral ligaments. The MCL is a commonly injured ligament (Fetto and Marshall, 1978; Sawant et al., 2004) that consists of a well-defined bundle of parallel fibers that run from the inner side of the femur to the upper inner region of the tibia (Neumann, 2016). Its primary function is to resist valgus motion, or the inward bending of the knee in the frontal plane (Phisitkul et al., 2006). A widely recognized assessment for recognizing damage to the MCL is the Valgus test (Aronson et al., 2010). Conducting the Valgus test involves positioning the patient in a supine position. The examiner then places one hand at the superolateral aspect of the knee, acting as a pivot point, while the other hand is placed at the foot. The medial joint line is palpated while the examiner simultaneously applies an abducting force at the foot, and a valgus force through the knee joint. Figure 3.2 illustrates the Valgus test conducted on a volunteer.

In this chapter, I design, develop, and evaluate TRAIN-KNEE: a passive haptic simulator intended to reproduce the effects of multiple MCL injury conditions and to enable users to conduct the Valgus test. Given the absence of established design guidelines for simulators of musculoskeletal physical assessment, I adopt a high-fidelity engineering approach in order to investigate which aspects of realism are essential and which may be simplified without compromising training value. In this context, fidelity refers to the extent to which the appearance and behaviour of the simulator correspond to those of the system being represented (Mori et al., 2015; Muender et al., 2022). Unlike more mature simulation domains such as interaction with virtual environments (Fang et al., 2023; Simeone et al., 2015), it remains unclear what level and type of fidelity are required when representing a human biological system across healthy and injured conditions. Insights from other fields suggest

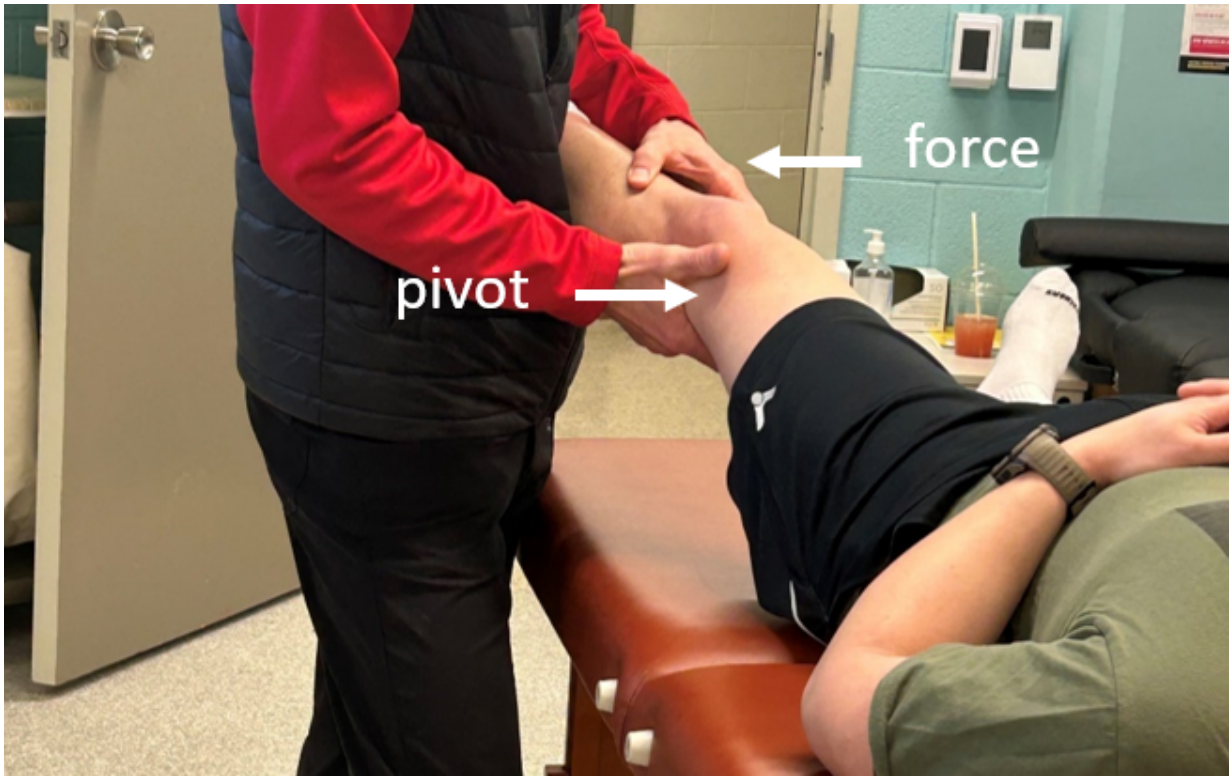


Figure 3.2: The Valgus stress test (Aronson et al., 2010), a widely recognized physical assessment for detecting injuries to the medial collateral ligament in the knee joint.

that haptic fidelity can often be selectively reduced while preserving learning effectiveness (Norman et al., 2012), but it is not yet known how this translates to musculoskeletal assessment training. Due to its relatively simple configuration and well-defined biomechanical function (Phisitkul et al., 2006), the MCL provides a suitable starting point for controlled investigation of injury simulation and assessment tasks.

To design and develop TRAIN-KNEE (Figure 3.1), I worked closely with a clinician from the University of Waterloo, an athletic therapist with over 25 years of experience in athletic therapy and kinesiology, who currently teaches full-time as a clinical instructor in the kinesiology program. In addition to these discussions, I observed firsthand how the Valgus test is demonstrated and taught in his class and how students practice the assessment on their peers. These interactions emphasized the importance of familiarity as a central design criterion, consistent with Bertolo et al. (2025), ensuring that the simulator aligns with the tactile expectations, movement patterns, and contextual cues that practitioners encounter in real clinical settings. Guided by this principle, the clinician and I identified the most pertinent design aspects for a simulator resembling a human-like knee joint, intended to simulate multiple MCL injury conditions. These included:

1. *Anatomy.* The simulator should closely resemble the anatomy of a human knee, encompassing the dimensions and contours of the bones, joint surfaces, and ligaments.

2. *Joint Mechanics.* The simulator should replicate the intricate movements and actions of a human knee joint, encompassing flexion-extension, internal-external rotation, and abduction-adduction.

3. *Materials.* The construction materials used should have properties akin to human skin, such as elasticity, softness, and texture.

4. *Injury Display.* The simulator should mimic multiple MCL injury conditions.

5. *Training Platform.* The simulator should allow users to conduct the Valgus test.

6. *Sensing Mechanisms.* The simulator should be equipped with sensors to 1) capture applied pressure on various locations and 2) offer a metric associated with MCL injury conditions.

To meet with the aforementioned design criteria, TRAIN-KNEE a) incorporates an approach from prior research to emulate the appearance and tactile characteristics of human skin; b) reproduces the biomechanics of the human knee joint; c) simulates multiple injury conditions using a simple electromechanical system; and d) enables users to perform the Valgus test. This chapter also presents the results of three research evaluations conducted with domain experts, including certified physiotherapists and athletic therapists.

3.2 System Architecture

I divide the system architecture of TRAIN-KNEE into four components: a) anatomy and biomechanics, b) skin layers, c) injury simulation, and d) sensing.

3.2.1 Anatomy and Biomechanics

To incorporate bone representations in the simulator, I used a human knee joint model (Walfront, Model: x75z2su03). This model 1) comes with segments of the femur, tibia, and fibula bones; 2) shows the structure and shape of a human knee joint; and 3) illustrates the anatomy and biomechanics of a knee joint. The cost of this model is approximately $32 USD. Since the model does not represent an entire leg, I affixed aluminum members to the ends of the femur and tibia to lengthen them. Additionally, I attached a 3D-printed foot-like piece to enhance its similarity to a human lower limb. A complete mechanical schematic of TRAIN-KNEE is presented in Figure 3.3.

3.2.2 Skin Layers

To mimic the look and feel of human skin in TRAIN-KNEE, I used a bio-driven approach proposed in soft robotics literature (Teyssier et al., 2019), which strives to replicate the main visual and haptic properties and layers of the human skin. The skin is divided into three primary layers (Edwards and Marks, 1995): epidermis, dermis, and hypodermis. The epidermis, the outermost layer, offers both visual and tactile sensations, while the dermis layer functions as the sensory layer, housing the majority of sensory receptors that respond to tactile and kinesthetic feedback associated with touch. The hypodermis layer, situated between the skin and muscles, is the thicker layer of skin primarily used for fat storage.

Since I wanted to provide a realistic tactile and visual experience, I exclusively focused on replicating the *pigmentation* and *texture* characteristics of the skin. Pigmentation provides insights into age, ethnicity, and health (Fink et al., 2006). Texture, which is

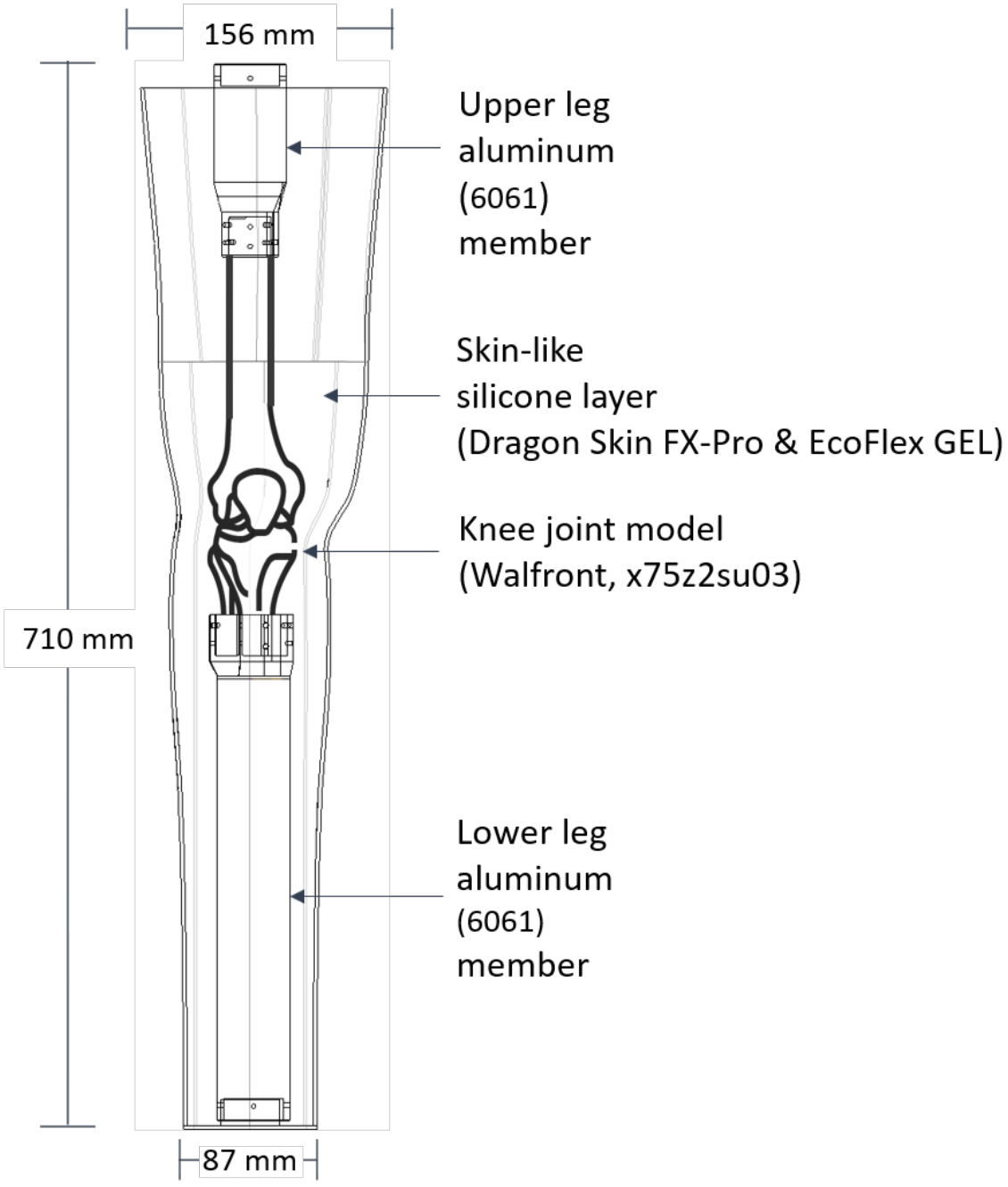


Figure 3.3: a) Mechanical design of TRAIN-KNEE. Full assembly of all fundamental components, including alumnimum members, skin-like layer, and knee joint model.

both visual and tactile, is determined by factors such as pore size and wrinkles (Teyssier et al., 2019). Properties related to biological features (e.g., anatomical barriers preventing pathogens (Joodaki and Panzer, 2018) are outside the scope of my work. This focused approach allows for a practical solution for users requiring realistic skin simulations.

In order to replicate these skin properties, I selected two silicone products from Smooth-On Inc. The first one, *Dragon Skin FX-Pro*, is a platinum-cured silicone that has previously been employed to simulate the epidermis and dermis layers (Teyssier et al., 2019). The second one, *Ecoflex Gel*, has been found to be appropriate for mimicking the hypodermis layer (Wang et al., 2018). To further enhance the visual fidelity, I used medium beige pigmentation. This choice represents only one of many possible skin tones and, consistent with prior work (Teyssier et al., 2019), was selected primarily for prototyping purposes.

I used 3D printing to create molds resembling the upper and lower sections of a human leg. I initiated the process by creating cross-sectional views of a human leg at various heights using Fusion 360 software, and referencing anatomical literature (e.g., Frauziols et al., 2017). I then converted these views into a solid model, which I hollowed out with consistent wall thickness. Due to the model's size exceeding a desktop printer's volume, I divided it into three pieces. Each piece was individually 3D-printed. Subsequently, I assembled the pieces and introduced the bone models with the aluminum members affixed. I then filled the remaining internal volume with the two silicone products, which adhered directly to the bones and aluminum members during curing (Figure 3.4).

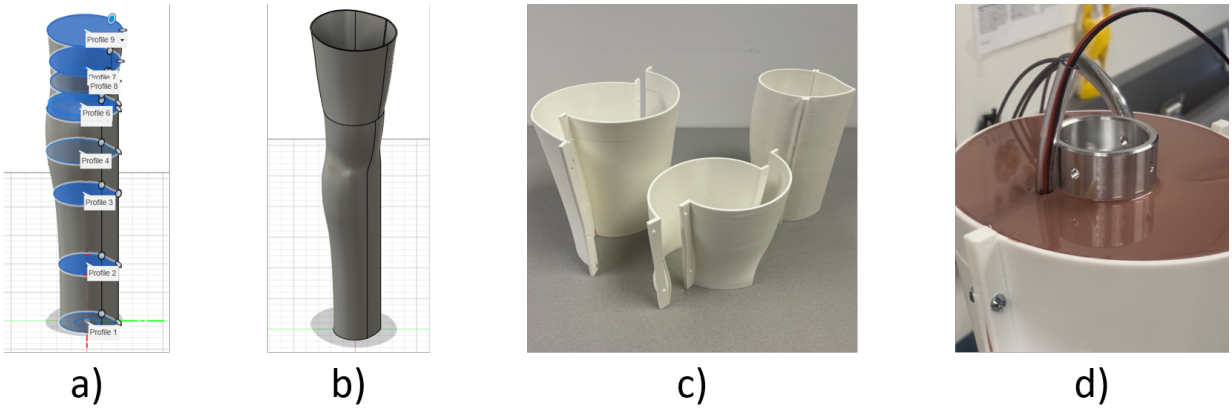


Figure 3.4: Skin fabrication in Train-Knee. a) A leg-like model is generated using cross-sectional profiles of a human leg at multiple heights, with each highlighted region representing a cross-section. b) A hollow version of the model is constructed. c) The model is fabricated via 3D printing in separate components. d) The components are assembled and filled with silicone.

3.2.3 Injury Mechanism

Some background is provided before discussing the details of TRAIN-KNEE's injury mechanism. Fundamentally, ligaments are densely packed collagen fibers that run in the inner region of the knee (Woo et al., 1999), and their primary role is providing stability throughout the knee joint. The MCL spans, on average, approximately 8 to 10 centimeters in length (Andrews et al., 2017). It is commonly damaged by external pressure or strain on the outer side of the knee, which results in a range of injuries such as stretching, partial or complete tearing (Phisitkul et al., 2006).

MCL injuries are categorized into grades (Andrews et al., 2017). Grade 1 tears involve only a few fibers damaged, joint gap (laxity) of about 3-5 mm, and negligible instability of

the knee. Grade 2 tears involve a disruption of more fibers, laxity amounts between 6 mm and 10 mm, and minimal instability. Grade 3 injuries are complete tears of the ligament that result in instability and more than 10 mm of laxity. A healthy condition means the absence of fiber damage and no presence of laxity. Laxity refers to the gap or separation between the femur and the tibia at the joint (Phisitkul et al., 2006). In TRAIN-KNEE, I reproduced laxity in a way that closely mimics the biomechanics of a real human knee.

In order to not only generate laxity but also manipulate its amount, I used a turnbuckle, which is a mechanism employed to modify the tension of wires, ropes, cables, and other tension-based systems (Cai et al., 2019; Roberts, 2011). I mimicked the MCL with four 1/16 inch (1.6 mm) steel wires, whose tension is adjusted by the turnbuckle. As the tension of the wires decreases, TRAIN-KNEE presents increased laxity and approaches an injured condition (i.e., grades 1 through 3). Conversely, when the tension increases, TRAIN-KNEE shows a decrease in laxity, thus approaching a healthy condition. Users can modify the tension by manually turning a 3D-printed gear that rotates the frame of the turnbuckle. I also installed a multi-turn linear potentiometer (variable resistor) with its shaft including a second 3D-printed gear connected to the gear attached to the turnbuckle frame. In this setup, therefore, the gear on the turnbuckle serves as the driving gear, while the gear on the potentiometer's shaft acts as the driven gear and modifies the internal amount of resistance in the potentiometer. If a DC signal were applied across its terminals, any change in resistance would result in a corresponding change in the signal's amplitude as well. In subsection 3.3.1, I discuss how I correlated this amplitude change (i.e., potentiometer reads) with injury conditions. I include TRAIN-KNEE's injury mechanism in Figure 3.5.

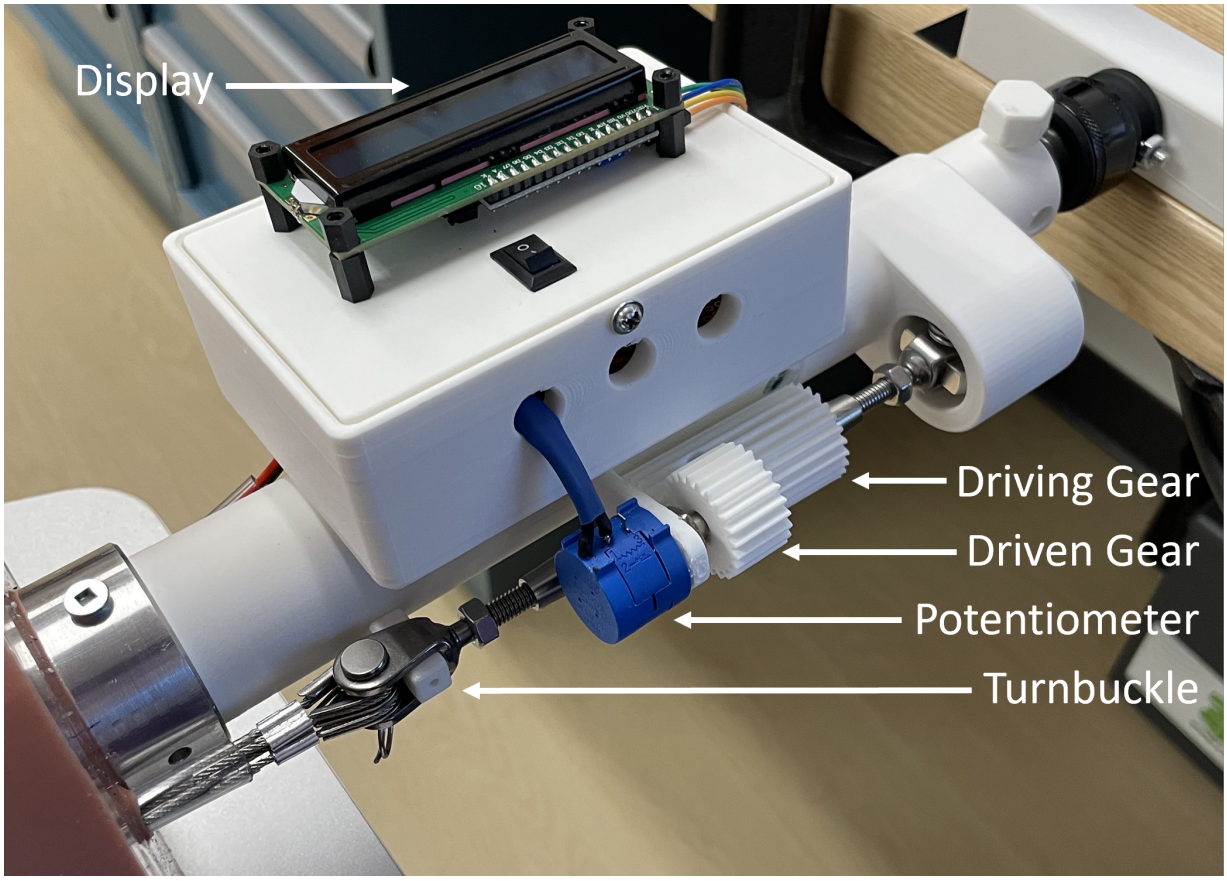


Figure 3.5: Injury mechanism. A turnbuckle holds four 1/16" steel wires mimicking the MCL. The tension of the wires is modified by turning a 3D-printed gear (driving) that rotates the frame of the turnbuckle. A second gear (driven) attached to a multi-turn potentiometer rotates concurrently with the driving gear. A display shows a numeric representation of the signal across the potentiometer.

3.2.4 Sensing

Wires Tension

To estimate injury conditions, the driving gear adjusts the tension in the wires, which causes the driven gear to rotate, changing the potentiometer's resistance and therefore changing the amplitude of a signal across its terminals. I set the potentiometer so that as the tension decreases, the signal (in volts) approaches zero, and vice versa. This signal is then read by an analog input of an Arduino Nano. The analog readings range from 10 to 910 on a 0–1023 scale, reflecting the output of the Arduino's internal ADC. These values indirectly represent wire tension and are mapped to injury conditions ranging from healthy to grades 1 through 3, as described in Figure 3.8. The range does not span the full 0–1023 scale because the potentiometer never reaches zero resistance, and significant tension is achieved well before the maximum limit.

Applied Pressure

To meet the need for on-skin pressure sensing, I embedded four force-sensitive resistors (FSR) in the simulator. The positioning of all FSRs (Model ZD10-100, maximum force: 500 g) in TRAIN-KNEE is on the joint model and on the aluminum members. One FSR is located in the upper section of the simulator, specifically on the outer area of the thigh, and another is positioned in the MCL area. Two additional are placed in the lower section, on the inner side of the shin. The Arduino Nano reads the output signals from these sensors. The placement of the FSR was guided by my collaborating clinician, as examiners often interact with these areas through palpation or applying valgus stress.

Circuit Schematic

The schematic in Figure 3.6 shows the electric circuitry in TRAIN-KNEE. I used two Arduino Nano boards that communicate via HC-05 Bluetooth modules to minimize wiring, which could interfere with the execution the test. The leader board (Figure 3.6a) reads the FSR located within the upper section of the simulator and the output voltage across the potentiometer linked to the injury mechanism, while the follower board (Figure 3.6b) monitors the three FSRs in the lower section. The leader board transmits the readings obtained from the potentiometer's voltage and the four FSRs to a laptop via USB.

3.3 Experimental Methods

I conducted an evaluation of TRAIN-KNEE that consisted of three experiments designed to 1) evaluate its capability to replicate various MCL injury conditions, 2) determine the consistency of injury condition ratings among multiple certified professionals and assess the appropriateness of haptic fidelity, and 3) perform an analysis of range of motion comparing TRAIN-KNEE, configured to represent a healthy joint, with measurements obtained by my collaborating clinician on a healthy individual. This evaluation was approved by the Research Ethics Office at the University of Waterloo under protocol number #43571 - eCampus - Kinesiology Education. The approval was granted on February 22, 2023.

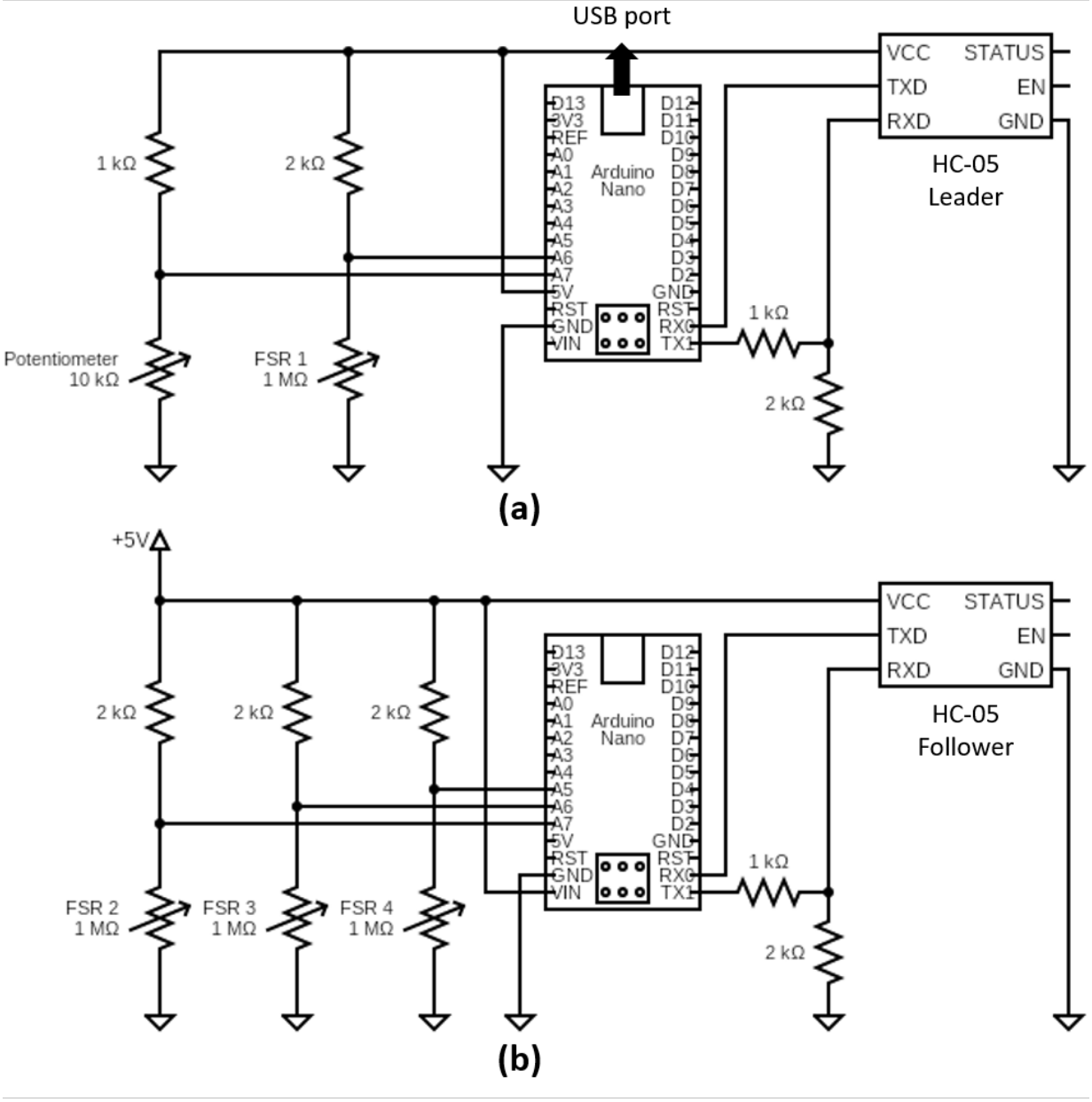


Figure 3.6: Circuit Schematic. a) The leader board reads the FSR located in the upper section of TRAIN-KNEE, along with the voltage across the potentiometer in the injury mechanism. b) The follower board reads the three FSRs in the lower section. The leader board is powered via USB and transmits all four FSR readings, as well as the potentiometer signal, to a laptop.

3.3.1 Experiment 1 Protocol: Mapping Potentiometer Values to Medial Collateral Ligament Injury Grades

In the first experiment, I sought to determine if TRAIN-KNEE could replicate the feel of all MCL injury conditions. If so, my goal was to map the numeric values within the 10-910 range to specific injury conditions. I used the adaptive, up-and-down staircase psychophysics method (Cornsweet, 1962), which efficiently estimates thresholds by adjusting stimulus intensities based on previous responses (Jones and Tan, 2013). In the context of this work, the stimuli were represented by potentiometer values, and users rated each value according to an injury condition (i.e., healthy, grade 1, grade 2, or grade 3). My collaborating clinician was the only participant of this experiment.

3.3.2 Experiment 2 Protocol: Acceptance Test with Experts

In the second experiment, I investigated the consistency of the injury condition ratings defined in the first experiment among multiple certified professionals. Additionally, I studied the haptic fidelity of TRAIN-KNEE by evaluating how closely it resembles a real human knee and how well it assisted users in performing the Valgus test.

I recruited 6 participants (all female) with ages from 30 to 44 ($M = 35.7$, $SD = 5.43$). All participants were certified physiotherapists or athletic therapists. Each participant completed a 30-minute session, providing qualitative and quantitative feedback on the simulator. I remunerated each of the participants with $30 CAD.

Following a brief introduction to the simulator, I encouraged participants to freely interact with it, allowing them to become familiar with its features. After this, I assessed the consistency of the injury condition ratings established in Experiment 1. To accomplish this, I set the potentiometer at a value midway within the range defined for the healthy condition; this value was only seen by the researcher running the study. Participants were then asked to conduct the valgus test (Figure 3.7) and verbally express the perceived condition. This process was repeated for the healthy, grade 1, grade 2, and grade 3 injury conditions. Each condition was assessed twice, totaling 8 trials, and the sequence of these trials was randomized. To conclude, the participants were given a questionnaire to assess the fidelity of TRAIN-KNEE and its capacity to conduct Valgus stress testing. Through this questionnaire, they shared their open-ended feedback on its physical aspects, such as shape, weight, and skin feel.

3.3.3 Experiment 3 Protocol: Range of Motion of simulator

In the third experiment, I conducted a technical evaluation of TRAIN-KNEE by measuring its abduction range in two configurations: a healthy MCL and a grade 3 MCL injury. I used the OptiTrack motion capture system with eight PrimeX 13 cameras and passive infrared reflective markers. I placed five markers on the upper leg and five on the lower leg to capture motion data. Abduction was quantified by measuring the relative angle between the femur and tibia in the frontal plane (Neumann, 2016) using the OptiTrack system. To validate the biomechanical accuracy of the measurements, I conducted a comparative analysis between TRAIN-KNEE in its healthy configuration and a healthy individual with no MCL pre-



Figure 3.7: One of the 6 certified practitioners applying valgus force on TRAIN-KNEE. This research study took place in a clinic at the University of Waterloo.

existing issues. The individual's range of motion was recorded the same way. He wore an Optitrack motion capture suit with markers on his right leg, and the collaboratoring clinician performed the Valgus test on him. This comparison offers a reference point to assess whether the baseline behaviour of TRAIN-KNEE approximates realistic joint mechanics, and supports its potential as a future training tool.

3.4 Results

3.4.1 Experiment 1

To conduct any variant of the staircase method (Cornsweet, 1962), it is essential to define three predetermined parameters: 1) where to start, 2) how large the steps are, 3) when to end. I set the potentiometer reading at 400 in the first place, and established an initial step size of 50 until reaching 3 reversals. Afterward, I modified the step size to 20 and concluded the experiment after 6 reversals at this step size.

Figure 3.8 illustrates the results obtained from employing the staircase method for identifying the three threshold values that distinguish each of the four injury conditions. Determining each threshold involved computing the mean of the peak and valley values of the stimuli at the smaller step size (i.e., 20).

22 trials were required to establish the threshold value distinguishing between the healthy and grade 1 conditions, resulting in a value of 802 ($SD = 15$). In every trial, the clinician assigned an injury condition to the set value, using "0" for healthy and "1" for grade 1. As shown in Figure 3.8a, 13 trials were required to achieve 3 reversals with a step size of 50, and 9 trials to achieve 6 reversals with a step size of 20.

Using the same staircase procedure, I identified the threshold values between the grade 1 and grade 2 conditions as 700 ($SD = 20$) after 17 trials Figure 3.8b, and between the grade 2 and grade 3 conditions as 407 ($SD = 27$) after 16 trials Figure 3.8c. Reasonably, establishing the latter required the fewest trials, given that the initial number (400) was already in close proximity to the threshold value.

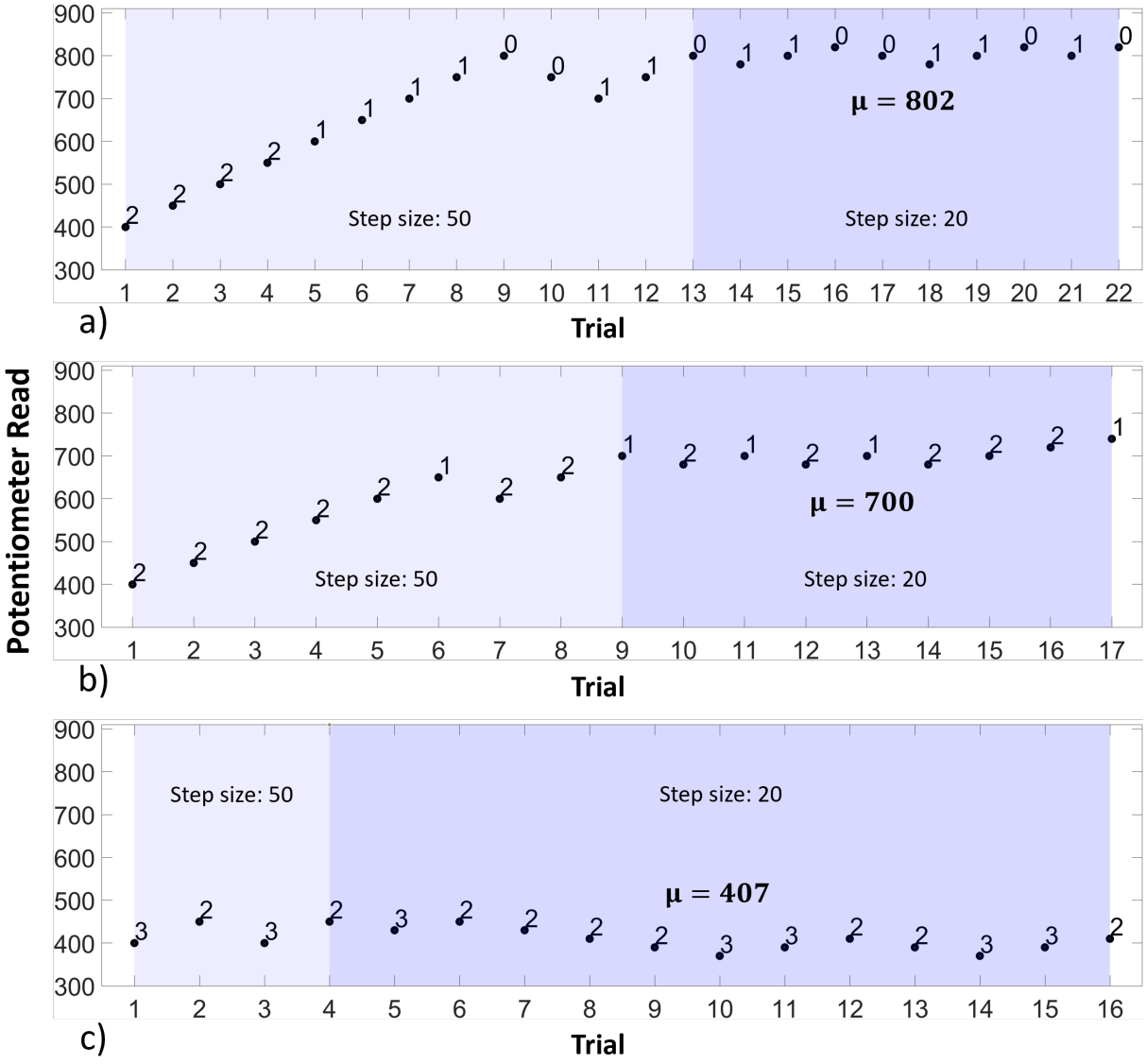


Figure 3.8: Results of adaptive staircase testing to distinguish: a) Healthy vs. Grade 1, b) Grade 1 vs. Grade 2, c) Grade 2 vs. Grade 3 injuries. Means were computed from values in small step-size (20) trials. Light purple shows large step-size; dark purple shows small step-size.

With the simple up-down method, thresholds at the 50% point on a psychometric function are estimated (Jones and Tan, 2013), which means that an individual is equally likely to rate the value of 802 in either healthy or grade 1 condition. Also, an individual is equally likely to rate 700 as either grade 1 or grade 2, and 407 as either grade 2 or grade 3.

To segment the range of values from 10 to 910 and establish intervals for each condition, I excluded values that deviate by two standard deviations above and below each threshold. I chose to report standard deviation to illustrate the variation in the clinicians' individual responses around the mean values. By reporting two standard deviations, I provide a range that includes the majority of the data (approximately 95%). The remaining values available are then used to define the resulting intervals for each condition, as shown by the highlighted regions in Figure 3.9.

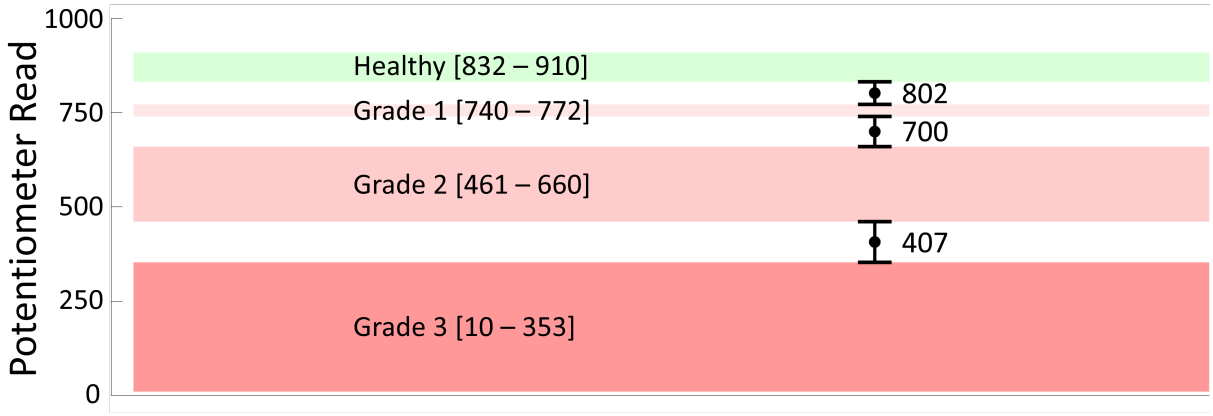


Figure 3.9: Mean potentiometer readings at MCL injury thresholds in TRAIN-KNEE, with bars showing ±2 standard deviations. Highlighted regions indicate value ranges for each injury grade.

3.4.2 Experiment 2

Injury Condition Ratings

For each participant, two of the eight trials expected a 'healthy' response and the remaining six expected an 'unhealthy' response (i.e., grade 1-3). My analysis (Figure 3.10a) showed 10 true positives (TP), where the simulator was correctly identified as healthy, and 36 true negatives (TN), where it was correctly identified as unhealthy. I observed no false positives (FP), indicating that the simulator, when configured as unhealthy, was never misclassified as healthy. However, there were two false negatives (FN), where it was mistakenly classified as unhealthy when configured as healthy. These findings suggest high accuracy in the participants' assessments.

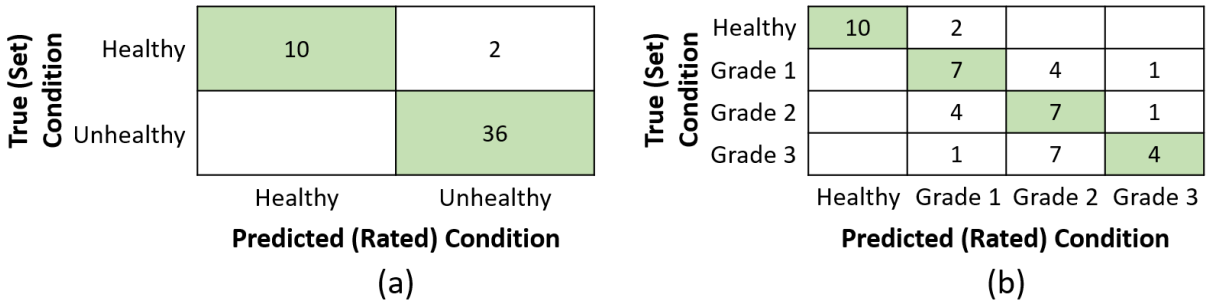


Figure 3.10: a) Confusion matrix for the classification of TRAIN-KNEE's two primary conditions by six participants across eight trials. b) Confusion matrix for the classification of Train-Knee's four conditions by six participants across eight trials.

I calculated the sensitivity (Se), specificity (Sp), accuracy (Acc), and precision (Precis) of the healthy and unhealthy conditions. These are reported in Table 3.1. To reflect the

Table 3.1: Performance metrics of the ratings predicting the two main conditions of TRAIN-KNEE. I summarize sensitivity (Se), specificity (Sp), accuracy (Acc), and precision (Precis). Confidence intervals (95%) were estimated via bootstrap percentiles.

Condition	**Se**	**Sp**	**Acc**	**Precis**
Healthy	0.83 [0.59, 1.00]	1.00 [1.00, 1.00]	0.96 [0.89, 1.00]	1.00 [1.00, 1.00]
Unhealthy	1.00 [1.00, 1.00]	0.83 [0.57, 1.00]	0.96 [0.89, 1.00]	0.95 [0.86, 1.00]

variability of each metric, I include 95% confidence intervals calculated using the bootstrap percentile method.

I also investigated the consistency of the ratings at the different levels of injury (Figure 3.10b). Although the specificity across the four conditions remained high, I found a noticeable variation in sensitivity. The healthy condition had the highest number, followed by the grade 1 and grade 2 conditions, and the grade 3 condition had the lowest. In Table 3.2, I report sensitivity, specificity, accuracy, and precision for each condition as well as confidence intervals (95%) obtained using the bootstrapping method.

Table 3.2: Performance metrics of the categorization system predicting the four conditions of TRAIN-KNEE. I summarize sensitivity (Se), specificity (Sp), accuracy (Acc), and precision (Precis). Confidence intervals (95%) were estimated via bootstrap percentiles.

Condition	**Se**	**Sp**	**Acc**	**Precis**
Healthy	0.83 [0.60, 1.00]	1.00 [1.00, 1.00]	0.96 [0.90, 1.00]	1.00 [1.00, 1.00]
Grade 1	0.58 [0.30, 0.87]	0.81 [0.66, 0.92]	0.75 [0.60, 0.85]	0.50 [0.25, 0.78]
Grade 2	0.58 [0.27, 0.85]	0.70 [0.54, 0.84]	0.67 [0.52, 0.79]	0.39 [0.17, 0.61]
Grade 3	0.33 [0.08, 0.62]	0.94 [0.86, 1.00]	0.79 [0.67, 0.90]	0.67 [0.25, 1.00]

To complete the quantitative analysis, I calculated an overall intra-rater reliability score using Cohen's kappa (κ) (McHugh, 2012). This score measures the consistency with which

my six participants rated the same injury condition on two separate occasions, providing an indication of the reliability of their judgments. The resulting κ was 0.4444, with 95% confidence intervals of (0.4407, 0.4474) obtained using the bootstrapping method.

Haptic Fidelity

I also collected qualitative feedback covering various areas, including anatomy, joint mechanics, skin appearance, and the simulator's efficacy as a training tool in physiotherapy education. This was conducted through a computer-administered survey including three Likert scale statements for rating (Figure 3.11, along with four open-ended questions. These questions gathered opinions on 1) the usefulness of the knee model for educational purposes, 2) the necessity of full skin coverage versus selective coverage for the Valgus test, 3) the essential movements and rotations required for the Valgus test if the knee model were generic, and 4) suggestions for simplifying other components of the simulator without compromising the test's completion.

Regarding the open-ended questionnaire, participants generally agreed that the current state of TRAIN-KNEE would be useful as a training tool for inexperienced practitioners. However, some additional enhancements or upgrades are needed. Multiple participants (*P1*, *P2*, *P4*) mentioned the importance of having anatomical landmarks, such as the joint line and patella, on the knee model. These landmarks would help practitioners identify the correct location for testing and palpation. Some participants highlighted the challenge of accurately differentiating between different grades of laxity on the knee model. They (*P1*,

P3) noted that while the model provides a good approximation, it may not fully replicate the feel of a real knee with higher grades of laxity (i.e., grade 3).

I heard differing opinions on the skin aspect of TRAIN-KNEE. *P1*, *P2*, *P6* expressed preference for having skin covering the entire knee model to enhance its lifelike quality. However, *P3*, *P4*, *P5* suggested that while skin covering may not be essential for the entire knee model, it is important to have it in sections relevant for performing the Valgus test. This includes areas around the knee joint and ankle, where hand placements are typically made during the test.

To aim for a simplified, more cost-effective version of TRAIN-KNEE, the questionnaire aimed to pinpoint the fundamental kinematic requirements necessary for conducting the Valgus test. Flexion-extension was identified as crucial to execute the test, with participants *P1*, *P2*, *P4*, and *P5* suggesting that the knee model should achieve at least 30 degrees of flexion to replicate the conditions of a relaxed leg during testing. Additionally, participants *P1* and *P5* emphasized the importance of hip rotation. Participants *P3* and *P6* noted that if the test is performed at 0 degrees, the amount of flexion-extension required could be reduced.

Overall, there was a perception among participants that most components of the simulator were necessary for conducting the Valgus test effectively. While some areas for potential simplification were identified (i.e., foot and amount of skin), participants generally did not feel strongly about removing or significantly altering any specific component.

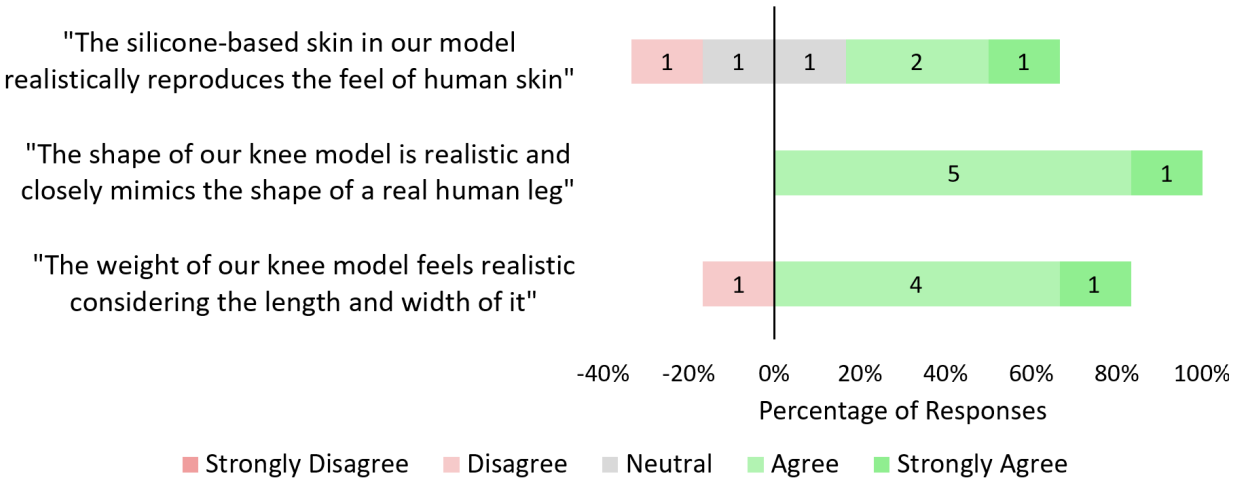


Figure 3.11: Distribution of responses to three Likert scale statements on weight, shape, and skin aspects of TRAIN-KNEE. Each statement was answered by six participants. The number of responses for each category is shown within the corresponding colored region.

3.4.3 Experiment 3

I present the findings of the technical evaluation of the range of motion of TRAIN-KNEE in Figure 3.12. Valgus force was applied more frequently on the simulator than on the real knee, where it was applied only three times. This explains the greater number of peaks and valleys observed in some of the plots. When a valgus force was applied at full extension (zero flexion), the simulator showed an abduction angle of approximately 7° when the steel wires simulating the MCL were adjusted to their loosest tension. Under identical conditions, it showed only 2° of abduction approximately when the wires were set to their tightest tension. In comparison, the real individual without known MCL pre-existing issues showed an abduction angle of roughly 2.75°. These results confirm that TRAIN-KNEE

responds differently depending on the simulated ligament tension and may approximate the behavior of a healthy knee.

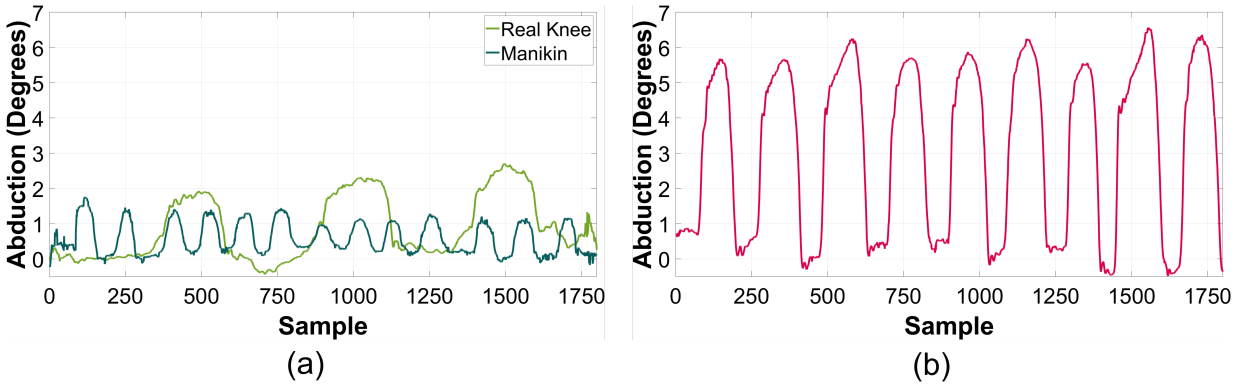


Figure 3.12: Comparative assessment of abduction angles. a) Abduction angle for the healthy knee versus TRAIN-KNEE in a healthy condition. b) Abduction angle in TRAIN-KNEE in an injured condition. Angles were computed from quaternion data collected with the OptiTrack Motion Capture System.

3.5 Discussion

The high-level goal of this work is to evaluate the appropriateness of TRAIN-KNEE as a training tool for inexperienced practitioners in physiotherapy education (i.e., mastering the Valgus test), to explore TRAIN-KNEE's capability to simulate all MCL injury conditions, and to analyze the consistency in the assessment of these injury conditions among multiple professionals. The three-experiment study is a first step toward this higher-level goal by first calibrating with a trained professional (which also provides a proof of concept that the technology is feasible), second attempting to confirm this calibration generalizes to

other practitioners, and third evaluating the range of motion of TRAIN-KNE and how it compares to a healthy knee. I used a mixed-methods approach that incorporates a combination of Valgus test trials, Likert scale responses, and open-ended questions to gather feedback on various aspects of the simulator's design and functionality.

3.5.1 TRAIN-KNEE successfully simulated healthy and unhealthy MCL conditions

The metrics in Table 3.1 indicate that the tension-adjustment method was largely successful in simulating both healthy and unhealthy MCL conditions. The ten true positives and thirty-six true negatives (Figure 3.10a) indicate that, when set to simulate an unhealthy condition, would not be incorrectly classified as healthy, thus highlighting its reliability in detecting unhealthy conditions. The presence of two false negatives suggests that while the simulator is highly accurate, there is still a slight margin for error when identifying healthy conditions. The sensitivity values closely match those reported in existing literature when applying Valgus stress at 30 degrees, but the specificity is substantially higher (Kastelein et al., 2008).

3.5.2 TRAIN-KNEE encountered difficulty in simulating the Grade 1, Grade 2, and Grade 3 injury conditions

The metrics in Table 3.2 say that TRAIN-KNEE struggles to differentiate the severity of injuries. While I obtained high specificity across all conditions, sensitivity values de-

crease as I approach higher injury grades. This suggests that TRAIN-KNEE falls short in reproducing the most severe case of MCL injuries (i.e., grade 3). These findings are also consistent with participant feedback indicating the simulator's inability to accurately reproduce grade 3 injuries. *P3* and *P5* referred to this as the "no-end" condition, characterized by abnormal abduction and significant joint instability (Aronson et al., 2010). One possible explanation is the small difference in abduction angles between configurations of TRAIN-KNEE, with approximately 2° measured in the highest wire tension setting 7° in the lowest. This range may not produce sufficiently different haptic feedback to reflect a complete MCL tear. A potential solution is to loosen up the wires in future iterations.

Several other factors may have contributed to the decreased sensitivity, including the practitioners' level of experience, the varying amount of applied valgus force, the narrow margin that objectively differentiates the multiple injury grades (Phisitkul et al., 2006), the subjectivity in assessing joint laxity (Sawant et al., 2004), and the rarity of isolated grade 3 MCL injuries, which frequently co-occur with other injuries (Sawant et al., 2004).

3.5.3 TRAIN-KNEE has the potential to improve the clinical skills of both experienced and novice practitioners

While the study does not directly measure skill development, literature suggests that practitioners often struggle to accurately diagnose isolated grade 3 MCL injuries through manual knee examinations (Branch et al., 2017). TRAIN-KNEE could be a valuable tool for both experts and novices to gain exposure to these rare cases. However, implementing an objective method to estimate medial laxity in TRAIN-KNEE might be necessary. This

approach would allow us to verify whether the current tension settings for grade 3, which was the condition practitioners had the most difficulty recognizing, are accurate. Even though isolated grade 3 injuries are uncommon (Varelas et al., 2017), I could confidently calibrate TRAIN-KNEE based on objective data, regardless of practitioner experience. If the settings are incorrect, I would recalibrate the tensioning mechanism accordingly. If the objective measure aligns with the grade 3 settings, then the issue is that practitioners need more practice.

3.5.4 Practitioners perceive TRAIN-KNEE's shape and weight to be realistic

The agreement I observed on the realism of TRAIN-KNEE's weight and shape indicates that these aspects were well-received by the participants. Regarding the weight of the simulator, most participants found the weight realistic relative to the simulator's dimensions, but individual perceptions of realism may vary. In terms of the knee model's shape, a unanimous agreement was observed. This consensus is indicative of a successful design and fabrication of the mold created from cross-sectional views of a human leg. Nonetheless, the assessment of the silicone-based skin in TRAIN-KNEE yielded more varied responses. This diversity in perceptions highlights the complexity of replicating tactile properties such as skin texture with synthetic materials. Further refinement of the approach to skin application is necessary. Specifically, the amounts of DragonSkin Pro-Fx and Ecoflex GEL may need to be adjusted, or alternative products may need to be considered.

3.5.5 The tensioning mechanism may be a suitable solution to simulate ligament injuries in future anatomical systems

Fundamentally, ligaments are clusters of fibers that link two or more bones (Woo et al., 1999). Cables and ropes offer a mechanical representation of ligaments, crucial for replicating natural joint stability and movement dynamics. By altering their tension, participants in this research study evidently were able to sense differences in joint laxity, distinguishing between injured and non-injured conditions. Additionally, the method to obtain a metric representative of injury conditions presents a few advantages over traditional solutions for tension measurements. Using 3D-printed gears and a multi-turn potentiometer simplifies the design and troubleshooting processes. Tension transducers, such as an "S" type load cell (Thein, 2013), often require complex calibration and interfacing circuitry. In contrast, potentiometers are easier to install and debug, reducing the time and expertise needed to manage the system effectively. Moreover, this solution is low-cost and easy to replace.

3.5.6 TRAIN-KNEE has the potential to be a platform for education and research

While I did not directly measure learning in the research studies, functional anatomy involves complex mental manipulation of anatomical structures (Berney et al., 2015), which requires a comprehensive understanding that goes beyond simply recognizing and labeling structures (Wirz and Jakob, 1999) in textbooks, didactic lectures, or scaled-down models. TRAIN-KNEE has the potential to alleviate the significant cognitive effort required for

students to comprehend the spatial relationships between ligaments and bones during knee joint movements. Additionally, it could serve as an alternative to cadaveric study as 3D printed models are more durable, reproducible, and cost-effective (Smith and Jones, 2018). Overall, TRAIN-KNEE has the potential to enhance and enrich anatomy education for educators and students alike. Furthermore, knee joint simulators, such as the one I have developed, can serve as a foundation for clinicians, scientists, and engineers to explore research opportunities in various other areas, including conducting gait analysis (Young et al., 2021), providing surgical training through virtual reality (Goh et al., 2021), and implementing techniques for joint angle measurements (Seel et al., 2014).

3.6 Limitations

TRAIN-KNEE has several limitations that should be addressed in future research. The recruitment was limited by physiotherapists' and athletic therapists' busy schedules. The sample size of six, all from the University of Waterloo, may not be representative of the broader population of practitioners, and expanding the participant pool could provide more generalizable results. However, small sample sizes are common and often appropriate in studies involving populations with specialized knowledge, particularly when the goal is to obtain expert feedback. As noted in prior work (Caine, 2016), studies involving expert users frequently rely on small sample sizes to generate meaningful and actionable insights. In this context, the sample size reflects both logistical constraints of working with health practitioners and accepted norms for early-stage evaluation.

TRAIN-KNEE requires the potentiometer readings recalibrated for each injury condition whenever the wires are changed. To simplify this, there are several options to consider. One approach involves developing a standardized calibration protocol that can be easily carried out by end-users after wire replacement. Alternatively, the actual tension of the wires in TRAIN-KNEE could be measured using a portable tension meter (such as a spoke tension meter or a force gauge) to serve as a reference when making a new simulator.

The FSR sensors had difficulty capturing accurate pressure data. One stopped working after the silicone was poured, possibly because of mechanical stress or a loose electrical connection. The remaining sensors were overly sensitive to small forces, producing readings that quickly reached saturation (Scherz and Monk, 2016). This problem occurred because the fixed resistor in the voltage divider circuit was not well matched to the expected force range. Future designs could improve calibration by replacing the fixed resistor with a variable resistor. This will allow fine-tuning of the response once the FSR is embedded in the device. Other possibilities worth exploring include sensor modules made of a combination of conductive and non-conductive foam (Chacon et al., 2019) or soft sensors consisting of a conductive foam with a single wire (Watanabe et al., 2021).

Moreover, TRAIN-KNEE currently only simulates isolated MCL injuries and does not account for conditions such as swelling or concurrent injuries (e.g., ACL tears, bone bruises, PCL or LCL tears, and meniscus tears) that practitioners frequently encounter (Branch et al., 2017; Phisitkul et al., 2006; Varelas et al., 2017). Future work could explore how this method of using wires and a tensioner could be adapted for these additional ligamentous structures.

3.7 Conclusion

Research in haptic simulators for medical education has largely centered on training practitioners in surgical interventions and rehabilitation. Minimal attention has been given to simulators designed specifically for training in musculoskeletal assessment, particularly manual physical examination tests. The work I presented in this chapter offers a step toward addressing that gap. I introduce TRAIN-KNEE, a high-fidelity haptic simulator tailored specifically for simulating the biomechanical effect of MCL injuries and training practitioners in doing the Valgus test (Figure 3.2). The simulator was developed in collaboration with a clinician and evaluated with six certified physiotherapists and athletic therapists. The quantitative results of this expert evaluation demonstrate the ability of TRAIN-KNEE to reproduce both healthy and unhealthy conditions of the MCL, with limitations in reproducing all injury grades (i.e., 1-3). Qualitative feedback highlights the simulator's ability to realistically simulate the look and feel of a knee, with valuable suggestions for enhancements. Moving forward, this work paves the way for the development of haptic simulators for examining joint injuries, potentially revolutionizing kinesiology and health sciences education.

Chapter 4

Flex-Knee: A Low-Cost Passive Haptic Simulator for Injury Assessment Training

In this chapter, I present the second contribution (**C2**) of this dissertation, the Flex-Knee simulator (Figure 4.1). I discuss its development as a more cost-effective alternative to TRAIN-KNEE (C1), and I describe how it expands simulation capabilities to represent a wider range of MCL injury conditions, beyond the healthy and injured binary states simulated by TRAIN-KNEE.

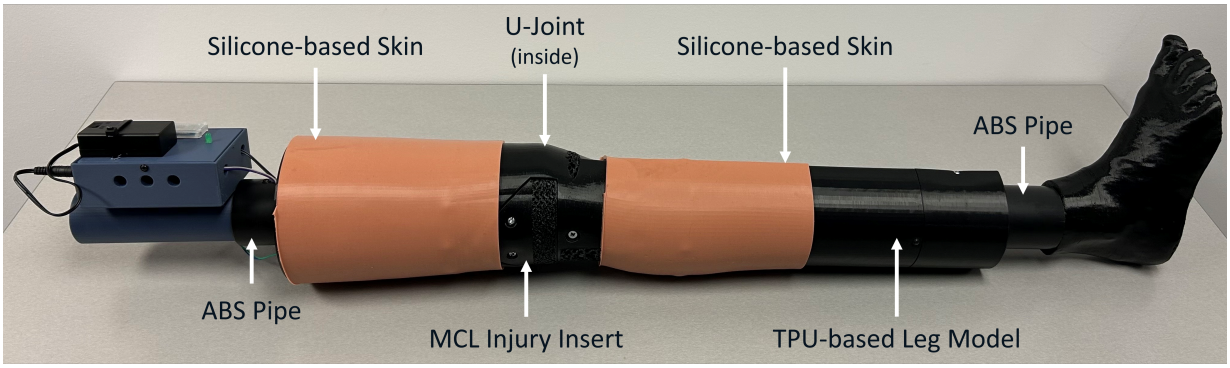


Figure 4.1: *Flex-Knee*: a low-cost passive haptic simulator for MCL injury assessment training. Flex-Knee combines a compliant skin layer, following the approach of Teyssier et al. (2019), with a universal joint that reproduces the primary biomechanical degrees of freedom of the knee during valgus loading. Interchangeable metamaterial-based inserts modulate medial joint stiffness, enabling the simulation of multiple MCL injury conditions.

4.1 Introduction

Training simulators face an iron triangle of fidelity, affordability (e.g., cost), and versatility (e.g., ability to replicate diverse patient conditions). Systems with high fidelity (Mori et al., 2015; Muender et al., 2022) offer accurate tactile feedback, but are often costly and require specialized equipment (Gunabushanam et al., 2019; Pepley et al., 2019), limiting adoption. In contrast, low-fidelity solutions are generally more affordable but often compromise realism, which is critical for effective training (Escobar-Castillejos et al., 2016). Additionally, many simulators struggle to reproduce a wide variety of scenarios that practitioners may encounter in real clinical practice (Pepley et al., 2019).

These limitations highlight the need for training simulators that can balance fidelity with affordability and versatility, while also allowing the underlying system to be readily

adapted to different conditions. In chapter 3, I attempted to address some of these limitations through TRAIN-KNEE, a high-fidelity haptic simulator for MCL assessment training. While the simulator was successful in reproducing healthy and injured conditions, it could not represent categories of injury severity and required considerable engineering expertise and resources to manufacture and assemble. For example, the simulator relied on custom-machined aluminum structural components and a commercially available anatomical knee model that could not be modified. These design constraints limited TRAIN-KNEE's adaptability, scalability, and ability to support anatomical diversity across training scenarios.

In this chapter, I present the design, development, and evaluation of Flex-Knee: a low-cost, scalable, and modular passive haptic knee simulator (shown in Figure 4.1) to support training in the Valgus test (Figure 3.2) for novice health science practitioners. The prototyping cost of a single Flex-Knee unit was $400 CAD. I co-designed Flex-Knee with the same certified clinician from the University of Waterloo that contributed to the development of TRAIN-KNEE. Flex-Knee a) uses an approach presented in prior research to mimic skin look and feel; b) reproduces the biomechanics of a human knee using 3D printing filament and a simple *universal* joint (u-joint) (Roberts, 2011); c) simulates multiple MCL injury conditions through *metamaterials* (Ion et al., 2016); and d) enables users to do the Valgus test. Importantly, Flex-Knee can be manufactured with widely available hardware components and a desktop 3D printer. I validated the design of Flex-Knee through three evaluations involving certified athletic therapists and physiotherapists, as well as kinesiology students enrolled in a Sports Injuries course. Flex-Knee, additionally, shows potential as a flexible platform for supporting multiple musculoskeletal simulation use cases or scenarios.

4.2 System Architecture

To define the system architecture of Flex-Knee, I again collaborated with the same clinician who contributed to the development of TRAIN-KNEE. This iteration aimed to meet the overall criteria outlined in section 3.1 while reducing cost and manufacturing complexity, which required simplifying elements that contribute to haptic fidelity. These simplifications are described in the following sections. Flex-Knee is structured around four main components: a) injury simulation, b) biomechanics and internal soft tissue, c) external soft tissue, and d) sensing and electronics. The components of the simulator and the tools required for assembly are illustrated in Figure 4.2, excluding the electronic elements. A complete bill of materials, including all electronics, is provided in Table 4.1.



Figure 4.2: Disassembled view of Flex-Knee, showing all individual components and the complete set of required hardware needed for assembly.

Table 4.1: Bill of Materials (BOM) for the Flex-Knee Haptic simulator

Part	**Quantity**	**Cost (CAD)**
U-joint and hip joint (PLA)	2.2 lbs	30.00
Leg-like parts (TPU 95A)	2.2 lbs	35.00
Silicone skin layers (DragonSkin FX-Pro)	2 lbs	40.00
Medium beige pigmentation (PMS 479C)	4 oz	25.00
2-inch ABS pipe (hollow)	3 ft	10.00
2-inch solid steel round bar (1020)	0.5 ft	25.00
Ball-and-socket joint (LX-113)	1	30.00
Mounting hardware set	1	15.00
Screwdriver set (MMC-9510)	1	25.00
Pliers set (8379857)	1	30.00
Arduino board (Nano)	1	35.00
Bluetooth module (HC-05)	1	20.00
9-V battery (with holder)	1	10.00
Wiring, connectors, resistors, PCB set	1	20.00
Pressure sensors (FSR 406B)	4	50.00
	Total	**400.00**

4.2.1 Joint Abstraction and Degrees of Freedom

A knee joint possesses three rotational degrees of freedom (DOF): flexion and extension in the sagittal plane, abduction (valgus) and adduction (varus) in the frontal plane, and internal and external (axial) rotation (Fathy and Messiry, 2016; Fujie et al., 1996). I simplified Flex-Knee to the first two DOF, as axial rotation plays a negligible role when the Valgus test is conducted (Aronson et al., 2010). The Valgus test is conducted at either 0° or 30° of flexion (Aronson et al., 2010; Kastelein et al., 2008), and the MCL restricts

motion in the frontal plane (Neumann, 2016). Based on these considerations, I determined that a universal joint (Roberts, 2011), or simply 'u-joint', was sufficient to enable the two motions relevant to the Valgus test. This choice reduces cost and complexity of Flex-Knee and facilitates straightforward adaptation. The use of a standard joint allows us to adapt Flex-Knee to different leg sizes, thus supporting anatomical diversity. Additionally, it ensures compatibility with other standard, readily available components.

I fabricated the u-joint using polylactic acid (PLA) 3D printing filament, incorporating upper and lower hinges and a cross shaft. To reduce filament use, maintain reasonable fabrication times, and allow production with desktop printers, I attached two acrylonitrile butadiene styrene (ABS) pipes to accomplish the length of an entire leg. Inside the pipes, I placed steel round bars with a diameter of 2 in to provide a more realistic weight. I show this in Figure 4.3a.

4.2.2 Anatomical Abstraction and Soft-Tissue Compliance

To mimic the shape and feel of a real leg in Flex-Knee, I followed a structured modeling process in Fusion 360. Referencing anatomical literature (e.g., Frauziols et al., 2017; Neumann, 2016), I began by creating a series of 2D sketches representing cross-sectional views of a human right leg at anatomically meaningful heights. I took views from the ankle, from multiple locations along the calf, from the joint region, and from the thigh. A total of twelve cross sections were used, which provided sufficient and realistic leg morphology. These sketches were then aligned vertically in accordance with their position along the leg. Once aligned, I applied the loft command to produce a continuous 3D model that captured

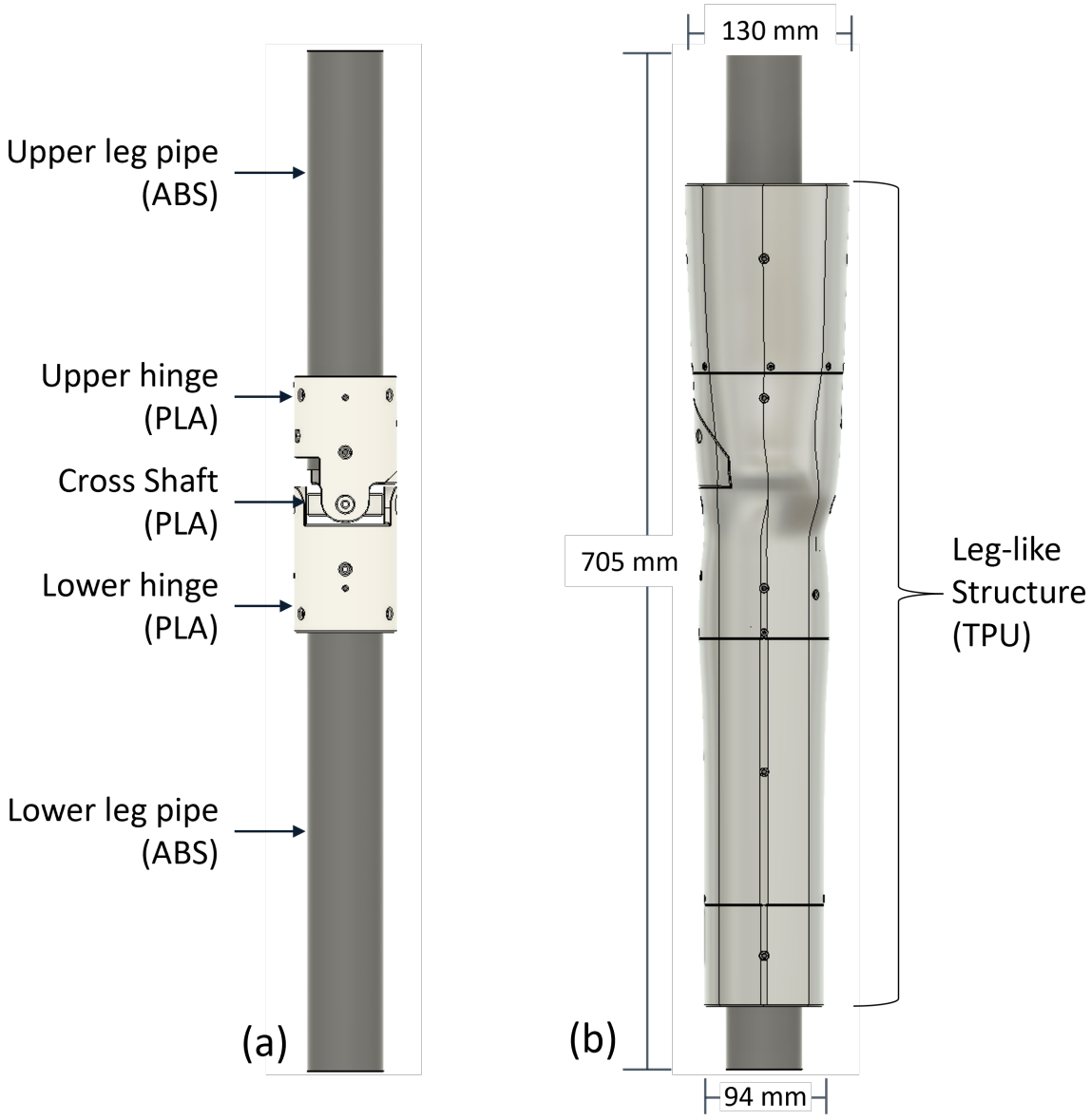


Figure 4.3: Disassembled view of Flex-Knee, showing each component and the required hardware for assembly.

the overall shape of a leg. I then extruded cylindrical sections through the center of the model along its length to fit the u-joint and pipes assembly, as shown in the mechanical schematic in Figure 4.3b.

To simulate the feel of soft tissue, I fabricated the structure using thermoplastic polyurethane filament with a shore hardness of 95A (TPU 95A). In the printer's slicer I used, I selected the gyroid infill pattern at 15% density for soft regions such as the thigh and calf, and at 60% for bony areas including the patella and the medial epicondyle of the femur. The choice of the gyroid infill pattern and density was made collaboratively with my clinician author's feedback. Among the infill patterns evaluated, gyroid was perceived as the most realistic.

In order to achieve compliance of the 3D model with the u-joint and enable flexion-extension, I drew inspiration from HapticPrint (Torres and Paulos, 2015). I customized the internal structure at the back of the 3D model by removing the outer walls and reducing the infill density (12%). This design adjustment allowed Flex-Knee to flex and extend more naturally. This method aligns with metamaterials principles (Ion et al., 2016), in which mechanical properties are tuned through structural geometry rather than by altering the base material.

Finally, to add a realistic skin-like appearance to Flex-Knee and reinforce the perception of soft tissue already provided by the TPU material, I fabricated 1.50 mm silicone layers (sleeves) to cover the upper and lower leg sections (shown in Figure 4.4). I used techniques and materials used in soft robotics literature (Teyssier et al., 2019). Specifically, the DragonSkin FX-Pro platinum-cured silicone has been demonstrated to simulate the

epidermis—the outermost layer of human skin (Teyssier et al., 2018, 2019), which made it well suited for my purposes. Furthermore, I enhanced visual fidelity with medium-beige pigmentation. Similarly, this choice was made primarily for prototyping purposes and represents only one of many possible skin tones.

4.2.3 Injury Simulation

To reproduce the effect of MCL injuries in Flex-Knee, I use a metamaterial-based approach as well. I hypothesized that by modifying the internal structure of a portion of Flex-Knee opposite to the MCL region (see Figure 4.4), I could incrementally reproduce the effect of increased joint laxity and abduction, similar to what happens when an MCL is damaged (Neumann, 2016). With this idea, applying valgus stress on the MCL side would cause a low-stiffness portion on the opposite side to compress, leading to greater joint laxity and increased abduction. In contrast, a high-stiffness portion would resist deformation and limit these effects. In Figure 4.4, the outlined triangle-like portion is the portion whose internal structure is modified to reproduce MCL injuries. For the remainder of this paper, I refer to this variable-stiffness portion as 'insert'.

I considered simulating injuries by varying the tension of ropes or wires on the MCL side, as done in the TRAIN-KNEE manikin (Moran-Ledesma et al., 2025). However, implementing a rope-tensioning system requires additional hardware (e.g., manual or automated tensioner, ropes, clamps, clips). This would increase the cost, introduce mechanical complexity, and require electronic components to define tension for each condition. The



Figure 4.4: Close view of the design to illustrate the injury concept. An injury 'insert' is a triangle-like removable part whose internal structure is customized to reproduce the effect of increased MCL laxity and abduction when valgus force is applied.

compression-based approach I used with inserts provides a simple, passive, and reproducible solution that is more aligned with my goal of building a low-cost educational tool.

To customize the internal structure of an insert, I remove the outer walls (perimeters) and vary the infill density of its base region in a 3D printing slicer. In Figure 4.5, I illustrate this process: (a) the insert as shown in the slicer, where a transparent box overlapping the bottom indicates the region I wish to modify; (b) the print preview, where the low-density infill gyroid pattern is shown; and (c) the final 3D printed insert, with an arrow marking its placement in Flex-Knee. In subsection 4.3.1, I discuss how the infill density at the base of the inserts was mapped to different injury conditions.

Instead of targeting displacements, I worked with a clinician to reproduce the perception of medial joint laxity. While injury grades are clinically defined by the amount of medial joint laxity in millimetres (approximately 3–5 mm for grade 1, 6–10 mm for grade 2, and >10 mm for grade 3) (Andrews et al., 2017), practitioners do not measure displacement directly during the Valgus test. Instead, they rely on the haptic feel of joint laxity and compare it to a healthy knee. My goal was therefore to reproduce the perceived change in movement, and using infill density as a design variable allowed us to accomplish this.

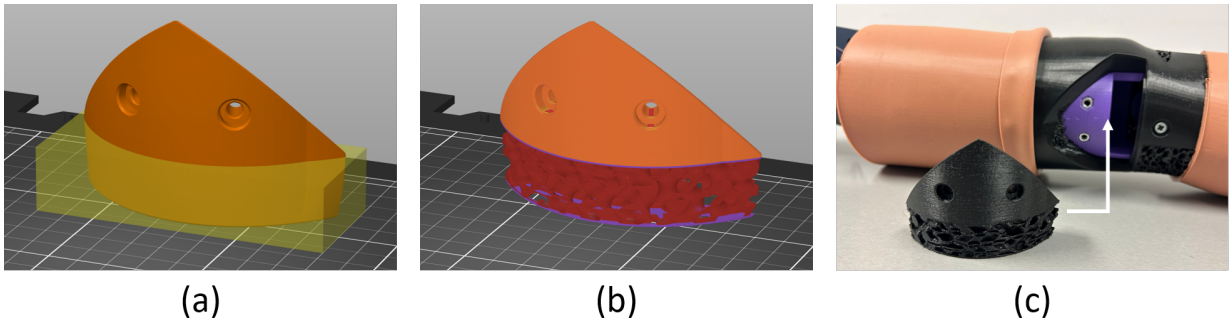


Figure 4.5: Close view of the design to illustrate the injury concept. An injury 'insert' is a triangle-like removable part whose internal structure is customized to reproduce the effect of increased MCL laxity and abduction when valgus force is applied.

4.2.4 Sensing Architecture

To capture pressure applied on Flex-Knee, I embedded four force-sensitive resistors (FSRs). Three of these sensors were placed on the outer area of the thigh, and another was positioned on the MCL area. The placement of the FSR was guided by the collaborating clinician, as examiners often interact with these areas. Once embedded, the baseline re-

sistance of each FSR was measured under the constant pressure of the TPU 95A print. The sensors were then calibrated, and their signals were acquired by an Arduino Nano and transmitted wirelessly to a laptop via Bluetooth.

4.3 Experimental Methods

4.3.1 Internal Evaluation

Range of Motion

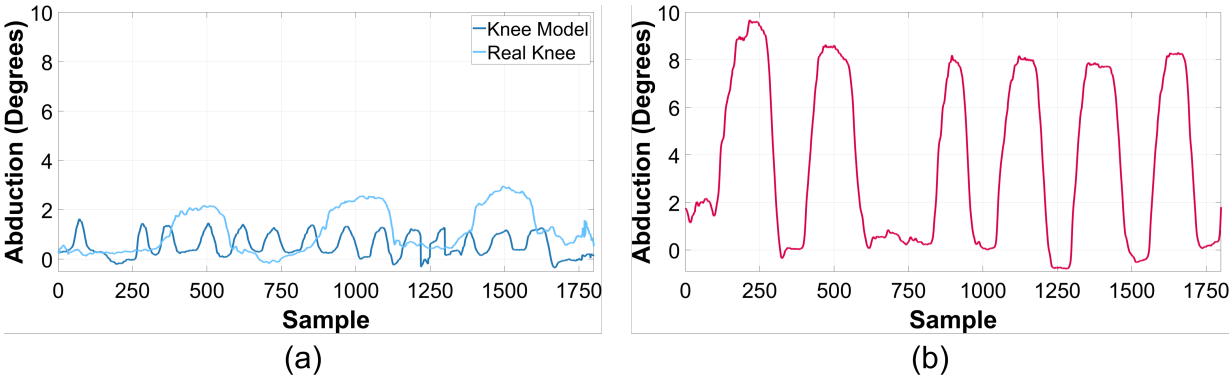


Figure 4.6: Comparative assessment of abduction angles. a) Abduction angle for the healthy knee versus Flex-Knee with the stiffest insert in place. b) Abduction angle in Flex-Knee with no insert in place. Angles were computed from quaternion data collected with the OptiTrack Motion Capture System.

I first conducted a technical evaluation of Flex-Knee by measuring its abduction range in two configurations: a healthy MCL and a grade 3 MCL injury. I used an OptiTrack

motion capture system with eight PrimeX 13 cameras and passive infrared reflective markers. I placed five markers on the upper leg and five on the lower leg of Flex-Knee to capture motion data. Abduction was quantified by measuring the relative angle between the femur and tibia in the frontal plane (Neumann, 2016) using the OptiTrack system. To validate the biomechanical accuracy of these measurements, I conducted a comparative analysis between the Flex-Knee in its healthy configuration and a healthy individual with no MCL pre-existing issues. I obtained this individual's data from the TRAIN-KNEE haptic manikin study (Moran-Ledesma et al., 2025), which used the same measurement technology. This comparison offers a reference point to assess whether the baseline behaviour of Flex-Knee approximates realistic joint mechanics.

I show my findings in Figure 4.6. Valgus force was clearly applied more frequently on Flex-Knee than on the real knee, where it was applied only three times. This explains the greater number of peaks and valleys observed in the plots. When a valgus force was applied at full extension (zero flexion), Flex-Knee simulating a healthy MCL showed an abduction angle of approximately 1°. In comparison, the real individual without known MCL issues showed an abduction angle of roughly 2.75°. Finally, in the absence of an insert (simulating a fully injured MCL), Flex-Knee showed an abduction angle of approximately 8°. These results confirm that Flex-Knee responds differently depending on the insert in place and may approximate the behavior of an actual knee.

Mapping Inserts to MCL Injuries

To map infill density to MCL conditions, I used the adaptive up-and-down staircase method (Cornsweet, 1962) with the collaborating clinician to identify the 50% point of subjective equivalence (PSE) between neighboring conditions (healthy-grade 1, grade 1-grade 2, and grade 2-grade 3).

I began with no insert in place (infill density of 0%) and used a step size of 10 until reaching 2 reversals. Afterward, I modified the step size to 5 and concluded the experiment after 5 reversals at this size. I chose this larger reversal number to assess whether the TPU 95A was becoming deformed, which could lead to a different stimulus. In this context, step size refers to the incremental change in the infill density (%) at the base of the inserts. For this experiment, I made 20 inserts with infill densities ranging from 5% to 100%.

Figure 4.7 presents the results obtained from the staircase method used to identify the threshold infill density at the base of the inserts for each of the four MCL conditions. Each threshold was determined by averaging the peak and valley values at the smaller step size (i.e., 5%). I needed 15 trials to establish the threshold infill density distinguishing between the healthy and grade 1 conditions, resulting in a mean of 33.3 ($SD = 7.0$). In each trial, the clinician conducted the Valgus test on Flex-Knee to assess laxity and rated the set value as a condition, with "0" for healthy and "1" for grade 1. As shown in Figure 4.7a, 7 trials were required to achieve 2 reversals with a step size of 10%, and 8 trials to achieve 5 reversals with a step size of 5%. Using the same procedure, I identified the thresholds between grade 1 and grade 2 at 12.5 ($SD = 2.7$) after 9 trials Figure 4.7b, and between grade 2 and grade 3 at 2.5 ($SD = 2.7$) after 8 trials Figure 4.7c.

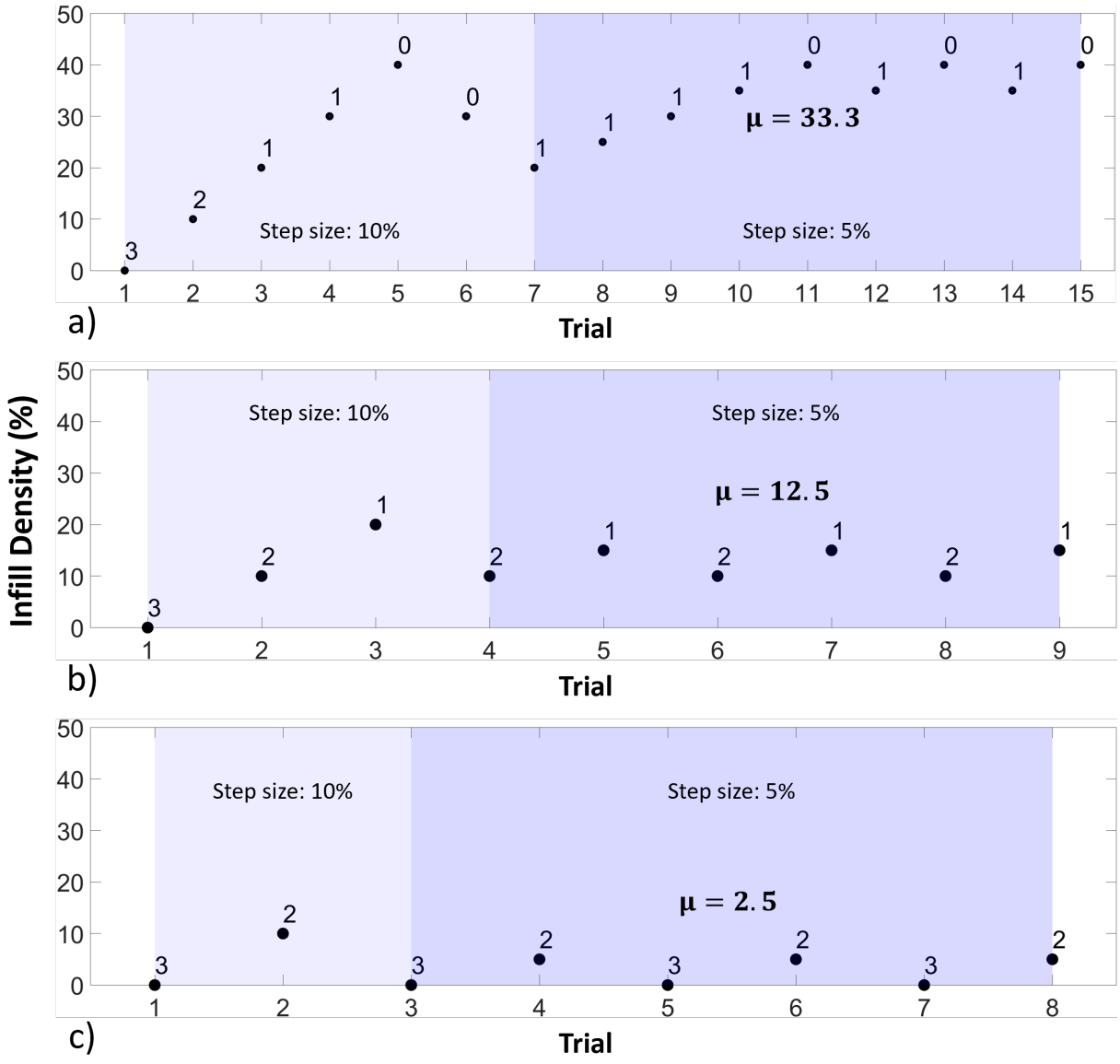


Figure 4.7: Results of adaptive staircase testing to distinguish: a) Healthy vs. Grade 1, b) Grade 1 vs. Grade 2, and c) Grade 2 vs. Grade 3 injuries. Means were computed from values in small step-size trials. Light purple shows large step-size; dark purple shows small step-size. Injuries are coded as 0 = Healthy, 1 = Grade 1, 2 = Grade 2, and 3 = Grade 3.

To segment the range of infill densities from 0% (no insert) to 100% (stiffest insert) and establish intervals for each condition, I excluded values within two standard errors of each threshold, which approximates a 95% confidence interval.

I chose standard error to capture the variability of sample means that would be expected across repeated sampling. The remaining values define the final intervals for each condition, as shown in Figure 4.8.

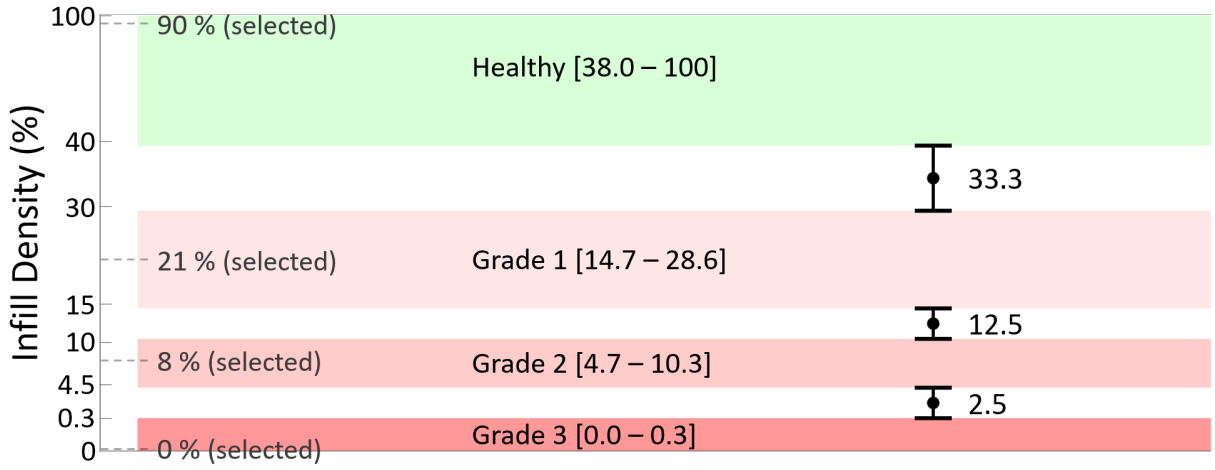


Figure 4.8: Mean infill densities at the base of inserts, with bars showing ±2 standard errors. Coloured regions indicate value ranges for each injury grade. I used 90%, 21%, 8% and 0% (no insert) for each condition in Flex-Knee.

Finally, I chose density values to represent the four conditions, using no insert for grade 3 and 90% infill for the healthy condition to represent both extremes safely. For the other two, I selected values near the midpoints of their respective regions in Figure 4.8, which were 21% for grade 1 and 8% for grade 2.

4.3.2 Study 1: Acceptance Test with Certified Professionals

In this study, I investigated the consistency of the injury condition ratings defined in Figure 4.8 among multiple professionals. Additionally, I evaluated the haptic fidelity of Flex-Knee by assessing its shape, weight, and overall feel compared to a real human knee. This study was approved on April 6, 2025 by the Research Ethics Office at the University of Waterloo under protocol number #47288 - *Enhancing Physiotherapy Training with a Reduced-Fidelity Haptic Manikin.*

I recruited 6 participants (1 male, 5 female) with ages from 22 to 45 ($M = 34.2$, $SD = 9.0$). All were certified physiotherapists or athletic therapists. Each participant completed a 40-minute session, providing feedback on Flex-Knee. I remunerated each participant with $30 CAD.

Following a brief introduction to Flex-Knee, I encouraged participants to freely interact with it, allowing them to become familiar with its features. After this, I assessed the consistency of the injury condition ratings established in Figure 4.8. Participants could see the insert, but the density was only known by the researcher running the study. Participants were then asked to conduct the valgus test (see Figure 4.9) and verbally express the perceived condition. This process was repeated twice for each of the healthy, grade 1, grade 2, and grade 3 injury conditions, resulting in 8 trials (presented in a random order). After the 8 trials, participants completed a questionnaire to assess the fidelity of the simulator and its capacity to conduct Valgus stress testing. Here, they shared their feedback on physical aspects, such as shape, weight, and skin feel.

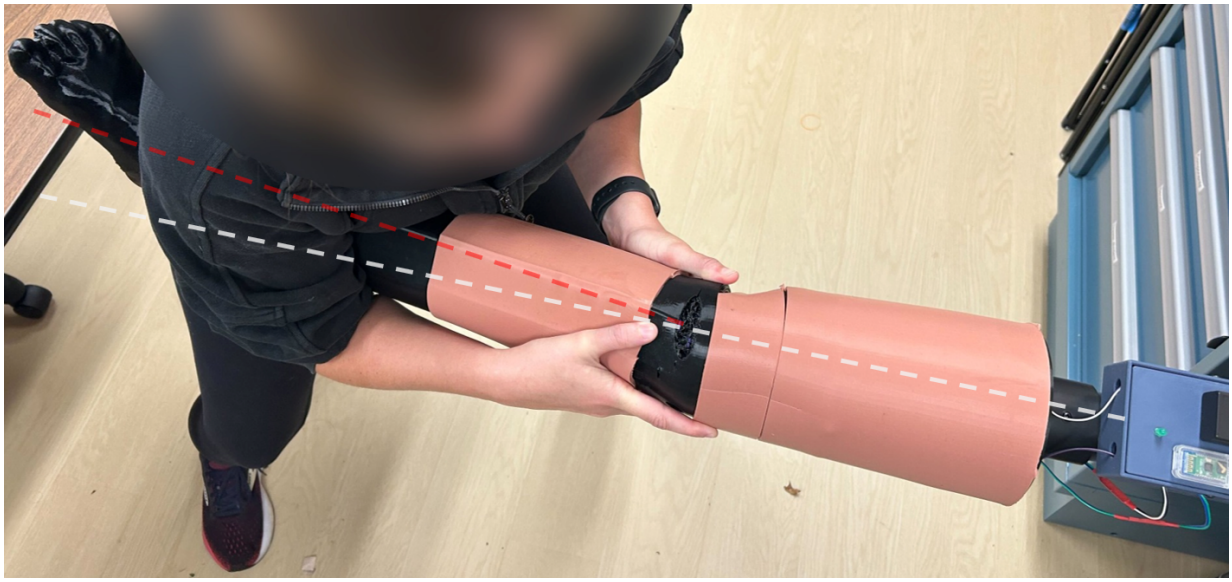


Figure 4.9: Certified professional conducting the Valgus test. The white dotted line represents the longitudinal axis of the femur (coincident with the overall leg axis in the healthy condition), while the red dotted line represents the longitudinal axis of the tibia. Divergence between the two axes under loading indicates altered tibiofemoral alignment consistent with an MCL injury.

Injury Ratings

I analyzed injury conditions ratings by considering 3 increasingly challenging frameworks: Healthy/Unhealthy; Healthy/Partially torn (Grade 1 or 2)/Fully torn (Grade 3) ; and Healthy/Grade 1/Grade 2/Grade 3. This allows us to contextualize Flex-Knee's performance in three different ways of framing the accuracy of the task.

Healthy/Unhealthy. In this framework, two of the eight trials (per participant) expected a 'healthy' response and the remaining six expected an 'unhealthy' response (i.e., grade 1-3). As shown in Figure 4.10a, participants correctly identified 10 healthy (TP) and

36 unhealthy (TN) conditions. There were no false positives (FP), meaning Flex-Knee was never mistaken for healthy when it was configured as unhealthy, but 2 false negatives (FN) occurred where Flex-Knee was misclassified as unhealthy when it was configured as healthy. I calculated sensitivity (Se), specificity (Sp), accuracy (Acc), and precision (Precis) values for this framework and report them in Table 4.2. To show variability of each metric, I include 95% confidence intervals calculated using the bootstrap percentile method.

Healthy/Partially torn MCL/Fully torn MCL. The results for this framework (Figure 4.10b) showed that participants most accurately identified the healthy and complete tear conditions, while partial tears were misclassified slightly more frequently. In some cases, participants rated Flex-Knee as grade 3 when it was configured to simulate a grade 1 or grade 2 injury. In contrast, all trials configured as grade 3 were correctly rated by participants. The performance metrics are included in Table 4.2.

Healthy/Grade 1/Grade 2/Grade 3. Finally, when analyzing the consistency of the ratings at the different grades of injury (Figure 4.10c), I observed that the specificity across the four conditions remained acceptable, but a noticeable variation in sensitivity. The grade 3 condition had the highest value, followed by the healthy and grade 2 conditions, and the grade 1 condition had the lowest (Table 4.2).

To complete the quantitative analysis, I computed an overall intra-rater reliability score using Cohen's kappa (κ) (McHugh, 2012). This measures the consistency with which the 6 participants rated the same condition on two separate occasions, providing an indication of the reliability of their judgments. The resulting κ was 0.5278, with 95% confidence intervals of (0.5061, 0.5322) obtained using the bootstrapping method.

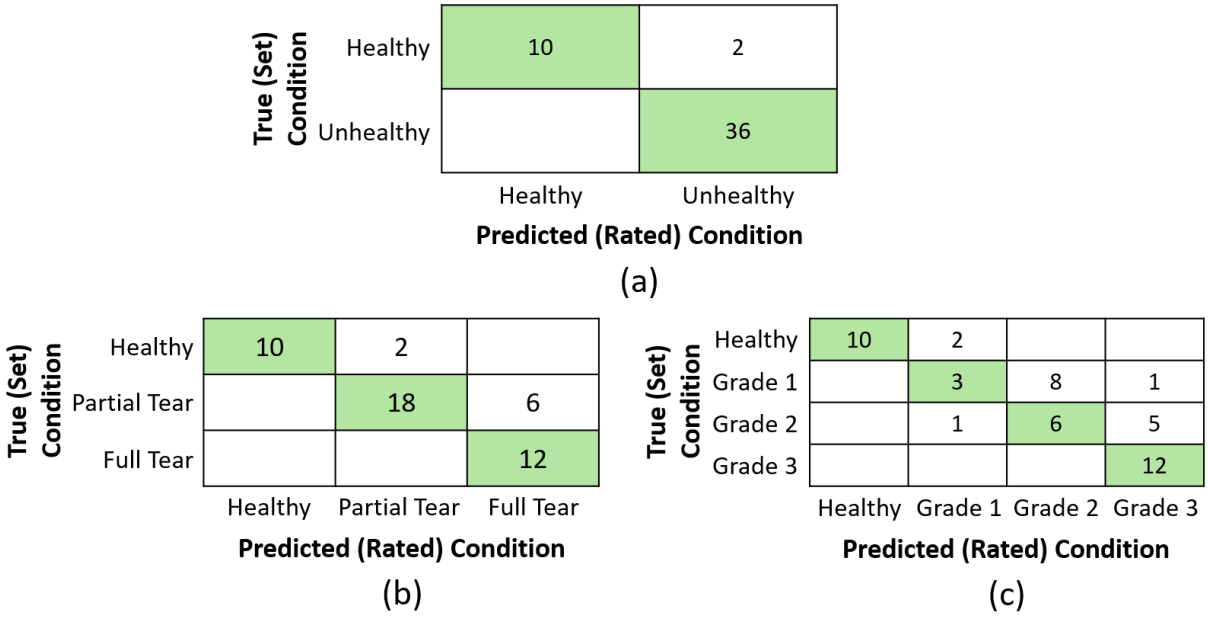


Figure 4.10: Confusion matrices for different categorizations of MCL injury conditions in Flex-Knee. Results are shown for the a) two-condition (healthy vs. unhealthy) and b) three-condition (healthy, partial tear, complete tear) and c) four-condition (healthy, grade 1, grade 2, grade 3) categorizations, based on the assessments of 6 certified professionals.

Haptic Fidelity

I administered three 5-point Likert-type items (Figure 4.11) and four open-ended questions. These evaluated Flex-Knee's potential as a teaching tool, perceptions of partial skin coverage, biomechanical realism during the Valgus test, and opportunities for simplification without compromising the experience.

Participants generally agreed that the current state of Flex-Knee has potential as a useful teaching tool. However, some refinements would strengthen its educational value.

Table 4.2: Performance metrics of Flex-Knee across different categorizations of MCL injury conditions. I summarize sensitivity (Se), specificity (Sp), accuracy (Acc), and precision (Precis). Confidence intervals (95%) were estimated via bootstrap percentiles.

Condition	**Se**	**Sp**	**Acc**	**Precis**
Healthy	0.83 [0.59, 1.00]	1.00 [1.00, 1.00]	0.96 [0.90, 1.00]	1.00 [1.00, 1.00]
Unhealthy	1.00 [1.00, 1.00]	0.83 [0.58, 1.00]	0.96 [0.90, 1.00]	0.95 [0.86, 1.00]
Healthy	0.83 [0.58, 1.00]	1.00 [1.00, 1.00]	0.96 [0.90, 1.00]	1.00 [1.00, 1.00]
Partial Tear	0.75 [0.57, 0.91]	0.92 [0.79, 1.00]	0.83 [0.73, 0.92]	0.90 [0.75, 1.00]
Complete Tear	1.00 [1.00, 1.00]	0.83 [0.70, 0.94]	0.88 [0.77, 0.96]	0.67 [0.44, 0.87]
Healthy	0.83 [0.58, 1.00]	1.00 [1.00, 1.00]	0.96 [0.90, 1.00]	1.00 [1.00, 1.00]
Grade 1	0.25 [0.00, 0.52]	0.91 [0.82, 1.00]	0.75 [0.62, 0.85]	0.49 [0.00, 1.00]
Grade 2	0.50 [0.20, 0.81]	0.78 [0.62, 0.90]	0.71 [0.56, 0.83]	0.42 [0.17, 0.69]
Grade 3	1.00 [1.00, 1.00]	0.83 [0.69, 0.94]	0.87 [0.77, 0.96]	0.67 [0.44, 0.88]

One participant (*P2*) emphasized the importance of allowing users to perform the Valgus test not only at 0° but also at 30°, noting that the MCL is fully isolated at 30° (Kastelein et al., 2008). Flex-Knee primarily supports testing at 0°, or with slight knee flexion.

Participants largely agreed that the partial coverage was acceptable, as it covered the areas where practitioners typically place their hands during the test. One participant (*P4*), however, suggested that skin over the entire simulator would enhance the aesthetic realism of Flex-Knee.

Participants felt the biomechanics of Flex-Knee were fairly realistic, but said that multiple aspects may improve the design. Three participants (*P2*, *P4*, *P5*) expressed the need for more flexion-extension. Another participant (*P1*) mentioned that Flex-Knee felt abnormally stiff when simulating a healthy MCL. One participant (*P6*) mentioned that

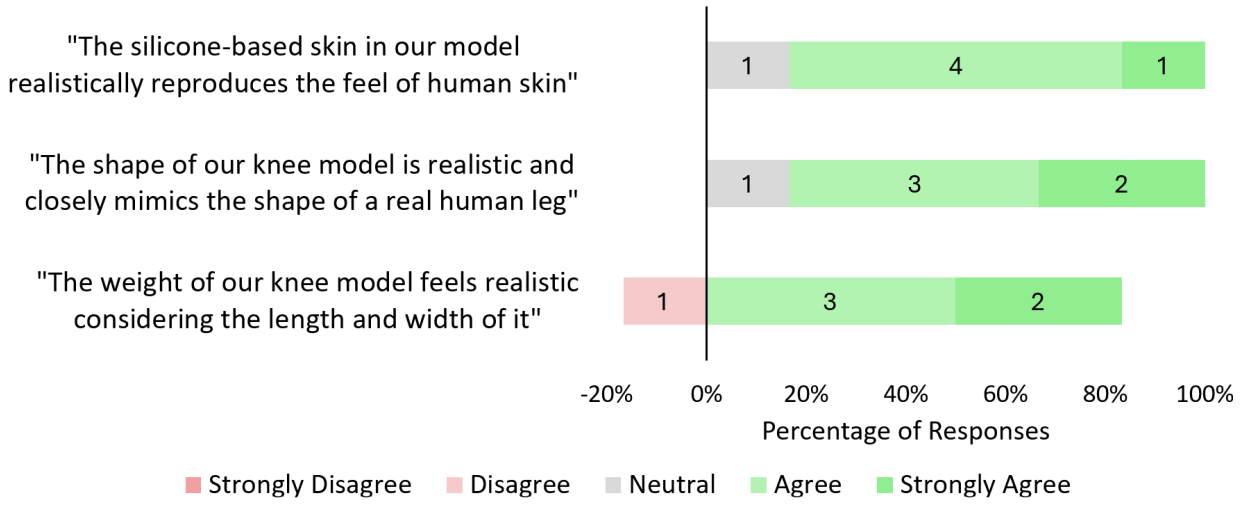


Figure 4.11: Distribution of responses to three Likert scale statements on weight, shape, and skin aspects of Flex-Knee. Each statement was answered by six participants. The number of responses for each category is shown within the corresponding colored region.

incorporating the ability to simulate patient "guarding" (muscle tension increase during the test) would be a valuable enhancement.

Finally, no additional suggestions for simplification were offered. According to two participants (*P3*, *P6*), further sacrifices may compromise its functionality.

4.3.3 Study 2: Showcase of Simulators in Kinesiology Lab

In this study, I showcased three versions of Flex-Knee to 16 kinesiology students (11 male, 5 female) in a kinesiology class who had just been given an introductory lecture on the Valgus test and practiced the maneuver on their classmates. I compensated each student $10 CAD. Each simulator presented a different condition, with one simulating a healthy

MCL, another a partial tear, and the third a nearly fully ruptured MCL. I selected this three-category setup as it was the most successful in the study with professionals (subsection 4.3.2). I used inserts with densities of 90%, 20% and 3%, and this was only known by the researcher conducting the study. Students did the test on each simulator in a randomized order and rated the condition they perceived using these classifications: 'healthy', 'partial tear', 'full tear'. The goal was to explore, as an initial investigation, whether students with minimal prior instruction to musculoskeletal injuries, could do the test correctly and perceive differences consistent with MCL injuries.

I also collected open-ended feedback on students' experiences with the three simulators, focusing on their perceptions of realism, the ease of performing the Valgus test, and the perceived learning potential of Flex-Knee.

To complete this study, I used the Haptic Experience Inventory (HXI) (Kim and Schneider, 2020; Shi and Schneider, 2025) to evaluate students' haptic experience with the three simulators across five dimensions: Autotelics, Realism, Harmony, Discord, and Involvement. With this questionnaire, I aimed to evaluate the intrinsic quality of Flex-Knee as a haptic interface by characterizing students' perceived interaction with the three simulators, independent of their ability to correctly classify clinical conditions.

Injury Ratings

As in the study with professionals (subsection 4.3.2), I analyzed students' ratings using multiple frameworks. However, I limited the analysis to two categories (Healthy/Unhealthy)



Figure 4.12: Students in a kinesiology class interacting with three Flex-Knee simulators and conducting the Valgus test. One simulator simulated a knee with a healthy MCL, another a knee with a partially torn MCL, and the third a knee with a nearly fully torn MCL; students were not informed of these conditions.

and three categories (Healthy/Partially torn/Fully torn) because students lacked clinical experience in patient evaluation.

Healthy/Unhealthy. I expected students to tell us that one simulator was healthy and the other two had a problem (i.e., were unhealthy). This analysis (Figure 4.13a) revealed that across the 16 students who participated, there were 16 true positives (TP) and 30 true negatives (TN). I had no false negatives (FN). However, I encountered 2 false positives (FP), as one person perceived all simulators as healthy.

Healthy/Partially torn/Fully torn MCL. All participants correctly classified the healthy MCL simulator as "healthy" (Figure 4.13b). Flex-Knee with partially torn MCL was also well recognized, with almost every participant perceiving some laxity indicative of a problem, but not enough to classify it as a complete rupture. The Flex-Knee simulator

with the most severe injury was perceived as such by nearly 70% of the participants, while a few still considered it insufficiently loose to simulate a fully torn MCL. These results suggest that students were generally doing the Valgus test correctly, as they were able to perceive the differences I expected across the three simulators.

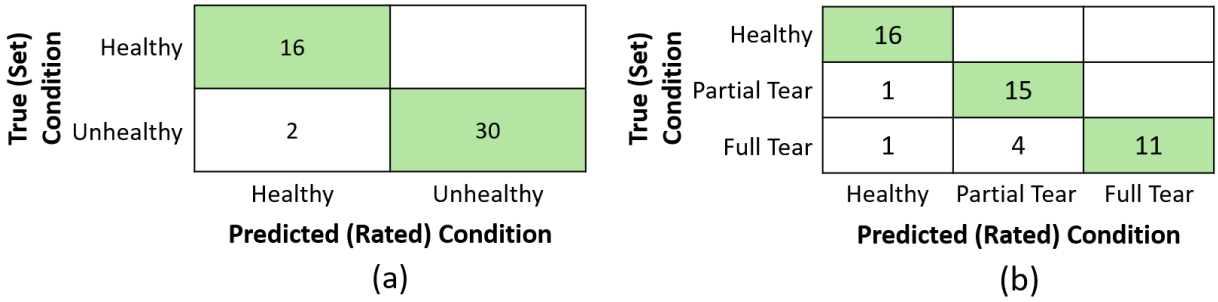


Figure 4.13: Confusion matrices for different categorizations of MCL injury conditions in Flex-Knee. Results are shown for the a) two-condition (healthy vs. unhealthy) and b) three-condition (healthy, partial tear, complete tear) categorizations, based on the assessments of 16 Kinesiology students.

Qualitative Results

I collected answers to six open-ended questions to gain insight into students' experiences using the three simulators. They generally found them to be valuable and realistic tools for practicing the Valgus test, particularly for experiencing different grades of laxity "side by side", which is something they rarely encounter in real patients (*P3*, *P4*, *P7*, *P10*, *P16*). A few reported (*P6*, *P7*, *P16*) that the simulators improved their confidence and helped them better understand what to look for during the test. None indicated that the simulators prevented them from naturally performing the maneuver. Some participants (*P2*, *P9*,

P12) highlighted the simulators' weight, size, and hip-joint setup as contributing to their realistic feel, while opinions on the skin texture were mixed. Many participants (*P1*, *P3*, *P6*, *P8*, *P12*, *P15*) noted that the simulators enhanced their understanding of the Valgus test by allowing them to experience true positive findings and different degrees of laxity not typically observed in classmates or peers. Limitations included restricted knee flexion-extension and the absence of a foot in two of the simulators, which one participant (*P5*) felt reduced leverage for conducting the test effectively. Suggested improvements included enabling greater knee flexion-extension (as also suggested by professionals in section 4.3.2), upgrading the skin to a more lifelike texture or fully covering the simulators (*P1*, *P9*), and incorporating variations in anatomy, size, and weight to broaden learning scenarios (*P1*, *P15*). Most participants envisioned the simulators as valuable tools for classroom and clinical lab learning, with some noting potential benefits for self-directed practice at home.

Haptic Experience Inventory (HXI) Results

Finally, I formally evaluated haptic experience using a validated scale. Using the Haptic Experience Inventory (Shi and Schneider, 2025), the 16 participants showed high levels of Autotelics ($M = 6.0$, $SD = 0.8$) and Involvement ($M = 5.8$, $SD = 0.8$), moderate Realism ($M = 5.1$, $SD = 1.1$) and Harmony ($M = 5.0$, $SD = 1.0$), and lower Discord ($M = 3.4$, $SD = 1.1$). The overall HXI score was 26.5 ($SD = 3.8$) out of a possible 35 (see Figure 4.14). Moreover, the 20 items of this scale showed acceptable reliability, with a Cronbach's alpha (Cho and Kim, 2015) of $\alpha = 0.704$.

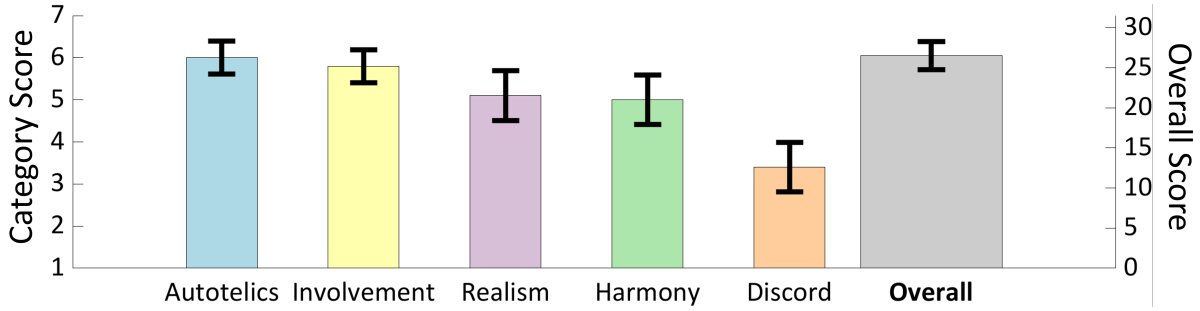


Figure 4.14: Results from the haptic feedback evaluation of Flex-Knee using the Haptic Experience Inventory (Shi and Schneider, 2025), showing the mean and 95% confidence intervals for each category and for the overall score.

4.4 Discussion

I now discuss the performance of Flex-Knee in simulating all MCL injury conditions, participants' (professionals' and students') perceptions of its haptic fidelity and realism, its potential as a low-cost and easy-to-manufacture learning tool in health sciences disciplines, and its adaptability to multiple use cases or scenarios.

4.4.1 Flex-Knee showed some success simulating healthy, partially torn, and fully torn MCLs

The metrics in Table 4.2 show that Flex-Knee was largely effective in simulating both a knee with healthy MCL and a knee with an unhealthy MCL. Results in Figure 4.10a demonstrate Flex-Knee's effectiveness in simulating scenarios where the MCL is compromised, and show a small margin for error in simulating scenarios where the MCL is intact. These results are

consistent with those obtained for TRAIN-KNEE (Figure 3.10). In addition, the sensitivity values align with those reported in existing literature (Kastelein et al., 2008) for Valgus testing at 30°, while the specificity was notably higher.

Using a three-condition framework—healthy, partially torn, and fully torn MCL—Flex-Knee proved effective in simulating three levels of MCL tear. Sensitivity values reported in Table 4.2 confirm that the 6 professionals from subsection 4.3.2 were generally able to identify these three relevant differences. In contrast, TRAIN-KNEE (chapter 3) was primarily successful in reproducing healthy and unhealthy MCLs, with clear discrepancies observed when practitioners attempted to differentiate between partial and full tears. This suggests that Flex-Knee offers improved realism in conveying injury severity.

4.4.2 Flex-Knee was less effective at simulating grade 1 and grade 2 MCL injuries

Sensitivity values in Table 4.2 show that the participants I recruited struggled to recognize and differentiate between grades 1 and 2 MCL tears. Flex-Knee cannot reliably reproduce Grade 2 injuries and performs poorly for Grade 1 injuries. These findings align with existing literature (Aronson et al., 2010; Fetto and Marshall, 1978), which indicates that clinicians also face challenges in recognizing these conditions in real patients. Several factors can complicate the examination, including pain, which may lead to guarding. Interestingly, grade 3 tears are often easier to diagnose, as pain is typically reduced and joint instability becomes more apparent (Phisitkul et al., 2006). In addition, both one participant (*P6*) and the collaborating clinician noted that grade 1 and grade 2 MCL tears are inherently

difficult to identify without supplementary clinical cues such as bruising, swelling, pain levels, and ligament tenderness, which are currently not represented in Flex-Knee. Given these complexities, it is therefore reasonable to expect that accurately reproducing the effects of these conditions in a physical simulator is also challenging. Other factors may have contributed to the decreased sensitivity in Table 4.2, including the practitioners' level of experience, the varying amount of applied valgus force, and the subjectivity in assessing joint laxity (Sawant et al., 2004).

While Flex-Knee struggled to reproduce these inner injury levels reliably, the participants were still able to detect that Flex-Knee was injured, and did not confuse these injuries with severe (grade 3) tears. To address this in future systems using the injury simulation method I proposed, a wider range of inserts with more subtle density variations could be incorporated, allowing practitioners to select values that, based on their own judgment, best represent grade 1 and grade 2 tears.

4.4.3 Flex-Knee demonstrated sufficient haptic fidelity and realism for training

The 6 certified professionals that I recruited generally perceived the haptic fidelity and realism of Flex-Knee as sufficient (see Figure 4.11). Most agreed that the weight of Flex-Knee felt realistic relative to its size (2 strongly agree, 3 agree, 1 disagree) and that its shape closely mimicked a real human leg (3 agree, 2 strongly agree, 1 neutral). Additionally, the silicone-based skin was reported to provide a reasonably realistic tactile experience, with 1 participant strongly agreeing and 4 agreeing, while 1 remained neutral. These results

suggest that, overall, Flex-Knee delivers an effective and believable physical experience for training purposes.

I also observed that none of the certified professionals reported that Flex-Knee's movements were insufficient for performing the Valgus test. The use of a generic universal joint (u-joint) that enabled flexion-extension (with some limitations) and abduction-adduction (the relevant DOFs for Valgus testing) was therefore a well-suited solution. Metamaterials combined with 3D printing allowed us to replicate the tactile experience of the leg's surface by customizing regions to feel hard, simulating bony structures, and soft, simulating tissue such as the calf. This strategy helps offset the compromises of a generic joint, and offers a low-cost, scalable, and easily customizable solution capable of representing other anatomies, including varying leg sizes, without relying on anatomically precise simulators.

Regarding the HXI questionnaire completed by 16 students, results for Autotelics and Involvement are consistent with some observational findings from Study 2 (subsection 4.3.3): students were attentive, curious, and motivated when interacting with the simulators. This suggests that these low-cost, passive simulators provide meaningful haptic experiences. Realism and Harmony scores were moderate, suggesting that while the simulators reasonably resembled a human knee and integrated well with other sensory cues, there is room for improvement. As noted earlier, participants frequently noted the need for greater knee flexion-extension and the absence of a foot in two simulators. Discord remained low, which indicates there was minimal sensory mismatch. These scores, in the end, are highly influenced by the fact that participants interacted with only a fake human leg rather than a real patient.

4.4.4 Flex-Knee has potential as a low-cost, easy-to-manufacture tool to support learning

Findings from Study 2 (Figure 4.13) suggest that even a simple, haptic simulator costing $400 CAD can effectively convey clinically relevant differences in MCL conditions to novice learners. This may represent a significant advancement in health sciences education because it shows that educators could provide meaningful hands-on experience in class without relying on real patients or expensive simulators. The results may also initially suggest that low-cost, passive engineered tools could support effective self-directed learning in homes, as mentioned by some participants. However, further research would be needed to ensure that users could correctly set up, assemble, and tweak these simulators on their own.

4.4.5 Flex-Knee may be adapted to multiple use cases

The current modularity of Flex-Knee could allow us to explore other human joints. For example, removing the leg-like structures (Figure 4.3) allows the u-joint to be reused for different applications. Given the similar mechanics of an elbow and a knee, a soft arm-like structure could potentially be constructed using the method described in subsection 4.2.2 and integrated with the existing joint. However, an additional module (e.g., a revolute joint in series (Roberts, 2011)) would be necessary to enable pronation and supination (Neumann, 2016). I explore this path in chapter 5.

Flex-Knee could also simulate other injury-related physiological effects. Musculoskeletal injuries fundamentally alter joint mechanics by producing subtle, moderate, or excessive

abnormal physiological movement (Jung et al., 2009). Metamaterials' function is to define the mechanical behavior of objects by modifying their internal structure, and thus enable controlled directional movement (Ion et al., 2016). This makes it a potential low-cost, easy-to-implement solution for other injuries. For example, similar metamaterial-based inserts could be designed to resemble the increased adduction observed in lateral collateral ligament (LCL) injuries of the knee, the instability characteristic of ulnar collateral ligament (UCL) injuries in the elbow, or even the altered mechanics resulting from fractures, such as those of the tibia.

4.5 Limitations

Flex-Knee has limitations that could be addressed in future research.

One limitation of Flex-Knee is that its calibration was performed with only one individual. The staircase method procedure used can be time-intensive, which was a constraint. This may have contributed to some of the variability observed in the two user studies, particularly in study 1 (subsection 4.3.2).

I also faced time constraints when recruiting participants for study 2 (subsection 4.3.3), due to the busy schedules of physiotherapists and athletic therapists. The sample size of 6 may not be representative of a broad population of practitioners, and expanding the participant pool could offer more generalizable results. However, small sample sizes are common in studies involving populations with specialized knowledge. As noted in prior work (Caine, 2016), studies involving expert users frequently rely on small sample sizes

to generate meaningful and actionable insights. In summary, the sample size reflects both logistical constraints of working with health science practitioners and accepted standards for early-stage evaluation.

Also, study 2 was conducted with only three leg configurations and three injury inserts, and I asked participants to rate what they felt within these options. This protocol introduces potential confounds, as participants could have inferred that there was a "correct" answer for each simulator based on prior trials. The results may reflect these expectations. In future studies, allowing participants to provide open-ended responses or using more simulators and inserts could reduce such biases.

Another limitation is that Flex-Knee simulates isolated MCL injuries only and does not account for concurrent injuries (e.g., ACL tears, PCL or LCL tears, and meniscus tears) that practitioners frequently encounter (Branch et al., 2017; Phisitkul et al., 2006; Varelas et al., 2017). I will explore how the metamaterials-inspired approach could be adapted or complemented for these additional structures.

An additional limitation is that Flex-Knee mostly enables users to do the Valgus test at 0°. Attempts to conduct it at 30° are uncomfortable due to the viscoelasticity of TPU 95A, which causes any applied flexion to quickly dissipate unless continuous force is maintained. Future iterations should explore alternative soft materials (e.g., TPU 85) with higher flexibility that can accommodate a wider range of motion while maintaining sufficient durability.

Finally, while I collected force data using four FSR sensors (three on the upper leg and one near the MCL side), comparing applied pressure among participants was difficult.

Variations in hand placement, grip style, and how participants applied the Valgus force led to inconsistent readings. The low spatial resolution of only four sensors was insufficient to capture these differences. Capturing all types of holds and grips would require more sensors, which would substantially increase system complexity. Future systems could benefit from wearable, minimally obstructive sensors, like those used by Lin et al. (2025).

4.6 Conclusion

Haptic simulators are widely used in healthcare education because they let students safely practice skills and improve learning compared to traditional methods. They also expose them to rare clinical cases early, which helps them build both familiarity and hands-on skills needed for accurate assessment. However, these simulators can be expensive and limited to a single training scenario. In this chapter, I designed and developed Flex-Knee: a low-cost ($400 CAD), modular haptic simulator to support training in manual physical assessments, focusing on the Valgus test for MCL injuries. Designed in collaboration with a certified clinician, Flex-Knee incorporates an abstract u-joint mechanism, silicone layers that approximate the look and feel of human skin, soft structural elements that mimic the form of a human leg, and metamaterial-inspired inserts that reproduce the biomechanical effects of multiple severities of MCL injury. Flex-Knee was evaluated through three stages: calibration with the collaborating clinician using a staircase psychophysics procedure, acceptance testing with six additional certified clinicians, and classroom demonstrations involving 16 kinesiology students. Across these evaluations, Flex-Knee enabled both experts and novices to reliably distinguish between healthy, partially torn, and fully

torn MCL conditions. Participants also noted the realism of the simulator's weight, skin texture, and anatomical form. Overall, these findings highlight the potential of low-cost haptic simulators to support standardized and repeatable clinical training in kinesiology and related health sciences.

Chapter 5

A Template System for Modular, Scalable, and Low-Cost Musculoskeletal Injury Simulators

Both TRAIN-KNEE (C1) and Flex-Knee (C2) were designed for a single simulation use case: MCL injuries. In this chapter, I present the third contribution (**C3**) of this dissertation, which is a shared hardware template system to implement haptic simulators supporting multiple joints and injury types (Figure 5.1 and Figure 5.2). I demonstrate the approach through three use cases, and include preliminary evaluations of two of them.

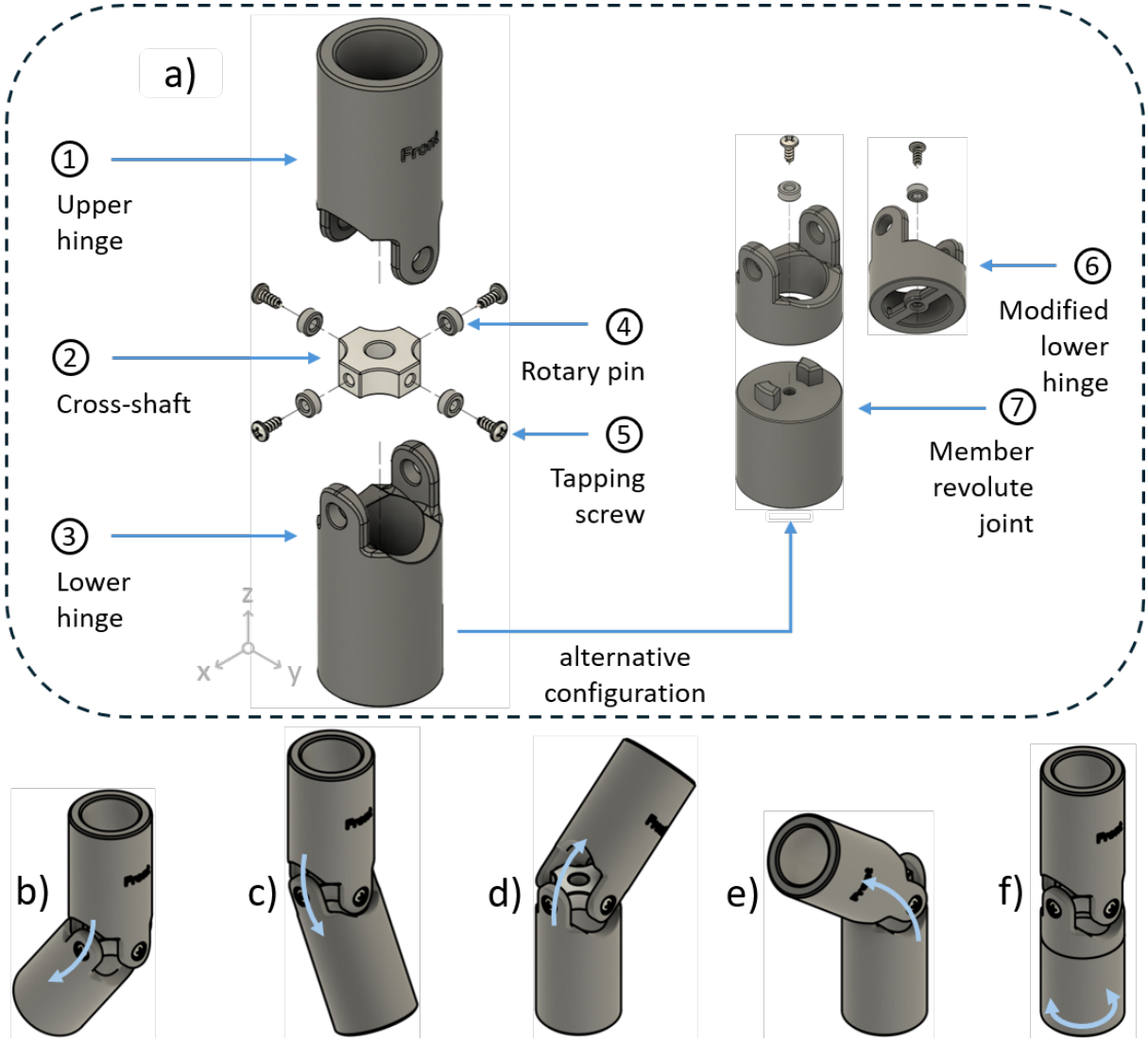


Figure 5.1: Mechanical diagram of u-joint. a) Exploded view showing all constituent components and illustrating how selected elements can be reconfigured or adjusted to modify joint behavior. b) to e) Representative motions achievable. In f), axial rotation is enabled through reconfiguration of the lower hinge.

5.1 Introduction

Training simulators for musculoskeletal assessment of joint injuries remain limited compared to those developed for other domains in the medical sector, such as surgery and rehabilitation. *SpinalLog* (Chacon et al., 2019) support training of spinal mobilisation techniques through a tangible spine model; *vARtebrae* (Tatsuzawa et al., 2025) uses XR and a tangible model for a similar training purpose. In chapter 3, I introduced TRAIN-KNEE, a simulator designed to replicate MCL injuries and support training of the Valgus test, and in chapter 4, I introduced *Flex-Knee*, which further expands MCL injury simulation capabilities while achieving it at a substantially lower cost.

However, these contributions remain largely restricted to supporting a single manual assessment technique and are not designed to accommodate multiple physical tests or injury types. In professional practice, clinicians must be able to perform a wide range of musculoskeletal assessments across different joints and conditions, such as the Lachman test to assess the integrity of the ACL and the elbow valgus test to evaluate the UCL. This highlights the need for simulators that move beyond task-specific training and instead enable exposure to multiple clinical scenarios.

I propose working towards a unified framework to address this gap. In this chapter, I present the foundations of a general approach to implement passive haptic simulators for musculoskeletal injury assessment training using shared hardware. I expand Flex-Knee (chapter 4) into a template system that supports development of passive haptic simulators for different injury cases. To do so, I employ an abstract mechanical joint with eight tunable parameters as a base design, human limb–like structures with variable material

composition, an injury simulation approach based on material properties, and silicone-based skin layers. I demonstrate three simulator prototypes: one that simulates MCL injuries and supports the Valgus test, one that mimics UCL injuries in the elbow and allows elbow valgus testing, and one that can potentially reproduce ACL injuries and enables the Lachman test. I report the results of calibrating two of these cases, along with a preliminary evaluation of the third, with a certified clinical instructor.

This work establishes that this approach can adapt to different scenarios with sufficient fidelity to support their respective tasks and calibration by a clinician. I demonstrate how a baseline design can be extended to multiple use cases with interchangeable add-ons, providing a flexible tool that lays the groundwork for a future framework for haptic musculoskeletal injury simulators. In the long run, I envision a human body framework that allows practitioners to construct functional tools representing a variety of conditions across different joints, conduct the corresponding physical tests, and gain the practice necessary to develop clinical expertise. This work is a step toward realizing that vision.

5.2 Template System Design

I define a solution as a *template system*, a set of procedures and template designs that together can be adapted to produce a specific injury simulator. This template system consists of four components: (1) an abstract mechanical joint capturing task-relevant biomechanics, (2) a human limb-shaped structure with realistic external geometry and variable material composition, (3) an injury simulation piece, and (4) a skin-like layer.

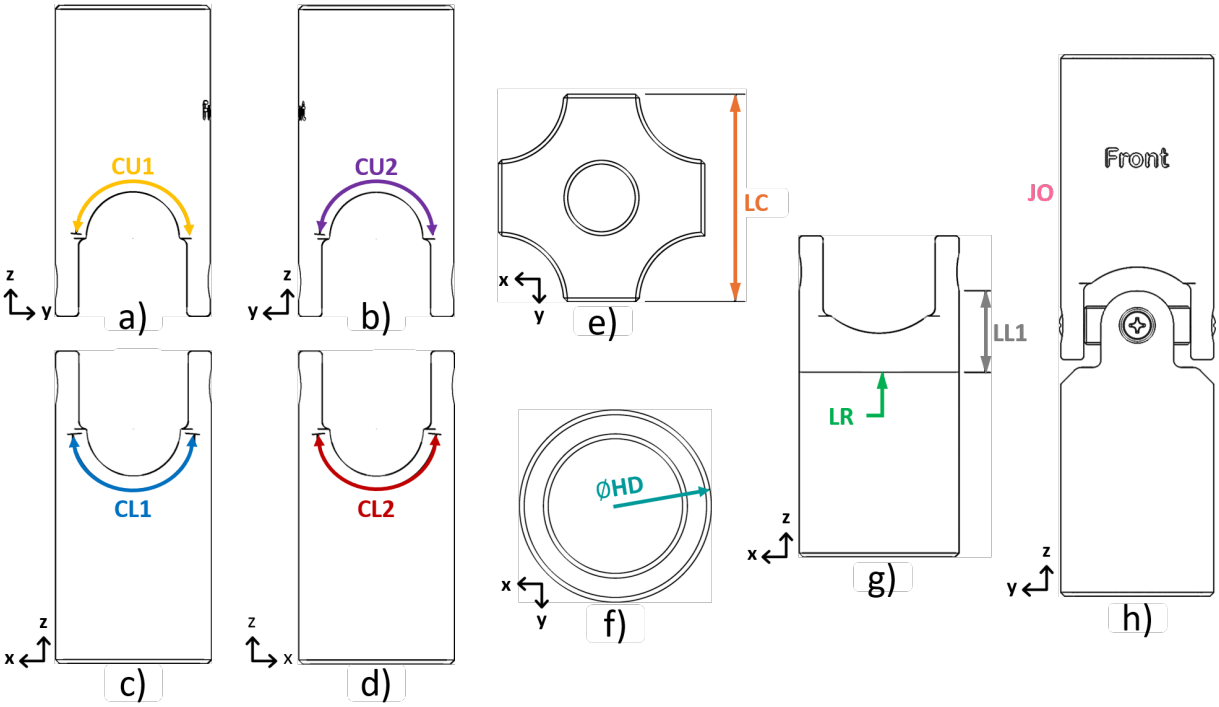


Figure 5.2: Parameter definitions for u-joint. (a-b) Upper hinge cutouts (CU1 lateral, CU2 medial) control arc length. (c-d) Lower hinge cutouts (CL1 anterior, CL2 posterior) function analogously, with (g) lower hinge length (LL1) allowing addition of an auxiliary revolute joint (LR). (e) Cross-shaft length (LC) connects upper and lower hinges, enabling two DOF. (f) Hinge outer diameter (HD) and (h) joint orientation (JO) define geometry and axis alignment, and enable configuration for other use cases. Example parameter values are provided in Figure 5.5

5.2.1 Abstract Mechanical Joint

The abstract joint reproduces the biomechanical degrees of freedom (DOF) relevant to a given manual physical test. Rather than replicating full anatomical complexity, the joint selectively adds and removes DOF and their ranges of motion based on their relevance to the

clinical test being trained. In this work, I use a *universal joint* (u-joint) (Wilson and Sadler, 2003), composed of an upper hinge, a lower hinge, and a connecting cross-shaft Figure 5.1. A revolute joint may be added into a modified (shortened) lower hinge, producing a total of three rotational DOF. From this base design, the u-joint is defined by six geometric parameters, one optional auxiliary component, and one orientation parameter. Together, these parameters enable a systematic configuration of joint kinematics for different manual physical tests while preserving a shared mechanical foundation.

Upper Hinge Parameters (CU1, CU2, HD)

Assuming the joint in Figure 5.1 mimics a right limb, I define two parameters on the side edges of the upper hinge: a cutout on the lateral edge (CU1) and a cutout on the medial edge (CU2) (Figure 5.2a-b). CU1 and CU2 define the arc length traced between the two hinge "forks". Increasing CU1 prevents collision with the lower hinge, whereas decreasing it causes a collision that restricts the motion illustrated in Figure 5.1e. Similarly, increasing CU2 avoids collision with the lower hinge on the medial side, while decreasing CU2 produces a collision that limits the motion shown in Figure 5.1d. Additionally, I define the hinge outer diameter as HD (Figure 5.2f).

Lower Hinge Parameters (CL1, CL2, LL1, LR, HD)

For the lower hinge, an anterior cutout (CL1) and a posterior cutout (CL2) (Figure 5.2c-d) operate analogously to the upper hinge parameters. These parameters similarly permit or constrain motion through controlled collisions, but in this case govern the motions

illustrated in Figure 5.1b-c. The lower hinge shares the same hinge diameter (HD) as the upper hinge. However, unlike the upper hinge, I define an additional parameter governing its length (LL1). Reducing LL1 makes room to incorporate an auxiliary revolute joint (LR) (Figure 5.2g), which enables the motion illustrated in Figure 5.1f. The inclusion of LR is treated as a binary design parameter; when present, the u-joint is connected in series with a revolute joint.

Cross-Shaft Length (LC)

The cross-shaft length (LC) connects the upper and lower hinges and governs the distance between their rotational axes (Figure 5.2e). LC introduces compliance in either the anterior-posterior or medial-lateral direction by allowing relative translation between the upper and lower hinges.

Joint Orientation (JO)

Finally, the orientation of the u-joint (JO) is a configurational parameter necessary for adapting it to different use cases. In the default configuration (shown in Figure 5.1a), the two forks of the upper hinge point anterior-posterior, while the two forks of the lower hinge point medial-lateral. Rotating the assembly by 90° exchanges these directions.

5.2.2 Realistic Limb Structure

The second component is a limb-shaped structure that resembles external anatomy. The u-joint is embedded within this structure, which provides both visual and haptic fidelity. I

leverage a method shown in Flex-Knee to enable spatially varying compliance, mimicking the softness of human tissue. For example, in an elbow-like structure Figure 5.3, the tip (olecranon region) should feel rigid and bony, while the forearm section should be softer and comply with pronation-supination (Neumann, 2016) motions. This method aligns with metamaterials principles (Ion et al., 2016), in which mechanical properties are tuned through structural geometry rather than by altering the base material. Fabricating these structures requires flexible 3D-printing filament, such as thermoplastic polyurethane (TPU) 85A or 95A.

5.2.3 Skin-like Layer

The third component is a skin-like layer, implemented as a silicone-based sleeve that covers at least the sections where practitioners place their hands to conduct a test. I use techniques drawn from soft robotics literature (Teyssier et al., 2019) and materials that mimic visual and tactile properties of human skin. Manufacturing this layer requires *Dragon Skin FX-Pro* platinum-cured silicone, which has been demonstrated to simulate the epidermis—the outermost layer of human skin (Teyssier et al., 2019). This layer is essential for a realistic clinical evaluation, as practitioners place their hands directly on a patient's skin during physical tests. Figure 5.3 shows a skin layer for an arm-like model.

5.2.4 Injury Simulation

Finally, to simulate injuries, I control the amount of abnormal motion associated with the condition of interest. I accomplish this with interchangeable "inserts" 1) within the limb

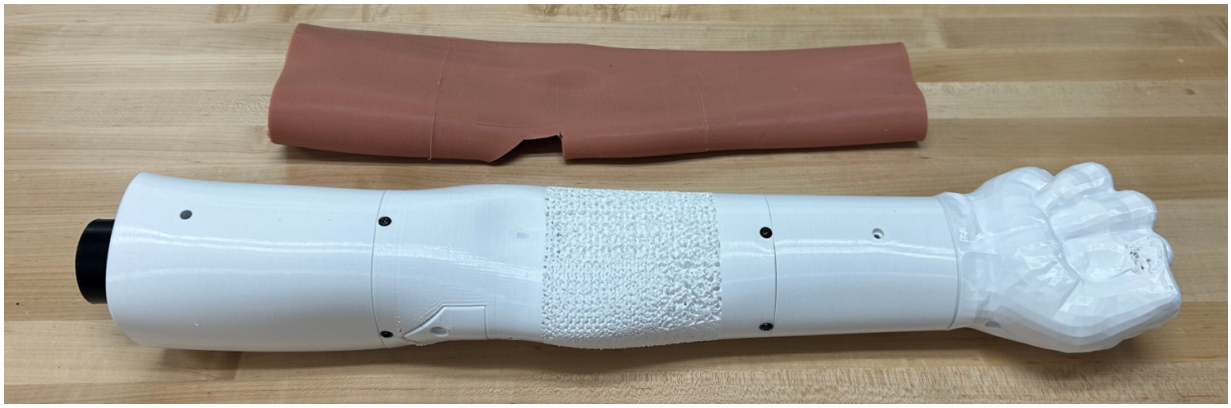


Figure 5.3: 3D-printed elbow-shaped structure and the corresponding silicone-based skin layer used to cover it. A hand prop is included for visual fidelity purposes only.

structure or 2) within the abstract joint that varies in material composition. Figure 5.4 shows two insert designs for the elbow model shown in Figure 5.3. One insert has a less stiff lower section than the other, achieved by using flexible 3D-printing filament and setting a low infill density value (%). When positioned on the lateral side of the elbow, this insert compresses under valgus loading and produces the sensation of increased UCL laxity on the medial side. Contrarily, this effect decreases if a stiffer insert is placed. In either case, compression arises from two sources: the force applied through the structure during valgus testing and the contact between the upper hinge edge and the top of the lower hinge fork. Each material composition (infill density) produces a different amount of abnormal motion, which can then be mapped to an injury condition (e.g., healthy or grade 1-3 UCL injury).



Figure 5.4: Two variable-stiffness inserts with densities of 95% and 20% used to simulate UCL injuries, meant to be placed in the empty spot at the back of the elbow model.

5.3 Example Implementations

I present three simulator prototypes that I implemented using this generalized template system: 1) a knee that simulates MCL injuries, 2) an elbow that simulates UCL injuries, and 3) a second knee that simulates ACL injuries.

5.3.1 Knee Valgus (MCL)

This simulator corresponds to the Flex-Knee model from chapter 4. Here, I designed a u-joint that enables controlled flexion-extension as well as frontal plane valgus motion (abduction) to simulate MCL injuries and support the Valgus test. The parameters producing these biomechanical behaviors are shown in Figure 5.5a. A leg structure was fabricated with TPU 95A 3D-printing filament, with high infill density applied to bony regions (40%) and

low infill density applied to soft tissue regions (5%). An interchangeable injury insert was placed on the medial side of the knee structure, and the infill density at its lower section was varied to represent multiple injury conditions. Under valgus loading, a low-density insert causes MCL laxity and abduction, whereas a high-density insert approximates a healthy ligament. In Figure 5.5a, notice that the extruded medial side depicts a rectangular cut rather than an arc. This alternative simplifies the injury insert design, reducing it to a flat extrusion as illustrated in Figure 5.4. I refer to this feature as "rectangle" for the **CU1** parameter. Furthermore, I attached acrylonitrile butadiene styrene (ABS) pipes to each hinge to ensure proper fastening with the leg structure. I show Flex-Knee in Figure 5.6a.

5.3.2 Elbow Valgus (UCL)

For UCL injuries and the elbow Valgus test, I enhanced the u-joint used for Flex-Knee with a modified lower hinge and a revolute joint to include pronation–supination. To contribute to this, the forearm section of the arm structure was 3D-printed with no "walls" to enable mechanical compliance. Unlike in Flex-Knee, I used TPU 85A for this simulator, as it better supported the pronation–supination motion. To simulate UCL injuries, an interchangeable insert was taken from the lateral side, following the same approach I used in Flex-Knee. The parameters necessary for this elbow simulator are shown in Figure 5.5b.

5.3.3 Knee Lachman (ACL)

For ACL injuries and the Lachman test, I modified the abstract joint to enable anterior tibial translation while excluding abduction and adduction motions. The cross-shaft length

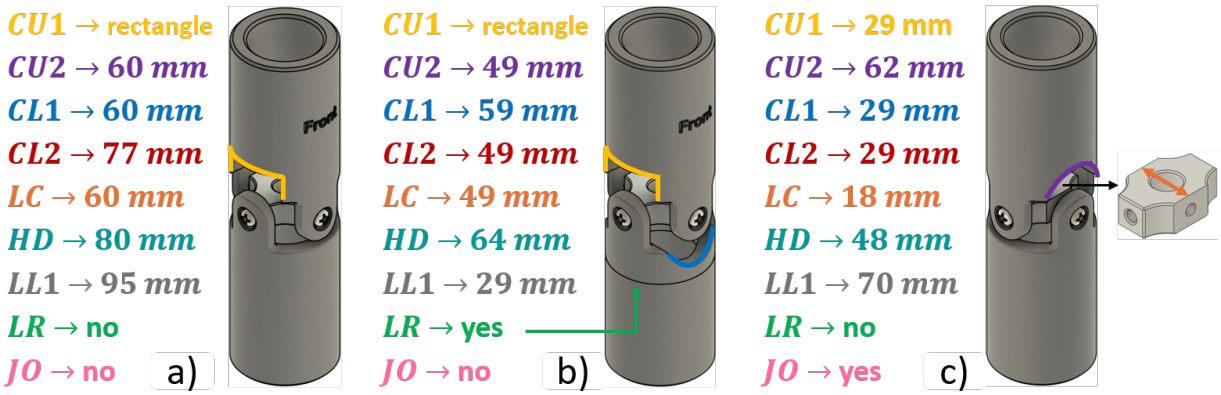


Figure 5.5: U-joint parameters for three simulators: (a) Knee MCL. Highlighted rectangular cut allowing excessive abduction, later controlled by variable-stiffness inserts. (b) Elbow UCL. Highlighted rectangular cut causing excessive abduction (yellow) and flexion–extension (blue), with pronation–supination enabled by the revolute joint. (c) Knee ACL. Back view showing reorientation of u-joint and the parameter enabling flexion–extension (purple), as well as a closer view of the cross-shaft with reduced length (LC) to permit anterior tibial translation.

is reduced to permit this translation, and the joint is rotated 90° clockwise relative to the orientation used for the knee MCL and elbow UCL simulators. Unlike in these two previous simulators, here the knee structure is split into two parts to facilitate the Lachman test, reducing the effort required by the examiner. To simulate injuries, this time a custom-designed injury insert is introduced into the gap created by the reduced cross-shaft: a rigid insert eliminates anterior translation, whereas a very soft insert permits it. This configuration (shown in Figure 5.5c) mimics the effects of ACL injuries in the knee.

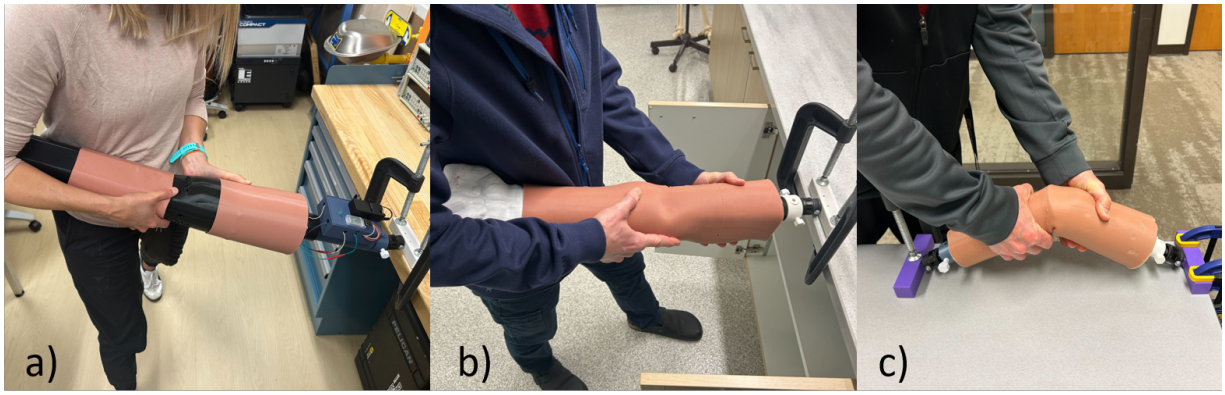


Figure 5.6: Manual physical tests being conducted on the three simulators: a) Knee valgus (from Moran-Ledesma et al. (2026b)), b) Elbow valgus, and c) Lachman tests.

5.4 Internal Evaluation and Calibration

5.4.1 Knee MCL and Elbow UCL

To map insert infill density to clinical conditions for the Flex-Knee and elbow UCL prototypes, I conducted the adaptive up-and-down staircase method (Cornsweet, 1962) with an experienced clinical instructor to identify the 50% point of subjective equivalence (PSE) between neighbouring injury conditions in the implemented models. I include these results in Figure 5.7. In all cases, I began with no insert in place (density of 0%) and used a step size of 10 until reaching 2 reversals. Afterward, I modified the step size to 5 and concluded the experiment after 5 reversals. For each case, the threshold was computed as the mean of the peak and valley values obtained at the smaller step size. To segment the range of infill densities from 0% (no insert) to 100% (stiffest insert) and establish intervals for

each condition, I excluded values within two standard errors (SE) of each threshold, which approximates a 95% confidence interval. I picked SE to capture the variability of sample means that would be expected across repeated sampling. The remaining values are then used to define the resulting intervals for each condition, as shown in Figure 5.8.

5.4.2 Knee ACL

For the knee ACL prototype, I conducted a preliminary qualitative evaluation with a certified clinician to explore the validity of the design (Figure 5.6c). In this evaluation, the clinician performed the Lachman test on the model and reported that the configuration reproduced the biomechanical feel of both a healthy and a partially torn ACL. The current prototype is unable to reproduce the effect of a fully torn ACL given the hard stop felt upon the collision of the cross-shaft and the hinge of the u-joint. However, as emphasized by the clinician, *"under realistic conditions, the stopping mechanism should produce a soft, compliant response"*.

5.5 Discussion

5.5.1 Evaluation of knee and elbow simulators

The results from the staircase procedure and the preliminary evaluation of the knee ACL simulator illustrate how the proposed template system can be adapted across multiple joints and injury scenarios. Although the elbow model showed lower perceptual resolution

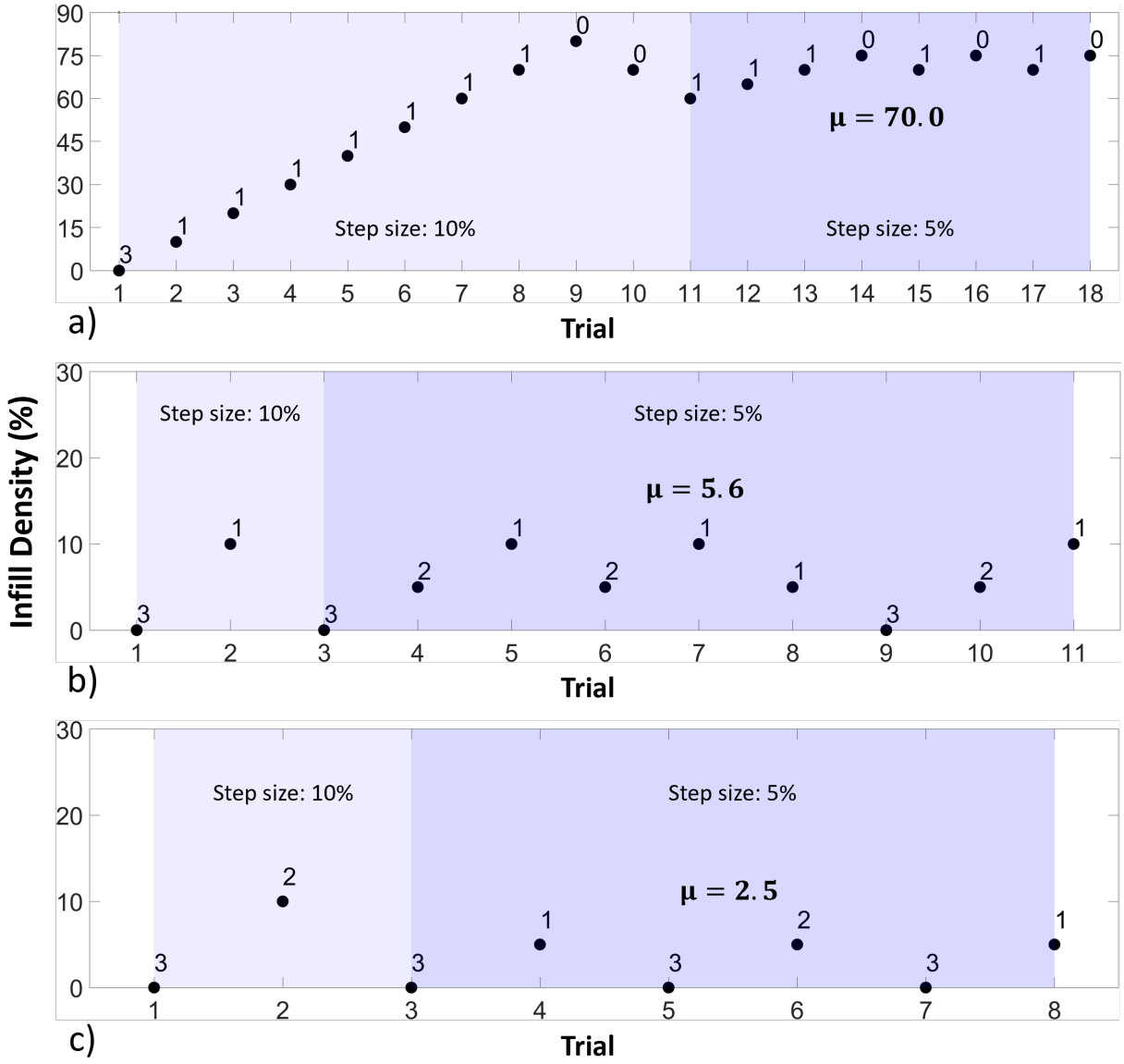


Figure 5.7: Results of adaptive staircase testing to distinguish: a) Healthy vs. Grade 1, b) Grade 1 vs. Grade 2, and c) Grade 2 vs. Grade 3 injuries. Means were computed from peak and valley values in small step-size trials. Light purple shows large step-size; dark purple shows small step-size. Injury grades are coded as 0 = Healthy, 1 = Grade 1, 2 = Grade 2, and 3 = Grade 3.

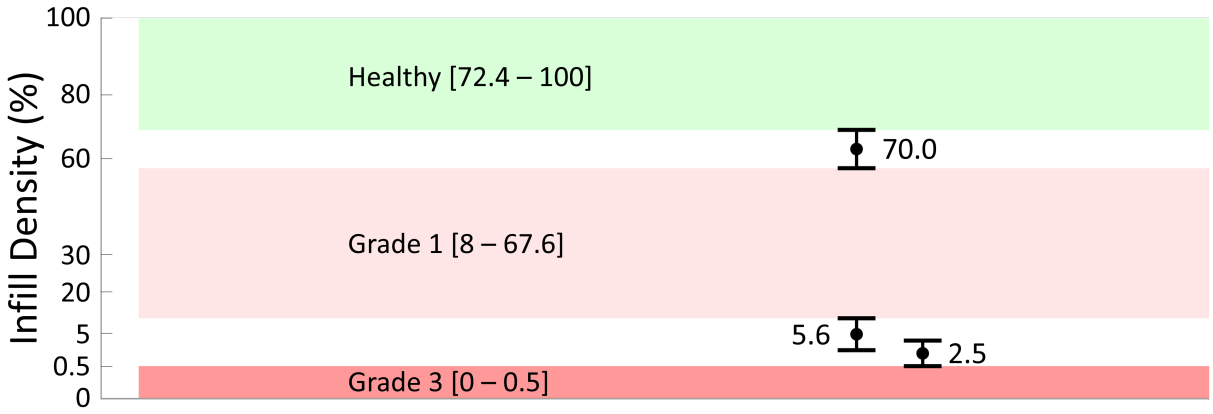


Figure 5.8: Mean infill densities at the base of inserts, with bars showing ±2 standard errors. Coloured regions indicate value ranges for each injury grade.

than Flex-Knee (Figure 5.8), this limitation is unlikely to be clinically consequential, as differentiating between grade-1 and grade-2 injuries using the Valgus test alone is challenging without additional factors such as pain, swelling, and patient feedback (Aronson et al., 2010). Integration with a virtual reality interface could help address this limitation. Importantly, in both cases, the clinician was consistently able to distinguish healthy, partially torn, and fully torn ligament conditions, and to relate the haptic feedback of the simulators to injury conditions encountered in real practice. The preliminary evaluation of the knee ACL simulator further supports this approach, as the clinician could sense at least a healthy and an injured ACL. Moreover, as I reported in Flex-Knee, students with minimal knowledge of the Valgus test are able to perceive differences produced by the injury inserts (Moran-Ledesma et al., 2026b), suggesting that the generated cues are meaningful to even inexperienced users. Together, these evaluations suggest that the proposed template

system can produce interpretable and clinically relevant haptic cues, which strengthens its potential as a flexible foundation for physical injury assessment training.

5.5.2 Extension to additional use cases

The template system of this work extends to other collateral ligaments within the knee and the elbow. Reproducing knee LCL and elbow LCL injuries is straightforward with the proposed design approach. Enabling adduction (varus) motion requires only adjusting parameter **CU2** in the abstract joint. In addition, the injury insert should be relocated to the medial side of the limb structure. This highlights the flexibility and extensibility of the proposed approach to similar injuries.

The template system rapidly scales to different sizes by adjusting the hinge diameter (**HD**), which linearly scales the overall joint geometry. Minor additional adjustments may be required to ensure compatibility with standard ABS pipe dimensions used to extend the hinges and accomplish full-size limbs. This scalability is particularly valuable because it would allow practitioners to evaluate a range of anatomies and ages. In clinical practice, they cannot choose their patients, as patients present with varying body sizes. The ability to train and test across diverse anatomies is therefore essential.

In some cases, the template system may also extend to other human joints in a straightforward manner, such as joints in human hands. Metacarpophalangeal (knuckle) joints are supported by ligaments that allow flexion and extension as well as abduction and adduction, whereas interphalangeal (finger) joints permit flexion and extension only (Neumann, 2016). To represent a hand finger other than the thumb, three small u-joints would be

assembled in series, corresponding to one knuckle, and two finger (distal and proximal) joints. In essence, I would be connecting three of the abstract u-joints in series.

5.5.3 Potential for Framework for Haptic Models

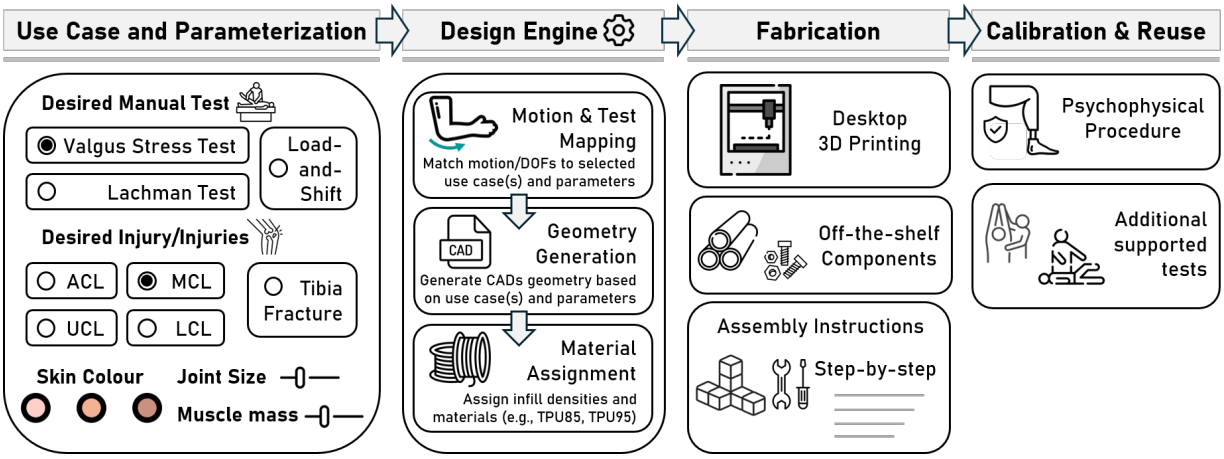


Figure 5.9: Conceptual overview of a future framework for haptic simulators. Users begin by selecting a training scenario and specifying parameters such as manual test, injury, joint size, skin, and muscle mass. The Design Engine translates these high-level inputs into concrete technical specifications, including u-joint geometry, materials, and material composition of elements. Fabrication integrates 3D-printed joint components with off-the-shelf parts, following assembly instructions produced by the Design Engine. The assembled model is then calibrated using a psychophysical method. If applicable, the same model may support multiple manual tests.

Beyond the three simulators presented in this chapter, the template system points toward a broader framework for designing passive haptic simulators for injury examination training in kinesiology and health sciences education. Li et al. (2020) and Feick et al. (2020) presented approaches that enable the rapid design and development of haptic devices

for a broad range of interactions using shared hardware platforms, while Kovacs et al. (2017) introduced an integrated end-to-end system for designing large structures through a software platform that allows users to define high-level specifications. Inspired by these approaches, I envision a framework that supports the implementation of multiple injury examination simulators using shared hardware components alongside a software interface that allows users to define high-level characteristics of the intended training scenario. A conceptual overview of this framework is illustrated in Figure 5.9. In this framework, users begin by selecting a training scenario, specifying the manual physical test, target injury, joint size, and other characteristics such as skin or muscle mass. A design engine then translates these high-level inputs into precise technical parameters, such as u-joint exact geometry, injury insert configuration, and sectional material composition. As demonstrated throughout this dissertation, the list of hardware is expected to incorporate both off-the-shelf components and 3D-printed structures. Users can then assemble the simulator using a set of guidelines generated by the engine. The completed model is calibrated by an expert using a psychophysical method in order to correctly define injury inserts for each condition (injury). In some cases, the software interface may recommend additional training scenarios (e.g., other injury conditions) based on the specifications initially provided by users, which prompts reuse.

5.6 Conclusion

Musculoskeletal assessment in clinical practice involves a diverse set of manual examination techniques rather than isolated procedures. While haptic simulators provide a promising

complement to traditional instruction, existing systems remain limited to single use cases and lack flexibility across multiple injuries or anatomical variations. I present a template system for haptic simulators that uses shared hardware to support multiple joints and injury types (i.e., knee and elbow injuries). The system integrates a tunable u-joint, limb-like structures with variable material composition, variable-stiffness injury inserts, and silicone-based skin. Validation across three simulator prototypes of MCL, UCL, and ACL injuries, together with psychophysical calibration with a certified clinical instructor, shows both fidelity and flexibility. The approach presented in this work provides a foundation for developing flexible and accessible passive haptic simulators for multiple use cases and scenarios, which facilitates safe and effective clinical training.

Chapter 6

Discussion, Limitations, Future Work

6.1 Discussion

The main goal of this work is to teach how to perform manual examination tests for joint injuries, rather than how to independently diagnose an injury. TRAIN-KNEE (chapter 3), Flex-Knee (chapter 4), and the template system for other injury cases (chapter 5) are intended to provide repeated opportunities to practice positioning the limb, conducting an examination technique (e.g., the Valgus test), and interpreting the resulting response. In clinical practice, diagnosis of MCL, ACL, or UCL injuries involves multiple sources of information beyond the response obtained during the physical examination, including pain, swelling, and patient history. Therefore, the simulators developed in this work should be viewed as complementary tools for developing examination skills rather than replacements

for comprehensive clinical assessments. Collectively, these contributions help address the three challenges that motivated this dissertation (outlined in section 1.1).

6.1.1 Design Strategy and Development Insights

A key design insight that emerged throughout this dissertation was that musculoskeletal assessment simulators do not necessarily require complete anatomical replication. Instead, meaningful training experiences can be achieved by identifying and reproducing the mechanical and perceptual cues that practitioners rely upon during manual examination. This principle was evident from the initial development of TRAIN-KNEE, where I represented MCL injuries using tensioned wires and an electromechanical system rather than attempting to replicate human ligaments. This approach reproduced the clinically relevant outcome of increased valgus motion associated with MCL injury and avoided unnecessary anatomical complexity.

This design philosophy became further evident through the progression from TRAIN-KNEE to Flex-Knee. The development of Flex-Knee demonstrated that the biomechanics required for the Valgus test could be reproduced without replicating the full complexity of the knee joint. Since internal-external rotation does not contribute significantly to the assessment, a simplified universal joint was sufficient to reproduce the relevant motion. Similarly, I reduced the extensive silicone-based skin layer used in TRAIN-KNEE by leveraging low-density TPU structures for compliance and applying a thin silicone layer in relevant spots. I also abstracted the injury simulation mechanism by focusing on a mechanical constraint responsible for resisting valgus motion. Removing an insert on the

opposing side of the MCL produced increased valgus motion similar to that observed in an MCL injury, while reinserting the component and varying its stiffness enabled control over the magnitude of the simulated injury conditions. This approach was inspired by metamaterials. While a more extensive investigation of parameters, such as cell patterns, geometries, and structural thicknesses, could offer a different response, the selected design controlling infill density was sufficient to enable practitioners to distinguish the four simulated MCL conditions. Importantly, these decisions reduced manufacturing complexity and cost while expanding injury simulation capabilities beyond TRAIN-KNEE, which address the challenge of developing more affordable training simulators.

A similar reasoning motivated the development of the generalized template system. Once it became clear that clinically meaningful mechanical behaviour depended primarily on reproducing specific effects (e.g., valgus motion) rather than recreating anatomical prototypes with high fidelity, I abstracted the underlying mechanical principles of Flex-Knee into a reusable template system. This abstraction enabled the development of a common design approach that can be adapted across multiple joints and examination procedures, which reduces the need to create independent simulators for each clinical scenario.

A critical factor that enabled the success of this design strategy was the sustained involvement of a certified clinician who conducted psychophysical calibration, who acted not only as a clinical evaluator but as an active member of this dissertation. His expertise in musculoskeletal assessment and familiarity with clinical training environments provided continuous guidance throughout the development, calibration, and evaluation of TRAIN-KNEE, Flex-Knee, and the template system. Unlike traditional evaluation approaches where practitioners are engaged primarily after system development, he con-

tributed throughout the design process by helping identify relevant requirements, assessing prototype behaviour, and guiding decisions regarding mechanical representation. His involvement highlights the importance of integrating domain expertise throughout the design process when developing educational technologies intended for clinical applications.

6.1.2 Simulators as Technology Development Platforms

TRAIN-KNEE, Flex-Knee, as well as the simulator developed for elbow valgus may extend beyond educational use and offer value as accessible platforms for research and technology development, particularly during early iteration and prototyping stages. Since they reproduce key biomechanical behaviors in a controlled and repeatable manner (e.g., flexion-extension and pronation-supination), they provide physical testbeds for evaluating emerging sensing, measurement, and interaction technologies without requiring access to human participants or cadaveric specimens. For example, research on wearable or embedded sensing systems for joint monitoring, such as the work by Young et al. (2021), often depends heavily on human trials. In contrast, the simulators presented in this dissertation can provide consistent and repeatable testing conditions that allow researchers to prototype, refine, and validate technologies in a low-risk and more accessible environment before transitioning to studies involving human participants.

Researchers are also able to select a platform according to the biomechanical requirements of the technology being studied. Some applications may only require simplified and repeatable flexion-extension or valgus-varus. In these cases, systems such as Flex-Knee with minimal modifications are sufficient, as it reproduces such motions while remaining

inexpensive, lightweight, and easy to manufacture. Other research directions, however, may require anatomically accurate physical structures and more complex joint mechanics. TRAIN-KNEE is especially valuable in these scenarios because it incorporates a realistic internal knee joint model capable of reproducing a complete biomechanical behaviour.

6.1.3 Seamless Interaction with Simulators without Training

Experts and students were able to understand how to operate all simulators quickly, without requiring instruction or prior exposure. In HCI research, one type of contribution is the development of an artifact that embodies a design concept and enables empirical investigation (Wobbrock, 2012; Wobbrock and Kientz, 2016). This was the case across chapter 3, chapter 4, and chapter 5 of this dissertation. However, unlike many HCI artifacts that require a period of on-boarding or familiarization before an interaction may occur, the simulators I developed were designed to be highly learnable. This outcome reflects a central design priority throughout this research: ensuring seamless interaction for both experienced practitioners and novice users by designing the artifacts to leverage users' existing domain knowledge and prior experience.

In all studies involving professionals, as well as in the showcase with 16 students (subsection 4.3.3), participants were able to quickly engage with the simulators and perform the intended manual assessments with minimal guidance. This suggests that the interaction paradigm successfully leveraged users' prior knowledge of physical examination techniques and eliminated the need for additional cognitive effort to learn how to use a simulator itself. As a result, participants could focus entirely on interpreting haptic feedback rather than on

understanding the technology. The only practical concern observed during testing related to the physical weight of TRAIN-KNEE. While the weight contributed positively to perceived realism (section 3.5), it also introduced a minor risk, as dropping the simulator could damage it or potentially cause injury if it landed on a participant's foot. Nonetheless, this was a logistical consideration rather than a usability barrier, and it did not interfere with participants' ability to immediately and effectively interact with the proposed prototype.

6.1.4 Design Considerations for Developing Practical Simulators Supporting Multiple Training Scenarios

An important consideration throughout this dissertation is that simulators should be deployable in the environments where training naturally occurs, rather than being restricted to specialized laboratory settings. Accordingly, the systems developed in this work were designed to minimize infrastructure requirements and support straightforward use in educational contexts such as classrooms and laboratories. Across the studies presented, the simulators were successfully deployed in a range of settings, including a campus clinical space, a dedicated research facility, and a kinesiology laboratory with students, and were also demonstrated at research conferences and academic symposia where participants were able to interact with and, in some cases, assemble the systems with minimal guidance (Figure 6.1). These deployments demonstrate the portability and ease of setup of the proposed systems, as well as their ability to be used without extensive instruction (as discussed above). Together, these characteristics support their practical integration into educational environments where time, supervision, and resources are often limited.



Figure 6.1: Student presenters with minimal prior experience assembling Flex-Knee at the 2026 Haptics Symposium conference, following only minimal instructional guidance.

The approach adopted in this dissertation also reflects a broader perspective on the role of research artifacts in medical training. Simulators for physical examination of knee and elbow injuries do not necessarily need to be highly specialized systems or provide a high level of haptic fidelity. Muender et al. (2022) highlighted that increasing haptic fidelity introduces system complexity and design constraints to haptic systems. While

this approach provides valuable research contributions, it may also introduce challenges for broader deployment in educational contexts (Daiber et al., 2020). In this dissertation, instead, I focused on developing practical, deployable, and easily manufacturable simulators, using standardized, off-the-shelf components that are widely available and familiar to general users. This design choice reduces barriers to adoption and ensures that setup and troubleshooting remain straightforward.

Furthermore, simulators should be designed to reproduce multiple scenarios. In the context of physical examination training for knee and elbow joint injuries, this dissertation suggests that such flexibility is achievable, particularly through the template system introduced in chapter 5. Prior to this work, it was unclear how readily haptic simulators in this domain could be generalized beyond a single injury or joint, and extending these systems to multiple scenarios involves trade-offs between system specificity and complexity, as highlighted in prior haptic design frameworks (Muender et al., 2022). Rather than constructing multiple isolated simulators for individual use cases, the template presented in chapter 5 demonstrates how a single design can be used to instantiate different simulator configurations through parameterized components within a reusable design pipeline. This approach also has implications for improving the cost-effectiveness of simulators.

6.1.5 Sensing Capabilities in Injury Simulation Mechanisms

Sensing capabilities were considered during the development of the injury simulation approaches implemented in both TRAIN-KNEE and Flex-Knee. In TRAIN-KNEE, varying the tension of wires allows the simulator to reproduce multiple injury conditions and gener-

ate different responses during user interaction, while Flex-Knee uses inserts with different material compositions to produce variations in perceived resistance. Directly measuring these effects was considered for both systems; however, incorporating additional sensors would increase the cost, hardware complexity, and debugging requirements of the simulators, conflicting with the broader goal of developing low-cost training tools.

Another consideration was that the literature does not report tension or compression measurements corresponding to specific injury conditions. Although human ligaments undergo deformation, existing literature provides measurements of laxity (Aronson et al., 2010; Phisitkul et al., 2006). Directly measuring laxity, however, presents different challenges in the two simulators. In Flex-Knee, laxity cannot be directly measured because the simulator does not incorporate a knee joint; instead, its mechanical structure is based on a u-joint. In TRAIN-KNEE, a proximity sensor could potentially be incorporated to measure joint displacement and estimate laxity, as explained in the existing literature (Sawant et al., 2004). However, this would require modifying the commercial knee joint model by drilling into it to position the sensor appropriately, which introduces additional hardware complexity.

Phisitkul et al. (2006) report the amount of laxity associated with each MCL injury grade. Incorporating a proximity sensor into TRAIN-KNEE capable of measuring this quantity could potentially improve the consistency with which both users perceive and classify the simulated injury conditions. Such measurements could also enable TRAIN-KNEE to operate as a closed-loop training system, in which the user's examination technique is measured and feedback is provided. This could further enhance its value as a teaching tool. However, substantially more research is needed for this. If TRAIN-KNEE were used in a

clinical setting equipped with an arthrometer (Allott, 2025), the device could potentially be used to obtain a quantitative measure of laxity. In Flex-Knee, laxity measurement is not feasible because laxity is defined by the relative displacement between the femur and tibia, neither of which is present in the simulator.

6.1.6 Perception of Intermediate Injury Grades

TRAIN-KNEE showed strong agreement among participants when distinguishing healthy from injured conditions, but greater difficulty when differentiating among Grades 1, 2, and 3. Flex-Knee similarly enabled participants to distinguish healthy, partial tear, and complete tear conditions, while greater difficulty was observed when differentiating Grades 1 and 2. Importantly, neither study involving expert practitioners resulted in an injured condition being perceived as healthy (Figure 3.10 and Figure 4.10). This distinction is important because incorrectly interpreting an injured ligament as healthy could result in an injury being missed and subsequently affect management and recovery (Chen et al., 2008). From a training perspective, reliably recognizing the difference between a healthy and injured condition is therefore a fundamental skill that I believe should be established before learners attempt to differentiate injury severity grades. The results suggest that both simulators were effective for this.

TRAIN-KNEE had greater difficulty differentiating grades 1, 2, and 3. Flex-Knee was able to distinguish healthy, partial tear, and complete tear conditions, but showed greater difficulty differentiating grades 1 and 2. The disagreement observed among participants when assigning individual injury grades does not necessarily indicate that the

simulators failed to reproduce meaningful injury-related responses. Rather, it could reflect the difficulty of distinguishing subtle differences within the injured conditions themselves without additional information (e.g., pain and patient input). From a clinical perspective, accurately characterizing injury severity is important because the grade of an MCL injury contributes to decisions regarding treatment and rehabilitation. Although grades 1 and 2 injuries are generally managed with non-operative treatment and rehabilitation, management of grade 3 injuries is more variable and depends on factors such as the extent and location of the injury and the presence of concurrent injuries (Encinas-Ullán and Rodríguez-Merchán, 2018). Some cases might need surgery, others might not. In training, misclassifications limit a novice practitioner's ability to accurately associate different examination responses with the corresponding severity of ligament injury, which could potentially carry over to clinical practice and contribute to an incorrect assessment of injury severity. However, as previously mentioned, a distinction between grade 2 and grade 3 injuries is not made from the test alone and requires consideration of other clinical findings (Chen et al., 2008). Instead of focusing solely on the consequences of learners incorrectly distinguishing grade 2 from grade 3 using TRAIN-KNEE or Flex-Knee, I propose enhancing these systems to simulate more realistic training environments, where learners can receive the additional information needed to develop a more complete assessment. In section 6.3, I discuss next steps for developing the simulators presented in this thesis into more complete and realistic training platforms.

6.2 Limitations

Minimal Quantitative Baseline for Injury Simulation

A quantitative baseline for the response associated with different injury conditions during tests like the Valgus test remains difficult to establish. For knee MCL, I identified only one study providing relevant quantitative measurements in the literature (Kastelein et al., 2008), and these measurements were reported at 30° of knee flexion, which limits its applicability to the range of conditions considered in this work. Consequently, I established the simulated injury conditions using expert practitioner assessment as a clinically informed reference. My approach was a practical basis for configuring the simulators, but the absence of an established quantitative biomechanical baseline limits the extent to which the simulated injury conditions can be objectively calibrated and validated. Further work is therefore needed to characterize the responses associated with different injury conditions and establish quantitative reference values for more objective calibration and validation of future simulators.

Sample Size Limitations in Research Studies

Another important limitation of this work relates to sample size and The distribution of participants across the calibration and evaluation stages. For both TRAIN-KNEE (chapter 3) and Flex-Knee (chapter 4), one clinician performed the calibration procedure through the staircase method, followed by evaluations conducted with six additional clinicians. A potential alternative approach would have been to increase the number of participants involved in the calibration while reducing the number of experts involved in the subsequent evaluations. However, recruiting practitioners presents substantial logistical challenges, as

clinicians often have demanding professional responsibilities and limited availability for research participation (Valentino and Juanico, 2020). Given the clinician's extensive experience in musculoskeletal assessment across clinical and field settings, I considered his judgment appropriate for establishing calibration of the injury conditions. However, sensitivity and specificity results obtained from evaluations with additional clinicians (Table 3.2 and Table 4.2) suggest that future work may investigate multi-clinician calibration to determine whether it improves agreement and grade differentiation.

The expert evaluations presented in this thesis should be interpreted as preliminary evaluations. Their primary objective was to obtain initial evidence regarding educational value and perceptual characteristics of the developed simulators rather than to refine the experimental protocol for a larger confirmatory study. Although the sample sizes are consistent with early-stage exploratory evaluations involving domain experts (Caine, 2016), they remain limited in terms of statistical power and generalizability. These findings therefore provide initial evidence of feasibility and motivate future validation with larger and more diverse participant populations.

Multi-ligament injuries were beyond the current scope

Combined injuries to the ACL and MCL are the most common multi-ligament knee injuries in the general population (Andrews et al., 2017; Westermann et al., 2019). Even with the template proposed in chapter 5, the current approach does not support such cases of multiple co-occurring conditions. The framework is designed to mimic and vary a single injury at a time, which limits its ability to represent more complex clinical presentations

where multiple structures may be affected at the same time. This becomes particularly clear when comparing Flex-Knee with the knee ACL model (section 5.3). In the latter, the leg-like structure must be divided into two separate parts to enable the anterior tibial translation required for the Lachman test. However, this design choice undermines the MCL use case, which relies on maintaining a single continuous structure at the knee joint level (Figure 4.3). A unified structure supporting both use cases would need to be sufficiently compliant at the joint level to reproduce tibial translation, while simultaneously remaining stiff enough to avoid introducing undesired valgus/varus effects. More sophisticated metamaterial-inspired designs might help address these requirements, in which motion is selectively constrained in one direction while being highly enabled in another.

Applied user pressure remains a key limitation

Unlike other existing systems in the literature such as SpinalLog (Chacon et al., 2019) and vARtebrae (Tatsuzawa et al., 2025), the three simulators presented do not operate as closed-loop systems, as they lack integrated sensing mechanisms for measuring applied pressure during interaction. In particular, attempts to incorporate FSR sensors were not successful. One key challenge is the variability in how participants hold the simulators (illustrated in Figure 3.7, Figure 4.9, Figure 4.12), with hand placement differing significantly across users, making it difficult to rely on fixed FSR sensors. Achieving adequate coverage with FSRs would require distributing a large number of sensors across the simulators, which would substantially increase complexity. These limitations indicate the need for an alternative sensing approach that can provide higher spatial resolution while remain-

ing scalable and robust to variations in user interaction. Teyssier et al. (2019) proposes a potential solution for this limitation.

6.3 Future Work

Evaluation of educational effectiveness and learning transfer

If the goal is to avoid developing systems that are never deployed or evaluated in practice, then failing to validate them beyond a research setting risks wasting both time and resources. For instance, a key (and obvious) next step for this line of work is a more systematic and longitudinal evaluation of learning outcomes. While the studies presented in this dissertation primarily focus on feasibility and design validation with experts, they do not yet address whether interaction with these simulators translates into measurable educational benefits. Future work should therefore investigate whether repeated exposure to the simulators improves diagnostic accuracy in students, enhances retention of clinical knowledge, and supports the transfer of skills to real-world clinical environments.

This is particularly important because the primary motivation (section 1.1) for developing such simulators is accelerating the learning process of novice practitioners in kinesiology and health sciences. While the collected qualitative and quantitative student feedback about their educational value was positive (subsection 4.3.3), it does not capture how well it supports learning over time or how durable that learning is. In a few words, empirical support is needed. Longitudinal studies (Premkumar et al., 2013), ideally involving comparisons with traditional training methods or alternative simulation approaches,

would be necessary to better understand the pedagogical value of the proposed simulators. Establishing this evidence base is essential to show that they work in practice and to ensure that design decisions truly support clinical training outcomes.

Despite the importance of such longitudinal validation, its implementation presents both methodological and logistical constraints that substantially increase the scope of this work. Instructional science suggests that the acquisition of clinical expertise is strongly influenced by *deliberate practice*, which involves repetitive task execution, rigorous structured assessment, targeted feedback, and progressively improved performance in a controlled environment (Issenberg et al., 2005). While the available cohort for this dissertation (undergraduate students in the KIN-491 course) is exposed to a range of joint injuries and practices multiple clinical examination tests, incorporating simulator-based assessments into this curriculum is limited by restricted instructional time and existing curriculum requirements. Short-term evaluations are feasible, but they may not adequately capture skill retention or longer-term learning effects (Cook et al., 2011). Additional limitations arise from the current design of the simulators developed in this dissertation, which operate as open-loop systems and do not provide performance feedback, which does not align with the deliberate practice framework. Evaluation is further complicated by variability in clinical practice, as even expert practitioners may differ in the execution of physical examination techniques such as the Valgus test. Finally, while existing laxity measurements (Kastelein et al., 2008) could provide a reference for indicating whether a learner performed a test correctly, the absence of a bone-based anatomical model in some simulators (e.g., Flex-Knee) limits the ability to establish a clear ground truth for learning assessment.

Effect of model scaling on infill density of inserts

An additional open question concerns the relationship between scale and mapping between infill density of inserts (in Flex-Knee and elbow UCL prototypes) and perceived injury condition. Currently, it is unclear whether increasing or reducing the physical size of the simulators alters how experts and students interpret or perceive differences. Addressing this uncertainty would require systematic evaluation across multiple model sizes to determine whether the current mappings (Figure 4.8 and Figure 5.8) remain stable or need to be recalibrated when scaling the designs.

Long-term material behaviour and stability of TPU inserts

An important aspect for future work concerns the long-term behaviour of the TPU 95A and TPU 85A inserts under repeated use. Flexible materials such as thermoplastic polyurethane are known to undergo gradual mechanical changes over time when subjected to continuous loading, repeated deformation, and environmental exposure such as moisture, temperature variations, and humidity (Slater et al., 2011). In the present work, I took precautions to mitigate such effects. I stored inserts in a dry environment, and the TPU spools used for fabrication were dried in a dehumidifier prior to printing. Nevertheless, over extended use, these effects may influence the mechanical response of the inserts, potentially altering their stiffness and deformation characteristics and, in turn, affecting how injury states are perceived. Investigating these effects in more detail would help better understand material stability and inform the design of more robust long-term systems.

Multimodal integration for more realistic training scenarios

A promising direction for extending this work is the integration of multimodal feedback, recognizing that clinical assessment does not rely solely on physical examination. In practice, clinicians combine tactile information with additional cues (Phisitkul et al., 2006), including patient-reported pain, muscular guarding, visible swelling, facial expressions, and contextual patient history. Future systems could therefore augment the haptic feedback provided by the simulators presented in this dissertation with complementary visual, auditory, and contextual information. One possible implementation could involve integrating the simulators with a VR interface in which the physical devices are co-located with the limbs of a virtual patient. In such a scenario, the virtual patient could verbally respond to examination procedures, display facial expressions associated with pain or discomfort, and provide relevant contextual information. Existing virtual patient assets and systems already demonstrate the feasibility of these interactions (Sushereba and Militello, 2020). Such environments could also support more self-directed learning experiences (Ruthenbeck and Reynolds, 2015). At the same time, adding more modalities should be carefully considered, as increased complexity may compromise the low-cost and simplicity aspects.

Another promising direction is the enhancement of the simulators to incorporate additional characteristics commonly encountered in clinical assessment. As discussed previously, clinical evaluation involves factors such as pain, swelling, and patient guarding (Lubowitz et al., 2008), which are not currently represented in the simulators presented in this dissertation. While approaches such as particle jamming techniques (Brown and Bello, 2024) to emulate swelling or inflammation through dynamically altered stiffness, and

active haptic mechanisms (McClelland et al., 2017) to simulate guarding responses such as reflexive muscular resistance, offer compelling possibilities, they may also introduce increased initial cost and system complexity. In this context, more affordable or scalable alternatives, including digital metamaterial designs (Ion et al., 2017), could be explored in future work. In addition, a second simulator representing an uninjured limb could be incorporated, reflecting common clinical practice in which practitioners compare the injured joint against the healthy limb (Lubowitz et al., 2008).

Classifying simulators within haptic fidelity frameworks

Finally, characterizing the new class of simulators I presented in terms of haptic fidelity—the capability to produce realistic or abstract feedback relative to the intent of the system (Muender et al., 2022; Vincenzi et al., 2009)—is relevant because it provides a structured means of articulating and comparing how different design decisions affect perceived realism and functional performance. This enables deeper analysis of their feedback characteristics and potentially informs the development of future designs.

To conduct this characterization, domain experts would be required to participate in a guided evaluation session, where TRAIN-KNEE, Flex-Knee, as well as the Elbow UCL and Knee ACL prototypes, are examined through the lens of a framework's key dimensions, such as the Haptic Fidelity Framework (Muender et al., 2022). Participants could be asked to compare how each simulator aligns with or diverges from real clinical examination experiences, and to discuss how these differences manifest in perceived diagnostic cues during use. The collected feedback could then be synthesized into a structured rating or

mapping of each simulator across the framework dimensions, allowing for both quantitative scoring and qualitative thematic analysis of expert interpretations. This would also help validate whether the dimensions proposed by Muender et al. (2022), originally developed for devices in VR but suggested by the authors to generalize to haptic systems more broadly, are applicable to the new class of artifacts proposed in this dissertation.

Chapter 7

Conclusion

This dissertation aims to provide tools that offer structured, safe, and repeatable training opportunities for manual musculoskeletal physical assessment in kinesiology and health sciences. In clinical education, practitioners rely heavily on experiential learning opportunities to interpret tactile cues from human joints; however, access to relevant injury conditions is limited in traditional training environments due to the use of healthy peers, ethical constraints, and variability in patient availability. Consequently, novice practitioners face challenges in developing competency across the breadth of conditions encountered in real clinical practice. This work investigates how passive haptic simulators can support and accelerate this learning process.

In doing so, three main limitations in existing research have been addressed. First, relatively little work has focused on simulators for manual physical examination, despite the importance of tactile feedback and hands-on manipulation in these skills. Second,

access to haptic simulators is often restricted to well-resourced institutions due to high cost and infrastructure requirements. This limits their availability for regular or independent practice, particularly for students and trainees. Third, many existing systems are designed for a single task and cannot easily be adapted to other assessments or injury types. This is a limitation given that clinical practice requires practitioners to perform a wide range of assessments across different joints and conditions. I addressed these limitations through three projects.

First, I presented TRAIN-KNEE: a high-fidelity passive haptic simulator designed to reproduce MCL injury conditions and support training in the Valgus test. TRAIN-KNEE was developed in collaboration with a certified clinician and evaluated through multiple studies involving clinicians and technical measurements (i.e., range of motion). Results demonstrated that TRAIN-KNEE can reliably represent healthy and injured conditions, although distinguishing between finer injury grades remains an area for improvement.

Second, I presented Flex-Knee, a low-cost, modular, and scalable alternative designed to preserve the core functional realism of TRAIN-KNEE while improving manufacturability and affordability. Flex-Knee was evaluated through calibration, clinician studies, and student testing, and demonstrated its ability to differentiate between healthy, partially torn, and fully torn MCL conditions. These results show that clinically relevant tactile experiences can be achieved with reduced cost and increased design flexibility, although refinement is still needed for intermediate injury grading (grades 1 and 2).

Third, I presented a generalized template system for designing passive haptic simulators for manual physical assessment across multiple joint types. This approach is based on a

base mechanical joint with tunable parameters and modular material design, which enables adaptation to different joints and injury scenarios. The template was demonstrated through knee and elbow simulators, with preliminary evaluations indicating sufficient fidelity for intended training tasks and accurate condition configuration across multiple use cases.

Together, these contributions establish a progression from a high-fidelity, task-specific simulator to a scalable and more cost-effective solution, and finally to a generalized design approach for passive haptic training simulators. Across these stages, this dissertation demonstrates that meaningful tactile experiences for joint injury assessment can be reproduced using passive approaches while progressively improving affordability, modularity, and adaptability. More broadly, this work advances the design space of haptic training tools in kinesiology and health sciences and provides a foundation for future systems that support safe, repeatable, and effective development of manual clinical skills.

References

Qingsong Ai, Congsheng Zhang, Weifeng Wu, Chi Zhang, and Wei Meng. Design and implementation of haptic sensing interface for ankle rehabilitation robotic platform. In *2018 IEEE 15th International Conference on Networking, Sensing and Control (ICNSC)*, pages 1–6. IEEE, 3 2018. ISBN 978-1-5386-5053-0. doi: 10.1109/ICNSC.2018.8361366. URL https://ieeexplore.ieee.org/document/8361366/.

Adil Ajuied, Fabian Wong, Christian Smith, Mark Norris, Peter Earnshaw, Diane Back, and Andrew Davies. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis. *The American Journal of Sports Medicine*, 42:2242–2252, 9 2014. ISSN 0363-5465. doi: 10.1177/0363546513508376. URL https://journals.sagepub.com/doi/10.1177/0363546513508376.

Stephen M Alessi. Fidelity in the design of instructional simulations. *Journal of computer-based instruction*, 1988.

Natasha E. H. Allott. The methods of quantifying knee laxity in the acl injured population: A review. *The Knee*, 2025. doi: 10.1016/j.knee.2025.04.009. URL https://doi.org/10.1016/j.knee.2025.04.009.

Kyle Andrews, Alex Lu, Lucas Mckean, and Nabil Ebraheim. Review: Medial collateral ligament injuries. *Journal of Orthopaedics*, 14:550–554, 12 2017. ISSN 0972978X. doi: 10.1016/j.jor.2017.07.017. URL https://linkinghub.elsevier.com/retrieve/pii/S0972978X17301563.

Patricia A. Aronson, Joe H. Gieck, Jay Hertel, Arie M. Rijke, and Christopher D. Ingersoll. Tibiofemoral joint positioning for the valgus stress test. *Journal of Athletic Training*, 45:357–363, 7 2010. ISSN 1062-6050. doi: 10.4085/1062-6050-45.4.357. URL https://meridian.allenpress.com/jat/article/45/4/357/111154/Tibiofemoral-Joint-Positioning-for-the-Valgus.

Jatin Arora, Aryan Saini, Nirmita Mehra, Varnit Jain, Shwetank Shrey, and Aman Parnami. Virtualbricks: Exploring a scalable, modular toolkit for enabling physical manipulation in vr. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pages 1–12. ACM Press, 2019. ISBN 9781450359702. doi: 10.1145/3290605.3300286. URL http://dl.acm.org/citation.cfm?doid=3290605.3300286.

Octave Nadile Bandiaky, Serena Lopez, Ludovic Hamon, Roselyne Clouet, Assem Soueidan, and Laurent Le Guehennec. Impact of haptic simulators in preclinical dental education: A systematic review. *Journal of Dental Education*, 88:366–379, 3 2024. ISSN 0022-0337. doi: 10.1002/jdd.13426. URL https://onlinelibrary.wiley.com/doi/10.1002/jdd.13426.

Sandra Berney, Mireille Bétrancourt, Gaëlle Molinari, and Nady Hoyek. How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3d

anatomical models. *Anatomical Sciences Education*, 8:452–462, 9 2015. ISSN 19359772. doi: 10.1002/ase.1524. URL https://onlinelibrary.wiley.com/doi/10.1002/ase.1524.

David Bertolo, Stéphanie Fleck, Camille Lemiere, and Isabelle Pecci. Tangible user interface in health: A scoping review. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 1–25. ACM, 3 2025. ISBN 9798400711978. doi: 10.1145/3689050.3704951. URL https://dl.acm.org/doi/10.1145/3689050.3704951.

Suzanne C. Beyea and Linda J. Kobokovich. Human patient simulation: A teaching strategy. *AORN Journal*, 80:738–742, 10 2004. ISSN 0001-2092. doi: 10.1016/S0001-2092(06)61329-X. URL https://aornjournal.onlinelibrary.wiley.com/doi/10.1016/S0001-2092%2806%2961329-X.

Bernd Bickel, Moritz Bächer, Miguel A. Otaduy, Hyunho Richard Lee, Hanspeter Pfister, Markus Gross, and Wojciech Matusik. Design and fabrication of materials with desired deformation behavior. *ACM Transactions on Graphics*, 29:1–10, 7 2010. ISSN 0730-0301. doi: 10.1145/1778765.1778800. URL https://dl.acm.org/doi/10.1145/1778765.1778800.

Robert Bloom, Zachary Huang, Kaitlyn Lavarias, Madeleine Ren, and Tania K. Morimoto. H 3 kit: Hand-held haptic kit for stem education. In *2024 IEEE Haptics Symposium (HAPTICS)*, pages 251–258. IEEE, 4 2024. ISBN 979-8-3503-4511-7. doi: 10.1109/HAPTICS59260.2024.10520857. URL https://ieeexplore.ieee.org/document/10520857/.

T. P. Branch, S. K. Stinton, R. Siebold, H. I. Freedberg, C. A. Jacobs, and W. C. Hutton. Assessment of knee laxity using a robotic testing device: a comparison to the manual clinical knee examination. *Knee Surgery, Sports Traumatology, Arthroscopy*, 25:2460–2467, 8 2017. ISSN 0942-2056. doi: 10.1007/s00167-015-3935-7. URL http://link.springer.com/10.1007/s00167-015-3935-7.

Joshua Brown and Fernando Bello. Design and characterisation of particle jamming-based variable stiffness displays using non-pneumatic actuators. In *2024 IEEE Haptics Symposium (HAPTICS)*, pages 379–384. IEEE, 4 2024. ISBN 979-8-3503-4511-7. doi: 10.1109/HAPTICS59260.2024.10520854. URL https://ieeexplore.ieee.org/document/10520854/.

Bohong Cai, Kanagasuntheram Rajendran, Boon Huat Bay, Jieying Lee, and Ching-Chiuan Yen. The effects of a functional three-dimensional (3d) printed knee joint simulator in improving anatomical spatial knowledge. *Anatomical Sciences Education*, 12:610–618, 11 2019. ISSN 1935-9772. doi: 10.1002/ase.1847. URL https://anatomypubs.onlinelibrary.wiley.com/doi/10.1002/ase.1847.

Kelly Caine. Local standards for sample size at chi. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 981–992. ACM, 5 2016. ISBN 9781450333627. doi: 10.1145/2858036.2858498. URL https://dl.acm.org/doi/10.1145/2858036.2858498.

D. Antony Chacon, Eduardo Velloso, Thuong Hoang, and Katrin Wolf. Spinallog: Visuo-haptic feedback in musculoskeletal manipulation training. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages

5–14. ACM, 3 2019. ISBN 9781450361965. doi: 10.1145/3294109.3295626. URL https://dl.acm.org/doi/10.1145/3294109.3295626.

Jack Shen-Kuen Chang, Georgina Yeboah, Alison Doucette, Paul Clifton, Michael Nitsche, Timothy Welsh, and Ali Mazalek. Tasc: Combining virtual reality with tangible and embodied interactions to support spatial cognition. In *Proceedings of the 2017 Conference on Designing Interactive Systems*, pages 1239–1251. ACM, 6 2017. ISBN 9781450349222. doi: 10.1145/3064663.3064675. URL https://dl.acm.org/doi/10.1145/3064663.3064675.

Lan Chen, Paul D. Kim, Christopher S. Ahmad, and William N. Levine. Medial collateral ligament injuries of the knee: current treatment concepts. *Current Reviews in Musculoskeletal Medicine*, 1:108–113, 6 2008. ISSN 1935-9748. doi: 10.1007/s12178-007-9016-x. URL https://link.springer.com/10.1007/s12178-007-9016-x.

Eunseong Cho and Seonghoon Kim. Cronbach's coefficient alpha: Well known but poorly understood. *Organizational Research Methods*, 18:207–230, 4 2015. ISSN 1094-4281. doi: 10.1177/1094428114555994. URL https://journals.sagepub.com/doi/10.1177/1094428114555994.

Janelle P. Clark, Sung Y. Kim, and Marcia K. O'Malley. The rice haptic rocker: Altering the perception of skin stretch through mapping and geometric design. In *2018 IEEE Haptics Symposium (HAPTICS)*, pages 192–197. IEEE, 3 2018. ISBN 978-1-5386-5424-8. doi: 10.1109/HAPTICS.2018.8357175. URL https://ieeexplore.ieee.org/document/8357175/.

Hazel M. Clarkson. *Musculoskeletal assessment*, pages 148–152. Routledge, 1 2022. ISBN 9781609138165. URL https://www.taylorfrancis.com/books/9781003045267/chapters/10.4324/9781003045267-26.

Timothy R. Coles, Dwight Meglan, and Nigel W. John. The role of haptics in medical training simulators: A survey of the state of the art. *IEEE Transactions on Haptics*, 4: 51–66, 1 2011. ISSN 1939-1412. doi: 10.1109/TOH.2010.19. URL http://ieeexplore.ieee.org/document/5453367/.

David A. Cook, Rose Hatala, Ryan Brydges, Benjamin Zendejas, Jason H. Szostek, Amy T. Wang, Patricia J. Erwin, and Stanley J. Hamstra. Technology-enhanced simulation for health professions education. *JAMA*, 306:978–988, 9 2011. ISSN 0098-7484. doi: 10.1001/jama.2011.1234. URL http://jama.jamanetwork.com/article.aspx?doi=10.1001/jama.2011.1234.

Tom N. Cornsweet. The staircase-method in psychophysics. *The American Journal of Psychology*, 75:485, 9 1962. ISSN 00029556. doi: 10.2307/1419876. URL https://www.jstor.org/stable/1419876?origin=crossref.

Florian Daiber, Donald Degraen, André Zenner, Frank Steinicke, Oscar Javier Ariza Núñez, and Adalberto L. Simeone. Everyday proxy objects for virtual reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–8. ACM, 4 2020. ISBN 9781450368193. doi: 10.1145/3334480.3375165. URL https://dl.acm.org/doi/10.1145/3334480.3375165.

Kamal Deep. Collateral ligament laxity in knees: What is normal? *Clinical Orthopaedics & Related Research*, 472:3426–3431, 11 2014. ISSN 0009-921X. doi: 10.1007/s11999-014-3865-6. URL https://journals.lww.com/00003086-201411000-00029.

Donald Degraen, André Zenner, and Antonio Krüger. Enhancing texture perception in virtual reality using 3d-printed hair structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–12. ACM, 5 2019. ISBN 9781450359702. doi: 10.1145/3290605.3300479. URL https://dl.acm.org/doi/10.1145/3290605.3300479.

Sébastien Delorme, Denis Laroche, Robert DiRaddo, and Rolando F. Del Maestro. Neurotouch: a physics-based virtual simulator for cranial microneurosurgery training. *Neurosurgery*, 71(1):ons32–ons42, 2012. ISSN 0148-396X. doi: 10.1227/NEU.0b013e318249c744. URL https://pubmed.ncbi.nlm.nih.gov/22233921/.

Steven Ding and Colin Gallacher. The haply development platform: A modular and open-sourced entry level haptic toolset. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–4. ACM, 4 2018. ISBN 9781450356213. doi: 10.1145/3170427.3186512. URL https://dl.acm.org/doi/10.1145/3170427.3186512.

Christopher Edwards and Ronald Marks. Evaluation of biomechanical properties of human skin. *Clinics in Dermatology*, 13:375–380, 7 1995. ISSN 0738081X. doi: 10.1016/0738-081X(95)00078-T. URL https://linkinghub.elsevier.com/retrieve/pii/0738081X9500078T.

Carlos A. Encinas-Ullán and E. Carlos Rodríguez-Merchán. Isolated medial collateral ligament tears: An update on management. *EFORT Open Reviews*, 3:398–407, 7 2018. ISSN 2058-5241. doi: 10.1302/2058-5241.3.170035. URL https://journals.bioscientifica.com/eor/article/3/7/398/2107/Isolated-medial-collateral-ligament-tears-An.

David Escobar-Castillejos, Julieta Noguez, Luis Neri, Alejandra Magana, and Bedrich Benes. A review of simulators with haptic devices for medical training. *Journal of Medical Systems*, 40:104, 4 2016. ISSN 0148-5598. doi: 10.1007/s10916-016-0459-8. URL http://link.springer.com/10.1007/s10916-016-0459-8.

Cathy Mengying Fang, Ryo Suzuki, and Daniel Leithinger. Vr haptics at home: Repurposing everyday objects and environment for casual and on-demand vr haptic experiences. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pages 1–7. ACM, 4 2023. ISBN 9781450394222. doi: 10.1145/3544549.3585871. URL https://dl.acm.org/doi/10.1145/3544549.3585871.

Faraz Faruqi, Maxine Perroni-Scharf, Jaskaran Singh Walia, Yunyi Zhu, Shuyue Feng, Donald Degraen, and Stefanie Mueller. Tactstyle: Generating tactile textures with generative ai for digital fabrication. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, pages 1–16. ACM, 4 2025. ISBN 9798400713941. doi: 10.1145/3706598.3713740. URL https://dl.acm.org/doi/10.1145/3706598.3713740.

Shereen Fathy and Magdi El Messiry. Study of the effect of cyclic stress on the mechanical properties of braided anterior cruciate ligament (acl). *Journal of Textile Science & Engineering*, 06, 2016. doi:

10.4172/2165-8064.1000252. URL https://www.omicsgroup.org/journals/study-of-the-effect-of-cyclic-stress-on-the-mechanical-properties-ofbraided-anterior php?aid=72475.

Martin Feick, Scott Bateman, Anthony Tang, Andre Miede, and Nicolai Marquardt. Tangi: Tangible proxies for embodied object exploration and manipulation in virtual reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 195–206. IEEE, 11 2020. ISBN 978-1-7281-8508-8. doi: 10.1109/ISMAR50242.2020.00042. URL https://ieeexplore.ieee.org/document/9284771/.

Martin Feick, Cihan Biyikli, Kiran Gani, Anton Wittig, Anthony Tang, and Antonio Krüger. Voxelhap: A toolkit for constructing proxies providing tactile and kinesthetic haptic feedback in virtual reality. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*, pages 1–13. ACM, 10 2023. ISBN 9798400701320. doi: 10.1145/3586183.3606722. URL https://dl.acm.org/doi/10.1145/3586183.3606722.

Renaud Felten, Kevin Bigaut, Thomas Wirth, Laurent Kremer, Lucas Gauer, Cécile Arnold, Irène Ollivier, Julien Godet, Marc Scherlinger, Maxime Dubois, Eden Sebbag, Jerome De Sèze, and Jacques-Eric Gottenberg. Advancing medical training with augmented reality and haptic feedback simulator: outcomes of a randomized controlled trial on lumbar puncture. *BMC Medical Education*, 25:1231, 8 2025. ISSN 1472-6920. doi: 10.1186/s12909-025-07536-6. URL https://bmcmededuc.biomedcentral.com/articles/10.1186/s12909-025-07536-6.

Joseph F. Fetto and John L. Marshall. Medial collateral ligament injuries of the knee. *Clinical Orthopaedics and Related Research*, 132:206–218, 5 1978. ISSN 0009-921X. doi: 10.1097/00003086-197805000-00038. URL http://journals.lww.com/00003086-197805000-00038.

Bernhard Fink, Karl Grammer, and Paul J. Matts. Visible skin color distribution plays a role in the perception of age, attractiveness, and health in female faces. *Evolution and Human Behavior*, 27:433–442, 11 2006. ISSN 10905138. doi: 10.1016/j.evolhumbehav.2006.08.007. URL https://linkinghub.elsevier.com/retrieve/pii/S1090513806000602.

Jonas Forsslund, Michael Yip, and Eva-Lotta Sallnäs. Woodenhaptics: A starting kit for crafting force-reflecting spatial haptic devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 133–140. ACM, 1 2015. ISBN 9781450333054. doi: 10.1145/2677199.2680595. URL https://dl.acm.org/doi/10.1145/2677199.2680595.

Muhammad Fouad, Tamer Mansour, and Tamer Nabil. Use of haptic devices in education: A review. *Suez Canal Engineering, Energy and Environmental Science*, 1:18–22, 1 2023. ISSN 2805-315X. doi: 10.21608/sceee.2023.279487. URL https://sceee.journals.ekb.eg/article_279487.html.

Fanny Frauziols, Pierre Badel, Laurent Navarro, Jérôme Molimard, Nicolas Curt, and Stéphane Avril. *Subject-Specific Computational Prediction of the Effects of Elastic Compression in the Calf*, pages 523–544. Elsevier, 2017. ISBN 9780128040607.

doi: 10.1016/B978-0-12-804009-6.00024-9. URL https://linkinghub.elsevier.com/retrieve/pii/B9780128040096000249.

Hiromichi Fujie, Glen A. Livesay, Masahiro Fujita, and Savio L-Y. Woo. Forces and moments in six-dof at the human knee joint: Mathematical description for control. *Journal of Biomechanics*, 29:1577–1585, 12 1996. ISSN 00219290. doi: 10.1016/S0021-9290(96)80009-1. URL https://linkinghub.elsevier.com/retrieve/pii/S0021929096800091.

Joshua W Giles, Yawen Chen, and Stuart Bowyer. Development of a knee physical exam haptic training simulator: Validation of the computational haptic environment. *CAOS 2017. 17th Annual Meeting of the International Society for Computer Assisted Orthopaedic Surgery*, 1:135–130, 2018. doi: 10.29007/bgl7. URL https://easychair.org/publications/paper/RKvr.

Graham S. Goh, Ryan Lohre, Javad Parvizi, and Danny P. Goel. Virtual and augmented reality for surgical training and simulation in knee arthroplasty. *Archives of Orthopaedic and Trauma Surgery*, 141:2303–2312, 12 2021. ISSN 0936-8051. doi: 10.1007/s00402-021-04037-1. URL https://link.springer.com/10.1007/s00402-021-04037-1.

Michel Goossens, Frank Mittelbach, and Alexander Samarin. *The LaTeX Companion*. Addison-Wesley, Reading, Massachusetts, 1994.

Gowthaman Gunabushanam, Felix Nautsch, Ian Mills, and Leslie M. Scoutt. Accessible personal ultrasound training simulator. *Journal of Ultrasound in Medicine*, 38:1425–

1432, 6 2019. ISSN 0278-4297. doi: 10.1002/jum.14820. URL https://onlinelibrary.wiley.com/doi/10.1002/jum.14820.

P.-A. Heng, C.-Y. Cheng, T.-T. Wong, Y. Xu, Y.-P. Chui, K.-M. Chan, and S.-K. Tso. A virtual-reality training system for knee arthroscopic surgery. *IEEE Transactions on Information Technology in Biomedicine*, 8:217–227, 6 2004. ISSN 1089-7771. doi: 10.1109/TITB.2004.826720. URL http://ieeexplore.ieee.org/document/1303565/.

Kerm Henriksen, David Rodrick, Erin N. Grace, and P. Jeffrey Brady. Challenges in health care simulation: Are we learning anything new? *Academic Medicine*, 93:705–708, 5 2018. ISSN 1040-2446. doi: 10.1097/ACM.0000000000001891. URL https://academic.oup.com/academicmedicine/article/93/5/705/8349068.

JC Hughston, JR Andrews, MJ Cross, and A Moschi. Classification of knee ligament instabilities. part i. the medial compartment and cruciate ligaments. *The Journal of Bone & Joint Surgery*, 58:159–172, 3 1976. ISSN 0021-9355. doi: 10.2106/00004623-197658020-00001. URL http://journals.lww.com/00004623-197658020-00001.

Alexandra Ion and Patrick Baudisch. Interactive metamaterials. *Interactions*, 27:88–91, 12 2019. ISSN 1072-5520. doi: 10.1145/3374498. URL https://dl.acm.org/doi/10.1145/3374498.

Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. Metamaterial mechanisms. In *Proceedings of the 29th Annual Symposium on User Interface Software and*

Technology, pages 529–539. ACM, 10 2016. ISBN 9781450341899. doi: 10.1145/2984511.2984540. URL https://dl.acm.org/doi/10.1145/2984511.2984540.

Alexandra Ion, Ludwig Wall, Robert Kovacs, and Patrick Baudisch. Digital mechanical metamaterials. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, volume 2017-May, pages 977–988. ACM, 5 2017. ISBN 9781450346559. doi: 10.1145/3025453.3025624. URL https://dl.acm.org/doi/10.1145/3025453.3025624.

Shun Ishikawa, Shogo Okamoto, Kaoru Isogai, Yasuhiro Akiyama, Naomi Yanagihara, and Yoji Yamada. Assessment of robotic patient simulators for training in manual physical therapy examination techniques. *PLOS ONE*, 10:e0126392, 4 2015. ISSN 1932-6203. doi: 10.1371/journal.pone.0126392. URL https://dx.plos.org/10.1371/journal.pone.0126392.

S. Barry Issenberg, William C. Mcgaghie, Emil R. Petrusa, David Lee Gordon, and Ross J. Scalese. Features and uses of high-fidelity medical simulations that lead to effective learning: a beme systematic review. *Medical Teacher*, 27:10–28, 1 2005. ISSN 0142-159X. doi: 10.1080/01421590500046924. URL http://www.tandfonline.com/doi/full/10.1080/01421590500046924.

James H. Johnson. Importance of dissection in learning anatomy: Personal dissection versus peer teaching. *Clinical Anatomy*, 15:38–44, 1 2002. ISSN 0897-3806. doi: 10.1002/ca.1090. URL https://onlinelibrary.wiley.com/doi/10.1002/ca.1090.

Lynette A. Jones and Hong Z. Tan. Application of psychophysical techniques to haptic research. *IEEE Transactions on Haptics*, 6:268–284, 7 2013. ISSN 1939-1412. doi: 10.1109/TOH.2012.74. URL http://ieeexplore.ieee.org/document/6381409/.

Hamed Joodaki and Matthew B. Panzer. Skin mechanical properties and modeling: A review. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 232:323–343, 4 2018. ISSN 0954-4119. doi: 10.1177/0954411918759801. URL http://journals.sagepub.com/doi/10.1177/0954411918759801.

Bibhushan Raj Joshi, Ana Lucia Diaz de Leon Derby, Jennifer J. Llewellyn, Kristina Llewellyn, Jennifer Roberts-Smith, and Oliver Schneider. Feel–play–imagine: Structured introduction and imagination of haptics with storytellers. *International Journal of Human-Computer Studies*, 208:103631, 1 2026. ISSN 10715819. doi: 10.1016/j.ijhcs.2025.103631. URL https://linkinghub.elsevier.com/retrieve/pii/S1071581925001880.

Ho-Joong Jung, Matthew B Fisher, and Savio L-Y Woo. Role of biomechanics in the understanding of normal, injured, and healing ligaments and tendons. *BMC Sports Science, Medicine and Rehabilitation*, 1:9, 12 2009. ISSN 2052-1847. doi: 10.1186/1758-2555-1-9. URL https://bmcsportsscimedrehabil.biomedcentral.com/articles/10.1186/1758-2555-1-9.

Marlous Kastelein, Harry P.A. Wagemakers, Pim A.J. Luijsterburg, Jan A.N. Verhaar, Bart W. Koes, and Sita M.A. Bierma-Zeinstra. Assessing medial collateral ligament

knee lesions in general practice. *The American Journal of Medicine*, 121:982–988.e2, 11 2008. ISSN 00029343. doi: 10.1016/j.amjmed.2008.05.041. URL https://linkinghub.elsevier.com/retrieve/pii/S0002934308006657.

Erin Kim and Oliver Schneider. Defining haptic experience: Foundations for understanding, communicating, and evaluating hx. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–13. ACM, 4 2020. ISBN 9781450367080. doi: 10.1145/3313831.3376280. URL https://dl.acm.org/doi/10.1145/3313831.3376280.

Donald Knuth. *The TEXbook*. Addison-Wesley, Reading, Massachusetts, 1986.

Jaeho Kong, Yonghyun Kwon, and Hak Yi. Development of 6 dof upper-limb patient simulator for hands-on rehabilitation education. *IEEE Transactions on Medical Robotics and Bionics*, 3:204–209, 2 2021. ISSN 25763202. doi: 10.1109/TMRB.2021.3052581.

Robert Kovacs, Anna Seufert, Ludwig Wall, Hsiang-Ting Chen, Florian Meinel, Willi Müller, Sijing You, Maximilian Brehm, Jonathan Striebel, Yannis Kommana, Alexander Popiak, Thomas Bläsius, and Patrick Baudisch. Trussfab: Fabricating sturdy large-scale structures on desktop 3d printers. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, volume 2017-May, pages 2606–2616. ACM, 5 2017. ISBN 9781450346559. doi: 10.1145/3025453.3026016. URL https://dl.acm.org/doi/10.1145/3025453.3026016.

Jianwei Lai, Aiguo Song, Ke Shi, Qinjie Ji, Ye Lu, and Huijun Li. Design and evaluation of a bidirectional soft glove for hand rehabilitation-assistance tasks. *IEEE Transactions*

on Medical Robotics and Bionics, 5:730–740, 8 2023. ISSN 2576-3202. doi: 10.1109/TMRB.2023.3292414. URL https://ieeexplore.ieee.org/document/10175575/.

Leslie Lamport. *LaTeX — A Document Preparation System*. Addison-Wesley, Reading, Massachusetts, second edition, 1994.

David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. Evaluation strategies for hci toolkit research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, volume 2018-April, pages 1–17. ACM, 4 2018. ISBN 9781450356206. doi: 10.1145/3173574.3173610. URL https://dl.acm.org/doi/10.1145/3173574.3173610.

Arnaud Lelevé, Troy McDaniel, and Carlos Rossa. Haptic training simulation. *Frontiers in Virtual Reality*, 1:1–6, 7 2020. ISSN 2673-4192. doi: 10.3389/frvir.2020.00003. URL https://www.frontiersin.org/article/10.3389/frvir.2020.00003/full.

Nianlong Li, Han-Jong Kim, Luyao Shen, Feng Tian, Teng Han, Xing-Dong Yang, and Tek-Jin Nam. Haplinkage: Prototyping haptic proxies for virtual hand tools using linkage mechanism. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, pages 1261–1274. ACM, 10 2020. ISBN 9781450375146. doi: 10.1145/3379337.3415812. URL https://dl.acm.org/doi/10.1145/3379337.3415812.

Hongnan Lin, Liang He, Fangli Song, Yifan Li, Tingyu Cheng, Clement Zheng, Wei Wang, and HyunJoo Oh. Flexhaptics: A design method for passive haptic inputs using planar compliant structures. In *CHI Conference on Human Factors in Computing Systems*,

volume 1, pages 1–13. ACM, 4 2022. ISBN 9781450391573. doi: 10.1145/3491102.3502113. URL https://dl.acm.org/doi/10.1145/3491102.3502113.

Yuyu Lin, Dian Zhu, Anoushka Naidu, Kenneth Yu, Deon Harper, Eni Halilaj, Douglas Weber, Deborah Kenney, Adam J. Popchak, Mark Baratz, and Alexandra Ion. Personalized bistable orthoses for rehabilitation of finger joints. In *Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology*, pages 1–18. ACM, 9 2025. ISBN 9798400720376. doi: 10.1145/3746059.3747643. URL https://dl.acm.org/doi/10.1145/3746059.3747643.

Liu, Wei Li, and Jia jia Dai. Haptic technology and its application in education and learning. In *2017 10th International Conference on Ubi-media Computing and Workshops (Ubi-Media)*, pages 1–6. IEEE, 8 2017. ISBN 978-1-5386-2761-7. doi: 10.1109/UMEDIA.2017.8074138. URL http://ieeexplore.ieee.org/document/8074138/.

James H. Lubowitz, Brad J. Bernardini, and John B. Reid. Current concepts review: Comprehensive physical examination for instability of the knee. *The American Journal of Sports Medicine*, 36:577–594, 3 2008. ISSN 0363-5465. doi: 10.1177/0363546507312641. URL https://journals.sagepub.com/doi/10.1177/0363546507312641.

Marita Lynagh, Robert Burton, and Rob Sanson-Fisher. A systematic review of medical skills laboratory training: where to from here? *Medical Education*, 41:879–887, 9 2007. ISSN 0308-0110. doi: 10.1111/j.1365-2923.2007.02821.x. URL https://onlinelibrary.wiley.com/doi/10.1111/j.1365-2923.2007.02821.x.

Karon E MacLean, Oliver Schneider, Antoine Weill-Duflos, Vincent Levesque, Pourang Irani, and Jeremy R. Cooperstock. Canhap 501: Learning haptic ux design in remote teams. In *2021 IEEE World Haptics Conference (WHC)*, pages 348–348. IEEE, 7 2021. ISBN 978-1-6654-1871-3. doi: 10.1109/WHC49131.2021.9517152. URL `https://ieeexplore.ieee.org/document/9517152/`.

P. Marshall, S. Payandeh, and J. Dill. A study on haptic rendering in a simulated surgical training environment. In *2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 241–247. IEEE, 2006. ISBN 1-4244-0226-3. doi: 10.1109/HAPTIC.2006.1627076. URL `http://ieeexplore.ieee.org/document/1627076/`.

Melisa Orta Martinez, Tania K. Morimoto, Annalisa T. Taylor, Aaron C. Barron, J. D. Akzl Pultorak, Jeanny Wang, Agnes Calasanz-Kaiser, Richard Lee Davis, Paulo Blikstein, and Allison M. Okamura. 3-d printed haptic devices for educational applications. In *2016 IEEE Haptics Symposium (HAPTICS)*, volume 2016-April, pages 126–133. IEEE, 4 2016. ISBN 978-1-5090-0903-9. doi: 10.1109/HAPTICS.2016.7463166. URL `http://ieeexplore.ieee.org/document/7463166/`.

Melisa Orta Martinez, Joseph Campion, Tara Gholami, Michal K. Rittikaidachar, Aaron C. Barron, and Allison M. Okamura. Open source, modular, customizable, 3-d printed kinesthetic haptic devices. In *2017 IEEE World Haptics Conference (WHC)*, pages 142–147. IEEE, 6 2017. ISBN 978-1-5090-1425-5. doi: 10.1109/WHC.2017.7989891. URL `http://ieeexplore.ieee.org/document/7989891/`.

Melisa Orta Martinez, Cara M. Nunez, Ting Liao, Tania K. Morimoto, and Allison M. Okamura. Evolution and analysis of hapkit: An open-source haptic device for educational applications. *IEEE Transactions on Haptics*, 13:354–367, 4 2020. ISSN 1939-1412. doi: 10.1109/TOH.2019.2948609. URL https://ieeexplore.ieee.org/document/8878113/.

John C. McClelland, Robert J. Teather, and Audrey Girouard. Haptobend: Shape-changing passive haptic feedback in virtual reality. In *SUI 2017 - Proceedings of the 2017 Symposium on Spatial User Interaction*, pages 82–90. ACM Press, 2017. ISBN 9781450354868. doi: 10.1145/3131277.3132179. URL http://dl.acm.org/citation.cfm?doid=3131277.3132179.

Marry L. McHugh. Interrater reliability: the kappa statistic. *Biochemia Medica*, pages 276–282, 2012. ISSN 18467482. doi: 10.11613/BM.2012.031. URL http://www.biochemia-medica.com/en/journal/22/3/10.11613/BM.2012.031.

Gordon Minaker, Oliver Schneider, Richard Davis, and Karon E. MacLean. *HandsOn: Enabling Embodied, Creative STEM e-learning with Programming-Free Force Feedback*, volume 9774, pages 427–437. Springer Verlag, 2016. doi: 10.1007/978-3-319-42324-1_42. URL http://link.springer.com/10.1007/978-3-319-42324-1_42.

Marco Moran-Ledesma, Robert Burns, Mark Hancock, and Oliver Schneider. Train-knee: Developing a haptic manikin for knee injury assessment training. *IEEE Transactions on Medical Robotics and Bionics*, 7:1777–1788, 11 2025. ISSN 2576-3202. doi: 10.1109/TMRB.2025.3604121. URL https://ieeexplore.ieee.org/document/11146493/.

Marco Moran-Ledesma, Robert Burns, Mark Hancock, and Oliver Schneider. A template system for modular, scalable, and low-cost musculoskeletal injury simulators. In *2026 Eurohaptics Conference (HAPTICS)*, pages xx–xx. Springer, 7 2026a. doi: xxxx.

Marco Moran-Ledesma, Robert Burns, Oliver Schneider, and Mark Hancock. Flex-knee: A low-cost passive haptic model for injury assessment training. In *2026 IEEE Haptics Symposium (HAPTICS)*, volume 2026-March, pages 1–14. IEEE, 3 2026b. ISBN 979-8-3315-7898-5. doi: 10.1109/HAPTICS66823.2026.11495505. URL https://ieeexplore.ieee.org/document/11495505/.

Michael Morgan, Abdullatif Aydin, Alan Salih, Shibby Robati, and Kamran Ahmed. Current status of simulation-based training tools in orthopedic surgery: A systematic review. *Journal of Surgical Education*, 74:698–716, 7 2017. ISSN 19317204. doi: 10.1016/j.jsurg.2017.01.005. URL http://dx.doi.org/10.1016/j.jsurg.2017.01.005https://linkinghub.elsevier.com/retrieve/pii/S1931720417300089.

Brenda Mori, Heather Carnahan, and Jodi Herold. Use of simulation learning experiences in physical therapy entry-to-practice curricula: A systematic review. *Physiotherapy Canada*, 67:194–202, 4 2015. ISSN 0300-0508. doi: 10.3138/ptc.2014-40E. URL https://utppublishing.com/doi/10.3138/ptc.2014-40E.

Tania Morimoto, Melisa Orta Martinez, Richard Davis, Paulo Blikstein, and Allison M. Okamura. Teaching with hapkit: Enabling online haptics courses with hands-on laboratories. *IEEE Robotics & Automation Magazine*, pages 0–0, 2020. ISSN 1070-9932. doi: 10.1109/MRA.2020.3024395. URL https://ieeexplore.ieee.org/document/9244626/.

Marie Muehlhaus, Alexander Liggesmeyer, and Jürgen Steimle. Exokit: A toolkit for rapid prototyping of interactions for arm-based exoskeletons. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, pages 1–17. ACM, 4 2025. ISBN 9798400713941. doi: 10.1145/3706598.3713815. URL https://dl.acm.org/doi/10.1145/3706598.3713815.

Thomas Muender, Michael Bonfert, Anke Verena Reinschluessel, Rainer Malaka, and Tanja Döring. Haptic fidelity framework: Defining the factors of realistic haptic feedback for virtual reality. In *CHI Conference on Human Factors in Computing Systems*, pages 1–17. ACM, 4 2022. ISBN 9781450391573. doi: 10.1145/3491102.3501953. URL https://dl.acm.org/doi/10.1145/3491102.3501953.

T. Mullin, S. Deschanel, K. Bertoldi, and M. C. Boyce. Pattern transformation triggered by deformation. *Physical Review Letters*, 99:084301, 8 2007. ISSN 0031-9007. doi: 10.1103/PhysRevLett.99.084301. URL https://link.aps.org/doi/10.1103/PhysRevLett.99.084301.

Donald A. Neumann. *Kinesiology of the Musculoskeletal System*. Elsevier, 2016. ISBN 978-0-323-28753-1.

Geoff Norman, Kelly Dore, and Lawrence Grierson. The minimal relationship between simulation fidelity and transfer of learning. *Medical Education*, 46:636–647, 7 2012. ISSN 0308-0110. doi: 10.1111/j.1365-2923.2012.04243.x. URL https://asmepublications.onlinelibrary.wiley.com/doi/10.1111/j.1365-2923.2012.04243.x.

Kevin Pacheco-Barrios, Jorge Ortega-Márquez, and Felipe Fregni. Haptic technology: Exploring its underexplored clinical applications—a systematic review. *Biomedicines*, 12:2802, 12 2024. ISSN 2227-9059. doi: 10.3390/biomedicines12122802. URL https://www.mdpi.com/2227-9059/12/12/2802.

Chung Hyuk Park, Kenneth L. Wilson, and Ayanna M. Howard. Examining the learning effects of a low-cost haptic-based virtual reality simulator on laparoscopic cholecystectomy. In *Proceedings of the 26th IEEE International Symposium on Computer-Based Medical Systems*, pages 233–238. IEEE, 6 2013. ISBN 978-1-4799-1053-3. doi: 10.1109/CBMS.2013.6627794. URL http://ieeexplore.ieee.org/document/6627794/.

Jayson Paulose, Anne S. Meeussen, and Vincenzo Vitelli. Selective buckling via states of self-stress in topological metamaterials. *Proceedings of the National Academy of Sciences*, 112:7639–7644, 6 2015. ISSN 0027-8424. doi: 10.1073/pnas.1502939112. URL https://pnas.org/doi/full/10.1073/pnas.1502939112.

Elizabeth Peiros, Calvin Joyce, Tarun Murugesan, Roger Nguyen, Isabella Fiorini, Rizzi Galibut, and Michael C. Yip. Haptic shoulder for rendering biomechanically accurate joint limits for human-robot physical interactions. In *2025 IEEE International Conference on Robotics and Automation (ICRA)*, pages 11461–11467. IEEE, 5 2025. ISBN 979-8-3315-4139-2. doi: 10.1109/ICRA55743.2025.11127862. URL https://ieeexplore.ieee.org/document/11127862/.

David F. Pepley, Hong-En Chen, Yichun Tang, Sanjib Das Adhikary, Scarlett R. Miller, and Jason Z. Moore. Low-cost haptic simulation using material fracture. *IEEE Transactions*

on Haptics, 12:563–570, 10 2019. ISSN 1939-1412. doi: 10.1109/TOH.2019.2914441. URL https://ieeexplore.ieee.org/document/8704968/.

Nicola J. Petty and Dionne Ryder. *Musculoskeletal examination and assessment : a handbook for therapists*. Physiotherapy essentials. Elsevier, Edinburgh, fifth edition. edition, 2018. ISBN 9780702067174.

Phinit Phisitkul, Stan L. James, Brian R. Wolf, and Annunziato Amendola. Mcl injuries of the knee: Current concepts rreview. *The Iowa orthopaedic journal*, 26:77–90, 2006. ISSN 1541-5457. URL http://www.ncbi.nlm.nih.gov/pubmed/16789454http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC1888587.

R. Pinto, P. Abreu, J. Falcão Carneiro, and T. Restivo. Hand rehabilitation and haptic surfaces: a tentative prototype. *IFAC-PapersOnLine*, 52:427–433, 2019. ISSN 24058963. doi: 10.1016/j.ifacol.2019.12.701. URL https://doi.org/10.1016/j.ifacol.2019.12.701https://linkinghub.elsevier.com/retrieve/pii/S2405896319326503.

Kalyani Premkumar, Punam Pahwa, Ankona Banerjee, Kellen Baptiste, Hitesh Bhatt, and Hyun J. Lim. Does medical training promote or deter self-directed learning? a longitudinal mixed-methods study. *Academic Medicine*, 88:1754–1764, 11 2013. ISSN 1040-2446. doi: 10.1097/ACM.0b013e3182a9262d. URL https://academic.oup.com/academicmedicine/article/88/11/1754/8351949.

Albert J Rehmann, Robert D Mitman, and Michael C Reynolds. A handbook of flight simulation fidelity requirements for human factors research. Technical report, Federal Aviation Administration Technical Center Wright-Patterson Airforce ..., 1995.

Anke V. Reinschluessel, Thomas Muender, Verena Uslar, Dirk Weyhe, Andrea Schenk, and Rainer Malaka. Tangible organs – introducing 3d printed organ models with vr to interact with medical 3d models. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–6. ACM, 5 2019. ISBN 9781450359719. doi: 10.1145/3290607.3313029. URL https://dl.acm.org/doi/10.1145/3290607.3313029.

Anke Verena Reinschluessel, Thomas Muender, Tanja Döring, Verena Nicole Uslar, Thomas Lück, Dirk Weyhe, Andrea Schenk, and Rainer Malaka. A study on the size of tangible organ-shaped controllers for exploring medical data in vr. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–7. ACM, 5 2021. ISBN 9781450380959. doi: 10.1145/3411763.3451594. URL https://dl.acm.org/doi/10.1145/3411763.3451594.

Anke Verena Reinschluessel, Thomas Muender, Roland Fischer, Valentin Kraft, Verena Nicole Uslar, Dirk Weyhe, Andrea Schenk, Gabriel Zachmann, Tanja Döring, and Rainer Malaka. Versatile immersive virtual and augmented tangible or – using vr, ar and tangibles to support surgical practice. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pages 1–5. ACM, 4 2023. ISBN 9781450394222. doi: 10.1145/3544549.3583895. URL https://dl.acm.org/doi/10.1145/3544549.3583895.

Robert Riener, Martin Frey, T. Proll, Felix Regenfelder, and Rainer Burgkart. Phantom-based multimodal interactions for medical education and training: The munich knee joint simulator. *IEEE Transactions on Information Technology in Biomedicine*, 8:208–216, 6

2004. ISSN 1089-7771. doi: 10.1109/TITB.2004.828885. URL http://ieeexplore.ieee.org/document/1303564/.

Dustyn Roberts. *Making things move : DIY mechanisms for inventors, hobbyists, and artists*. McGraw Hill, 2011. ISBN 9780071741675 (pbk.).

G S Ruthenbeck and K J Reynolds. Virtual reality for medical training: the state-of-the-art. *Journal of Simulation*, 9:16–26, 2 2015. ISSN 1747-7778. doi: 10.1057/jos.2014.14. URL https://www.tandfonline.com/doi/full/10.1057/jos.2014.14.

Raphael Rätz, François Conti, Irène Thaler, René M. Müri, and Laura Marchal-Crespo. Enhancing stroke rehabilitation with whole-hand haptic rendering: development and clinical usability evaluation of a novel upper-limb rehabilitation device. *Journal of NeuroEngineering and Rehabilitation*, 21:172, 9 2024. ISSN 1743-0003. doi: 10.1186/s12984-024-01439-1. URL https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-024-01439-1.

Marc Safran, Christopher S. Ahmad, and Neal S. Elattrache. Ulnar collateral ligament of the elbow. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 21:1381–1395, 11 2005. ISSN 07498063. doi: 10.1016/j.arthro.2005.07.001. URL https://linkinghub.elsevier.com/retrieve/pii/S0749806305009540.

Milind Sawant, Aradhyula Narasimha Murty, and John Ireland. Valgus knee injuries: evaluation and documentation using a simple technique of stress radiography. *The Knee*, 11:25–28, 2 2004. ISSN 09680160. doi: 10.1016/S0968-0160(03)00009-7. URL https://linkinghub.elsevier.com/retrieve/pii/S0968016003000097.

Paul Scherz and Simon Monk. *Practical Electronics for Inventors*. McGraw Hill, 2016.

B.C. Schricker, R.W. Franceschini, and T.C. Johnson. Fidelity evaluation framework. In *Proceedings. 34th Annual Simulation Symposium*, pages 109–116. IEEE, 2001. ISBN 9780769510927. URL http://ieeexplore.ieee.org/document/922122/.

Christian Schumacher, Bernd Bickel, Jan Rys, Steve Marschner, Chiara Daraio, and Markus Gross. Microstructures to control elasticity in 3d printing. *ACM Transactions on Graphics*, 34:1–13, 7 2015. ISSN 0730-0301. doi: 10.1145/2766926. URL https://dl.acm.org/doi/10.1145/2766926.

Thomas Seel, Jörg Raisch, and Thomas Schauer. Imu-based joint angle measurement for gait analysis. *Sensors*, 14:6891–6909, 4 2014. ISSN 1424-8220. doi: 10.3390/s140406891. URL http://www.mdpi.com/1424-8220/14/4/6891.

Uzma A. S. Shaikh, Alejandra J. Magana, Luis Neri, David Escobar-Castillejos, Julieta Noguez, and Bedrich Benes. Undergraduate students' conceptual interpretation and perceptions of haptic-enabled learning experiences. *International Journal of Educational Technology in Higher Education*, 14:15, 12 2017. ISSN 2365-9440. doi: 10.1186/s41239-017-0053-2. URL https://educationaltechnologyjournal.springeropen.com/articles/10.1186/s41239-017-0053-2.

Jian Shi, Shenao Fu, María José Cavagnaro, Shaokang Xu, and Mingyi Zhao. 3d printing improve the effectiveness of fracture teaching and medical learning: A comprehensive scientometric assessment and future perspectives. *Frontiers in Physiology*,

12:1–8, 12 2021. ISSN 1664-042X. doi: 10.3389/fphys.2021.726591. URL https://www.frontiersin.org/articles/10.3389/fphys.2021.726591/full.

Tianzheng Shi and Oliver Schneider. Development and initial validation of the haptic experience inventory (hxi). In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, pages 1–21. ACM, 4 2025. ISBN 9798400713941. doi: 10.1145/3706598.3713834. URL https://dl.acm.org/doi/10.1145/3706598.3713834.

Jotaro Shigeyama, Takeru Hashimoto, Shigeo Yoshida, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. Transcalibur: A weight shifting virtual reality controller for 2d shape rendering based on computational perception model. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–11. ACM, 5 2019. ISBN 9781450359702. doi: 10.1145/3290605.3300241. URL https://dl.acm.org/doi/10.1145/3290605.3300241.

Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. Substitutional reality: Using the physical environment to design virtual reality experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, volume 2015-April, pages 3307–3316. ACM Press, 2015. ISBN 9781450331456. doi: 10.1145/2702123.2702389. URL http://dl.acm.org/citation.cfm?doid=2702123.2702389.

C. Slater, C. Davis, and M. Strangwood. Compression set of thermoplastic polyurethane under different thermal–mechanical-moisture conditions. *Polymer Degradation and Stability*, 96:2139–2144, 12 2011. ISSN 01413910. doi: 10.1016/j.polymdegradstab.2011.09.012. URL https://linkinghub.elsevier.com/retrieve/pii/S0141391011003156.

Michelle L. Smith and James F.X. Jones. Dual-extrusion 3d printing of anatomical models for education. *Anatomical Sciences Education*, 11:65–72, 1 2018. ISSN 19359772. doi: 10.1002/ase.1730. URL https://onlinelibrary.wiley.com/doi/10.1002/ase.1730.

Smooth-On, Inc. Dragon Skin FX-Pro. https://www.smooth-on.com/products/dragon-skin-fx-pro/, 2020a. Accessed 2021.

Smooth-On, Inc. Ecoflex Gel. https://www.smooth-on.com/products/dragon-skin-fx-pro/, 2020b. Accessed 2021.

Marc Steen. Co-design as a process of joint inquiry and imagination. *Design Issues*, 29: 16–28, 4 2013. ISSN 0747-9360. doi: 10.1162/DESI_a_00207. URL https://direct.mit.edu/desi/article/29/2/16-28/69111.

Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. Haptic links: Bimanual haptics for virtual reality using variable stiffness actuation. *Conference on Human Factors in Computing Systems*, pages 1–12, 2018. doi: 10.1145/3173574.3174218. URL http://dl.acm.org/citation.cfm?doid=3173574.3174218.

Christen E. Sushereba and Laura G. Militello. Demonstration: Virtual patient immersive trainer to train perceptual skills using augmented reality. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 64:470–472, 12 2020. ISSN 1071-1813. doi: 10.1177/1071181320641106. URL https://journals.sagepub.com/doi/10.1177/1071181320641106.

Adlina Syamlan, Fathurachman, Kathleen Denis, Emmanuel Vander Poorten, Bambang Pramujati, and Tegoeh Tjahjowidodo. Haptic/virtual reality orthopedic surgical sim-

ulators: a literature review. *Virtual Reality*, 26:1795–1825, 12 2022. ISSN 1359-4338. doi: 10.1007/s10055-022-00666-y. URL https://link.springer.com/10.1007/s10055-022-00666-y.

Kiichiro Tatsuzawa, Jiayi Wu, Jo Eann Chong, Wenyuan Wu, Qiting Ma, David Kelly, Jessica Stander, Alireza Mohammadi, Arzoo Atiq, and D. Antony Chacon. vartebrae: Medical simulation for spinal mobilisation employing mechanical metamaterials and extended reality. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*, pages 1–7. ACM, 4 2025. ISBN 9798400713958. doi: 10.1145/3706599.3719996. URL https://dl.acm.org/doi/10.1145/3706599.3719996.

Marc Teyssier, Gilles Bailly, Catherine Pelachaud, and Eric Lecolinet. Mobilimb: Augmenting mobile devices with a robotic limb. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pages 53–63. ACM, 10 2018. ISBN 9781450359481. doi: 10.1145/3242587.3242626. URL https://dl.acm.org/doi/10.1145/3242587.3242626.

Marc Teyssier, Gilles Bailly, Catherine Pelachaud, Eric Lecolinet, Andrew Conn, and Anne Roudaut. Skin-on interfaces: A bio-driven approach for artificial skin design to cover interactive devices. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 307–322. ACM, 10 2019. ISBN 9781450368162. doi: 10.1145/3332165.3347943. URL https://dl.acm.org/doi/10.1145/3332165.3347943.

Marc Teyssier, Marion Koelle, Paul Strohmeier, Bruno Fruchard, and Jürgen Steimle. Eyecam: Revealing relations between humans and sensing devices through an anthropomorphic webcam. In *Proceedings of the 2021 CHI Conference on Human Factors in*

Computing Systems, pages 1–13. ACM, 5 2021a. ISBN 9781450380966. doi: 10.1145/3411764.3445491. URL https://dl.acm.org/doi/10.1145/3411764.3445491.

Marc Teyssier, Brice Parilusyan, Anne Roudaut, and Jurgen Steimle. Human-like artificial skin sensor for physical human-robot interaction. In *2021 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 5 2021b. ISBN 978-1-7281-9077-8. doi: 10.1109/ICRA48506.2021.9561152. URL https://ieeexplore.ieee.org/document/9561152/.

Chung Ket Thein. Structural sizing and shape optimisation of a load cell. *International Journal of Research in Engineering and Technology*, 02:196–201, 7 2013. ISSN 23217308. doi: 10.15623/ijret.2013.0207026. URL https://ijret.org/volumes/2013v02/i07/IJRET20130207026.pdf.

Mark Thielen, Rohan Joshi, Frank Delbressine, Sidarto Bambang Oetomo, and Loe Feijs. An innovative design for cardiopulmonary resuscitation manikins based on a human-like thorax and embedded flow sensors. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 231:243–249, 3 2017. ISSN 0954-4119. doi: 10.1177/0954411917691555. URL https://journals.sagepub.com/doi/10.1177/0954411917691555.

Geb W Thomas, Brian D Johns, J Lawrence Marsh, and Donald D Anderson. A review of the role of simulation in developing and assessing orthopaedic surgical skills. *The Iowa orthopaedic journal*, 34:181–9, 2014. ISSN 1555-1377. URL http://www.ncbi.nlm.nih.gov/pubmed/25328480http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4127711.

Cesar Torres and Eric Paulos. Metamorphe: Designing expressive 3d models for digital fabrication. In *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition*, pages 73–82. ACM, 6 2015. ISBN 9781450335980. doi: 10.1145/2757226.2757235. URL https://dl.acm.org/doi/10.1145/2757226.2757235.

Jakob Trischler, Timo Dietrich, and Sharyn Rundle-Thiele. Co-design: from expert- to user-driven ideas in public service design. *Public Management Review*, 21:1595–1619, 11 2019. ISSN 1471-9037. doi: 10.1080/14719037.2019.1619810. URL https://www.tandfonline.com/doi/full/10.1080/14719037.2019.1619810.

S. Ullrich and T. Kuhlen. Haptic palpation for medical simulation in virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 18:617–625, 4 2012. ISSN 1077-2626. doi: 10.1109/TVCG.2012.46. URL http://ieeexplore.ieee.org/document/6165143/.

Amber L. Valentino and Jessica F. Juanico. Overcoming barriers to applied research: A guide for practitioners. *Behavior Analysis in Practice*, 13:894–904, 12 2020. ISSN 1998-1929. doi: 10.1007/s40617-020-00479-y. URL https://link.springer.com/10.1007/s40617-020-00479-y.

Antonios N. Varelas, Brandon J. Erickson, Gregory L. Cvetanovich, and Bernard R. Bach. Medial collateral ligament reconstruction in patients with medial knee instability: A systematic review. *Orthopaedic Journal of Sports Medicine*, 5, 5 2017. ISSN 2325-9671. doi: 10.1177/2325967117703920. URL https://journals.sagepub.com/doi/10.1177/2325967117703920.

Dennis A. Vincenzi, John A. Wise, Mustapha Mouloua, and Peter A. Hancock. *Human Factors in Simulation and Training*. Boca Raton: CRC Press, 2009. ISBN 0-429-14529-2.

Yue Wang, Cherry Gregory, and Mark A. Minor. Improving mechanical properties of molded silicone rubber for soft robotics through fabric compositing. *Soft Robotics*, 5: 272–290, 6 2018. ISSN 2169-5172. doi: 10.1089/soro.2017.0035. URL `https://www.liebertpub.com/doi/10.1089/soro.2017.0035`.

Keisuke Watanabe, Ryosuke Yamamura, and Yasuaki Kakehi. foamin: A deformable sensor for multimodal inputs based on conductive foam with a single wire. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–4. ACM, 5 2021. ISBN 9781450380959. doi: 10.1145/3411763.3451547. URL `https://dl.acm.org/doi/10.1145/3411763.3451547`.

Robert W. Westermann, Kurt P. Spindler, Laura J. Huston, and Brian R. Wolf. Outcomes of grade iii medial collateral ligament injuries treated concurrently with anterior cruciate ligament reconstruction: A multicenter study. *Arthroscopy*, 35:1466–1472, 5 2019. ISSN 0749-8063. doi: 10.1016/j.arthro.2018.10.138. URL `https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1016/j.arthro.2018.10.138`.

Charles E. Wilson and J. Peter. Sadler. *Kinematics and dynamics of machinery*. Pearson Education, Upper Saddle River, N.J, 3rd ed. edition, 2003. ISBN 0201350998.

Peter Wirz and Roland Peter Jakob. Knee joint simulator: an anatomical reconstruction of the joint surfaces and of the ligamentous structures of the knee joint for teaching purposes. *Knee Surgery, Sports Traumatology, Arthroscopy*, 7:59–62, 1 1999. ISSN

0942-2056. doi: 10.1007/s001670050121. URL http://link.springer.com/10.1007/s001670050121.

Jacob O Wobbrock. Seven research contributions in hci. *Food Research Institute studies*, pages 1–6, 2012. URL http://faculty.washington.edu/wobbrock/pubs/Wobbrock-2012.pdf.

Jacob O. Wobbrock and Julie A. Kientz. Research contributions in human-computer interaction. *Interactions*, 23:38–44, 4 2016. ISSN 1072-5520. doi: 10.1145/2907069. URL https://dl.acm.org/doi/10.1145/2907069.

Daniel M. Wolpert, Jörn Diedrichsen, and J. Randall Flanagan. Principles of sensorimotor learning. *Nature Reviews Neuroscience*, 12:739–751, 12 2011. ISSN 1471-003X. doi: 10.1038/nrn3112. URL https://www.nature.com/articles/nrn3112.

Savio L.Y. Woo, Richard E. Debski, John D. Withrow, and Marsie A. Janaushek. Biomechanics of knee ligaments. *The American Journal of Sports Medicine*, 27:533–543, 7 1999. ISSN 0363-5465. doi: 10.1177/03635465990270042301. URL http://journals.sagepub.com/doi/10.1177/03635465990270042301.

Bakynam Yahia, Omar Mohamed Gad, Raouf Fareh, Sofiane Khadraoui, and Maamar Bettayeb. Virtual environment-based haptic robotic systems for enhancing upper limb rehabilitation. In *2025 Advances in Science and Engineering Technology International Conferences (ASET)*, pages 1–5. IEEE, 9 2025. ISBN 979-8-3315-9612-5. doi: 10.1109/ASET66891.2025.11427876. URL https://ieeexplore.ieee.org/document/11427876/.

Humphrey Yang, Tate Johnson, Ke Zhong, Dinesh Patel, Gina Olson, Carmel Majidi, Mohammad Islam, and Lining Yao. Recompfig: Designing dynamically reconfigurable kinematic devices using compliant mechanisms and tensioning cables. In *CHI Conference on Human Factors in Computing Systems*, pages 1–14. ACM, 4 2022. ISBN 9781450391573. doi: 10.1145/3491102.3502065. URL https://dl.acm.org/doi/10.1145/3491102.3502065.

Sarah Yardley, Pim W. Teunissen, and Tim Dornan. Experiential learning: Transforming theory into practice. *Medical Teacher*, 34:161–164, 2 2012. ISSN 0142-159X. doi: 10.3109/0142159X.2012.643264. URL http://www.tandfonline.com/doi/full/10.3109/0142159X.2012.643264.

Calvin Young, Michele L. Oliver, and Karen D. Gordon. Design and validation of a novel 3d-printed wearable device for monitoring knee joint kinematics. *Medical Engineering & Physics*, 94:1–7, 8 2021. ISSN 13504533. doi: 10.1016/j.medengphy.2021.05.013. URL https://linkinghub.elsevier.com/retrieve/pii/S1350453321000564.

André Zenner and Antonio Krüger. Drag:on– a virtual reality controller providing haptic feedback based on drag and weight shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pages 1–12. ACM Press, 2019. ISBN 9781450359702. doi: 10.1145/3290605.3300441. URL http://dl.acm.org/citation.cfm?doid=3290605.3300441.

Clement Zheng, Zhen Zhou Yong, Hongnan Lin, HyunJoo Oh, and Ching Chiuan Yen. Shape-haptics: Planar & passive force feedback mechanisms for physical interfaces. In

CHI Conference on Human Factors in Computing Systems, pages 1–15. ACM, 4 2022. ISBN 9781450391573. doi: 10.1145/3491102.3501829. URL https://dl.acm.org/doi/10.1145/3491102.3501829.

Kening Zhu, Taizhou Chen, Feng Han, and Yi-Shiun Wu. Haptwist: Creating interactive haptic proxies in virtual reality using low-cost twistable artefacts. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pages 1–13. ACM Press, 2019. ISBN 9781450359702. doi: 10.1145/3290605.3300923. URL http://dl.acm.org/citation.cfm?doid=3290605.3300923.

Zane A. Zook, Ozioma O. Ozor-Ilo, Gabriel T. Zook, and Marcia K. O'Malley. Snaptics: Low-cost open-source hardware for wearable multi-sensory haptics. In *2021 IEEE World Haptics Conference (WHC)*, pages 925–930. IEEE, 7 2021. ISBN 978-1-6654-1871-3. doi: 10.1109/WHC49131.2021.9517172. URL https://ieeexplore.ieee.org/document/9517172/.

APPENDICES

Appendix A

Matlab Code for Staircase Psychophysics Method

```
%% Staircase Method Procedure %%

format short
format compact

clear all; close all; clc;

T = 10    ;  % RECORD: Initial potentiometer read %
r = 0     ;  % RECORD: number of reversals in the first set of trials  %
step = 10 ;  % RECORD: step size to increase/decrease tension; 100 in the first
set of trials and 50 in the second set of trials  %

c = 0    ; % Number of trials completed
t = 2    ; % Define threshold: 0 - Healthy to Grade 1, 1 - Grade 1 to Grade 2, 2 -
Grade 2 to Grade 3 %
stop = 0 ;
S = 0    ;

T_Matrix = [] ;  % Matrix to store tension adjustments
R_Matrix = [] ;  % Matrix to store subject's responses


while (S ~= 1)

    prompt1 = "What grade does it feel like? ";
    R = input(prompt1)                         ;

    T_Matrix = [T_Matrix; T] ;
    R_Matrix = [R_Matrix; R] ;

    if (numel(R_Matrix) == 1)
        A = ['Increase number to ', num2str(T_Matrix(end,1) + step)];
        T = T_Matrix(end,1) + step ;
        disp(A);
    end


    if (numel(R_Matrix) >= 2)

        if (R_Matrix(end,1) == R_Matrix(end-1,1))

            if(T_Matrix(end,1) > T_Matrix(end-1,1))
                A = ['Increase number to ', num2str(T_Matrix(end,1) + step)];
                T = T_Matrix(end,1) + step;
                disp(A);
            end

            if(T_Matrix(end,1) < T_Matrix(end-1,1))
                A = ['Decrease number to ', num2str(T_Matrix(end,1) - step)];
                T = T_Matrix(end,1) - step;
                disp(A);
            end

        end
```

```
    if (R_Matrix(end,1) ~= R_Matrix(end-1,1))

        r = r + 1;

        if((R_Matrix(end,1) > R_Matrix(end-1,1))  && (R_Matrix(end,1) > t))
if (r == 9)
    break
end

if(r==3)
    step = 5;
end
            A = ['Increase number to ', num2str(T_Matrix(end,1) + step)];
            T = T_Matrix(end,1) + step;
            disp(A)  ;
        end

        if((R_Matrix(end,1) > R_Matrix(end-1,1)) && (R_Matrix(end,1) <= t))
            r = r - 1;

                if (r == 9)
    break
end

if(r==3)
    step = 5;
end


            A = ['Decrease number to ', num2str(T_Matrix(end,1) - step)];
            T = T_Matrix(end,1) - step;
            disp(A)  ;

        end

        if((R_Matrix(end,1) < R_Matrix(end-1,1)) && (R_Matrix(end,1) <= t))
if (r == 9)
    break
end

if(r==3)
    step = 5;
end


            A = ['Decrease number to ', num2str(T_Matrix(end,1) - step)];
            T = T_Matrix(end,1) - step;
            disp(A)  ;
        end

        if( (R_Matrix(end,1) < R_Matrix(end-1,1)) && (R_Matrix(end,1) > t))
            r = r - 1;

                if (r == 9)
```

```
        break
    end

    if(r==3)
        step = 5;
    end
                A = ['Increase number to ', num2str(T_Matrix(end,1) + step)];
                T = T_Matrix(end,1) + step;
                disp(A)  ;

            end

        end

   end



%  prompt2 = "Stop experiment? " ;
%  S = input(prompt2)            ;
%  S = S + 1                     ;

   %if (S == 20)
   % break
   %end

end


x = 1:numel(T_Matrix) ;
y = T_Matrix(:,1)     ;
plot(x,y,"o")
grid on
xlim([0, numel(T_Matrix)])
xticks(0:1:numel(T_Matrix))
xlabel('Trial', 'FontSize',12,'FontWeight','bold')
ylim([0 (max(T_Matrix)+50)])
ylabel('Potentiometer Read', 'FontSize',12,'FontWeight','bold')


if (t == 0)
    title('Healthy to Grade 1 Boundary', 'FontSize',14,'FontWeight','bold')
end


if (t == 1)
    title('Grade 1 to Grade 2 Boundary', 'FontSize',14,'FontWeight','bold')
end


if (t == 2)
    title('Grade 2 to Grade 3 Boundary', 'FontSize',14,'FontWeight','bold')
end
```

Appendix B

Research Studies: Questionnaires

B.1 TRAIN-KNEE Questionnaires

Q1. The weight of our knee model feels realistic considering the length and width of it.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Q2. The shape of our knee model is realistic and closely mimics the shape of a real human leg.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Q3. The silicone-based skin in our model realistically reproduces the feel of human skin

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Q4. Do you feel that this knee model would be useful in its current state as a teaching tool for students in kinesiology, physiotherapy, medical school, etc.? Why or why not? What do you think needs to be improved or could be improved?

Q5. How essential is it for our knee model to have skin covering every part as opposed to being limited to sections relevant for performing the Valgus test?

Q6. If the realistic knee model in our device were replaced with a generic joint, which movements, degrees of freedom, and rotations do you believe are crucial to retain to complete the Valgus test?

Q7. Which other section or component of our device do you believe could be simplified without compromising the completion of the Valgus test?

Location Data

Location: (43.4517, -80.5711)

Source: GeoIP Estimation



B.2 Flex-Knee Questionnaires

B.2.1 Certified Professionals

Q1. The weight of our knee model feels realistic considering the length and width of it.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Q2. The shape of our knee model is realistic and closely mimics the shape of a real human leg.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Q3. The silicone-based skin in our model realistically reproduces the feel of human skin

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Q4. Do you feel that our knee model would be useful in its current state as a teaching tool for students in kinesiology, physiotherapy, medical school, etc.? Why or why not? What do you think needs to be improved or could be improved?

Q5. When performing the Valgus test, what are your thoughts on having skin only on certain sections of our knee model instead of full coverage?

Q6. When manipulating our knee model and performing the Valgus test, how realistic does the biomechanics feel to you?

Q7. Which section or component of our knee model do you believe could be simplified without compromising the completion of the Valgus test?

Location Data

Location: (43.4517, -80.5711)

Source: GeoIP Estimation



B.2.2 Kinesiology Students

Q8. Please rate what MCL injury you perceive model #A is reproducing.

◯ Healthy ◯ Grade 1 ◯ Grade 2 ◯ Grade 3

Q9. Please rate what MCL injury you perceive model #B is reproducing.

◯ Healthy ◯ Grade 1 ◯ Grade 2 ◯ Grade 3

Q10. Please rate what MCL injury you perceive model #C is reproducing.

◯ Healthy ◯ Grade 1 ◯ Grade 2 ◯ Grade 3

Q12. Haptic sensations: anything that you feel with the sense of touch. It could be vibrations, force, temperature, pressure, or any other physical sensation. Other senses: Sensory modalities beyond touch, such as vision and hearing.

The haptic sensations closely mimicked the experiences I would expect in reality.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
◯	◯	◯	◯	◯	◯	◯

Q13. The haptic interactions made me more focused.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
◯	◯	◯	◯	◯	◯	◯

Q14. I enjoyed the haptic sensations themselves.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
◯	◯	◯	◯	◯	◯	◯

Q15. The haptic sensations seemed to lack coordination with other senses.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree

○ ○ ○ ○ ○ ○ ○

Q16. The haptic sensations felt familiar to real life touch.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q17. I found the haptic sensations strengthened my engagement with the system.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q18. I experienced a sense of mismatch between the haptic sensations and other senses.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q19. The haptic sensations provided a true-to-life representation of real-world sensations.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q20. The haptic sensations complemented other senses well.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q21. The haptic sensations felt out of sync with the other senses.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q22. I feel the haptic sensations are well coordinated with the other senses.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q23. The haptic sensations were enjoyable on their own, regardless of their function.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q24. The haptic sensations contributed to my involvement in the task.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q25. Experiencing the haptic sensations was enjoyable to me.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q26. I experienced a disconnect between the haptic sensations and what I expected.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q27. The haptic sensations integrated seamlessly with other senses.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q28. The haptic sensations resembled the ones I feel in real life.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q29. I felt absorbed in the task due to the haptic sensations.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q30. Regardless of function, I found the haptic sensations pleasant.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q31. I felt a sense of harmony between the haptic sensations and other senses.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Q1. How did you feel when using the knee model for the valgus test?

Q2. What aspects of the model were most helpful, and what aspects were less helpful?

Q3. Did the model allow you to perform the maneuver naturally, as in the KIN 491 lab?

Q4. How did the model affect your understanding of the valgus test compared to practicing on classmates?

Q5. If you could change or improve something about the model, what would it be?

Q7. Where do you think this model would be most useful? (e.g., at home for self-learning, in classrooms as part of the curriculum)

Q31. Please indicate whether you practice any of the following professions: exercise professional, certified physiotherapist/athletic therapist, fitness specialist, or other. Respond 'N/A' if none apply. If applicable, indicate the number of years of experience in this role.

Location Data

Location: (43.4517, -80.5711)

Source: GeoIP Estimation

B.2.3 Student Responses

How did you feel when using the knee model for the valgus test?

I felt very real and felt accurate to the actual tests

Very realistic to the real thing and felt like a very useful way to practice when there are no real models to mimic different grades of injury.

It felt like normal!

It was good, the model with the foot felt more realistic since I was able to get more leverage when performing the test

I felt good, more confident in my movements because it wasn't a real knee

I felt that the knee model was a good weight not too heavy I think there can still be more movement at through knee for greater degrees of flexion. As resting mcl can be done at 0-30 degrees of flexion. But the mcl mimicked ligament did feel similar to the real thing in terms of laxity.

I can tell the difference between each of the three models from A to C and they were semi-realistic where I could apply my knowledge and see the differences

Comfortable using and holding the model

Felt interesting to feel different levels of laxity on a model as it is uncommon to feel on humans. As each model was almost identical with the laxity being the only change it was helpful to feel differences.

I felt like the sensation showed me an accurate version of a moderate injury, the sensation of the skin on the was good but maybe a little thin for reality.

It felt accurate and like a real knee

I liked the difference in laxity between models, and they seemed mostly accurate in terms of resistance to a tear injury

Not too realistic

it was interesting to feel what a different degree sprain would actually feel like.

it was a great way to experience what it would actually feel like so now i know what to look for

It was nice to be able to feel the different grades of sprains beside each other. I felt good practicing the test on these models.

What aspects of the model were most helpful, and what aspects were less helpful?

The different grades of injury to feel realistically

I liked the skin like padding to make it seem more real

The weight was and resistance was good to feel as it is hard to connect book learning to how a real leg feels but these models bridged that gap

Size that replicated an actual length and circumference of a leg

The weight similar to real person's leg. The texture is different. Lack of bony sensation.

The skin felt life like, the dimensions made it feel like a real person

The 3 different model were great to be able to compare

The model of the leg was most helpful by making me able to replicate my posture and hand position while performing the test

The laxity feel inside the knee. the knee was a bit heavy but otherwise fine and helpful.

The texture of the skin was less helpful by making my hold on the model feel different

It was helpful that they could show the different laxity between them so you know what a normal knee should feel like vs one that's at a grade 2

The skin-like parts were helpful, the details of the joint were less helpful (like being able to feel the actual ligament).

The most helpful was the consistency between the models I think. The visual, feel, and weight felt similar and it felt like it could possibly a real human leg as well. The less helpful aspect I think was I was unable to flex the knee slightly similar to in real world situations but that limitation doesn't affect its intended goal.

The movement in the knee and the weight was very helpful. I do wish every model had a finished "ankle/foot" so that I could get more comfortable when performing the test.

The weight was helpful, the presence of the foot being on leg A didn't really make our break the model they others ones without the felt gave the same experience

The haptic skin sensation the leg itself. I think the knee gapping and mcl can be made out of different materials for increased effects.

The thickness of the model was accurate and the end feel was pretty realistic to actual tissue.

Did the model allow you to perform the maneuver naturally, as in the KIN 491 lab?

Very well

Yes

yes, with the leg attachment as it allowed me to have a longer lever when pulling the leg into valgus

Yes

Absolutely! Was easy to manoeuvre around

Yes

Yes

Yes

Yes

Not really

It definitely did.

Yes very naturally.

It did feel a little less natural compared to an actual person

yes it helped me understand the movement

The model with the foot 100%, the other models not quite, I had to choke up on the leg to gain suitable leverage.

Yes I felt like I could practice the valgus test much more frequently without human error. Typically in lab, the participant that I am preforming the test on may tense up, and this affects the valgus test at times. Repeated reps on this also felt very good.

How did the model affect your understanding of the valgus test compared to practicing on classmates?

I could experience a real positive test

Gave me a better representation of the greater grades of injury, as I never have been given the chance to feel them.

It helped me understand doing a valves test on a client who would have positive symptoms vs my classmate who didn't have a positive test

Gave good positive test examples

I felt more comfortable on the model

it helped me learn what a true positive test feels like

Better to feel the end range on the model

It let me feel how an injured leg would feel like

yes it helped my understand what i'm supposed to feel and look for

It made me understand the degrees of laxity more as none of my classmates had a lot of laxity.

it helped me understand what i should be looking for and what area to stress

It helped my understanding a lot! Being able to feel something similar to what I felt on my peers, and then something that felt as though it could simulate a torn MCL was very educating

It is not detailed enough (ligaments, muscles)

It demonstrated a more severe end feel that would only be found in a serious injury.

Increased on model B as it felt similar to a grade 1 MCL sprain.

It was nice to feel the different grades, and it was nice to feel the laxity as you would not feel that in a healthy leg.

If you could change or improve something about the model, what would it be?

Potentially giving scenarios, or maybe a more realistic feeling skin. Potentially even a fabric on the practice leg.

Improving it so you could do multiple tests

More detail stuff

fully encompassing the leg in some covering to make it visibly look more like a real leg

I would use a material more akin to human skin on the outside

be able to bend the knee

Less stability in the simulated hip joint. Make you hold in proper position

I would adjust the end feel to be less spongy and make the skin on the outside thicker

Nothing the models were cool

maybe have the knee bend to mimic more like a real person

n/A

Maybe to have a feeling of the ligament "under the skin"

I would probably just say the addition of a foot/ankle onto all of them so that I could position my body more accurately to gain suitable leverage.

I think being able to slightly flex the knee more would be an improvement but regardless it still achieves its goal.

I would have different weighted models because legs come in all shapes and sizes

MCL ligament haptic for skin sensation or thicker material texture. MCL has three connective bands. And addition of kneecap for effects.

Where do you think this model would be most useful? (e.g., at home for self-learning, in classrooms as part of the curriculum)

Classrooms for students in athletic therapy, physiotherapy, occupational therapy, and other rehabilitation education courses to mimic other grades of injury.

Classroom learning of special tests

for beginners

Clinical lab setting

Classroom

Classroom

I believe in similar type classroom and clinic setting

Practical learning as well as improving practical testing

Classroom

classrooms and home

I think it would be better at home for self learning if you don't have a partner

in classrooms as part of the curriculum

In classrooms as part of the curriculum as it would allow future physios or clinicians to identify more accurately what the feel should be like.

In the classroom is very helpful.

100% in university lab settings, In classes like kin 491 or even In physio school to help students practice without the need for a victim of MCL tears to be present

Physio and kin curriculum.

Appendix C

Standard Operating Procedures

C.1 TRAIN-KNEE simulator

UNIVERSITY OF WATERLOO

Department of Management Sciences

(SAMPLE) STANDARD OPERATING PROCEDURE

A Standard Operating Procedure (SOP) is to be created to direct and guide researchers when performing study protocols, especially those that have the potential to cause harm (or increase risk) to a study participant such as those outlined as a controlled act in the Regulated Health Professions Act of Ontario (RHPA).

SOPs are to follow the Deming Cycle, a cycle that identifies "Plan-Do-Check-Act." A SOP is created to:

- outline the procedures that must be executed to effectively follow the study protocol and outline the resources/equipment needed (i.e., PLAN),
- provide detailed instructions for research staff of the steps that must be implemented and the training that must be completed (i.e., DO),
- clearly document the study protocol (i.e., CHECK), and
- aid with continuous improvement (i.e., ACT)

All SOPs are to be maintained and controlled by the Principal Investigator/Faculty Supervisor. The Principal Investigator/Faculty Supervisor is responsible for the current and approved versions.

SOPs are reviewed by the Office of Research Ethics reviewers and/or Research Ethics Committee members in conjunction with their review of the procedures section in the Form 101 or Form 104 (modification request).

Submit only new SOP's or those which have not been previously approved in conjunction with a prior application. In the procedures section of the 101 form or 104 form state the SOP name, date, and the previously approved ORE number, if applicable.

Title of SOP: Artificial Knee Teaching Tool Device.

SOP created on: [03/31/2022] and **Ethics Clearance Received on:** pending

Revised on: [month/day/year] and **Ethics Clearance Received on**: [month/day/year or pending]

- Add additional "revised on" dates, as needed.
- Use tracking changes as needed to identify changes from a previous version.

SOP created by: [Oliver Schneider, Assistant Professor, Management Sciences]

Signature: 

Date:

□ I acknowledge that as the principal investigator/faculty supervisor I am responsible for updating this SOP and notifying the ORE through a modification form (Form 104) if any of the procedures as outlined above change or require revision.

A. PURPOSE AND BACKGROUND

This Standard Operating Procedure (SOP) establishes guidelines to utilize safely and properly our *Interactive Artificial Knee* prototype, currently stored and ready for use in the Games Institute at the University of Waterloo. All researchers, from the "eCampus - Kinesiology Education" study, are responsible for following this SOP.

B. PROCEDURES/STUDY PROTOCOL

Are there any controlled act(s) to be performed: No

1. Outline all of the procedures to be conducted, including any that are controlled acts, to perform the study protocol along with diagrams and/or flowcharts, as appropriate.

Participants will be:

1) presented with our prototype,

2) asked to familiarize with it (e.g., carry it, rotate it, touch it), and 3), and

3) asked to perform certain tasks as if they were assessing the injury of a real, human knee. To accomplish this, specifically, they will be performing an injury examination test (i.e., the Valgus test [1]).

C. EQUIPMENT

- 1 Interactive Artificial Knee Prototype
- 1 5 Volts 2Amps CSA approved or UL certified Power Adapter
- 1 USB 2.0 A Male to Mini B Cable

		
Prototype	Power Adapter	USB-to-Mini USB Cable

D. DESCRIPTION TO STUDY PARTCIPANTS

Remote education helps make education accessible for those with disabilities or who live in rural areas. However, most of this remote education requires the student to have reliable, high-speed internet and restricts the majority of this learning to online lectures. Courses in disciplines such as kinesiology and physiotherapy suffer in this regard, as lessons are low-quality without the ability to feel and touch a physical human limb when learning how to make diagnoses. As such, the next generation of remote learning platforms will need to support haptic technology (which engages the sense of touch via, e.g., vibration, force feedback, and temperature), among other things. To that end, we have built an artificial knee model which has haptic technology and VR capabilities to increase engagement in remote education students. This study is to assess the fidelity and quality of the haptic technology in the knee model in comparison to a real knee.

E. RISKS

There are no known risks with the use of this device. The device's circuitry and functions can be comparable to a commercially available device (e.g. a video game controller or laptop computer.

F. SAFEGUARDS/SAFETY PROCEDURES

No person is allowed to manipulate our prototype until they receive a formal orientation from PhD student Marco Moran-Ledesma (ID: 20754624). Once this requirement is fulfilled, strictly follow the next set of instructions:

1. Ensure the surrounding area is clear of objects, foods, and beverages.

2. Connect power adapter and USB cable to wall outlet and USB outlet respectively.

3. Connect male jack of power adapter to female port mounted on the prototype. After that, connect male end of USB cable to female port of the microcontroller board. See image below.

4. There are no major limitations or restrictions to manipulate our prototype in a 3D space. Users only need to account for the length of the USB and power cables. They must remain within a 2-meter diameter to prevent unplugging the prototype accidentally.

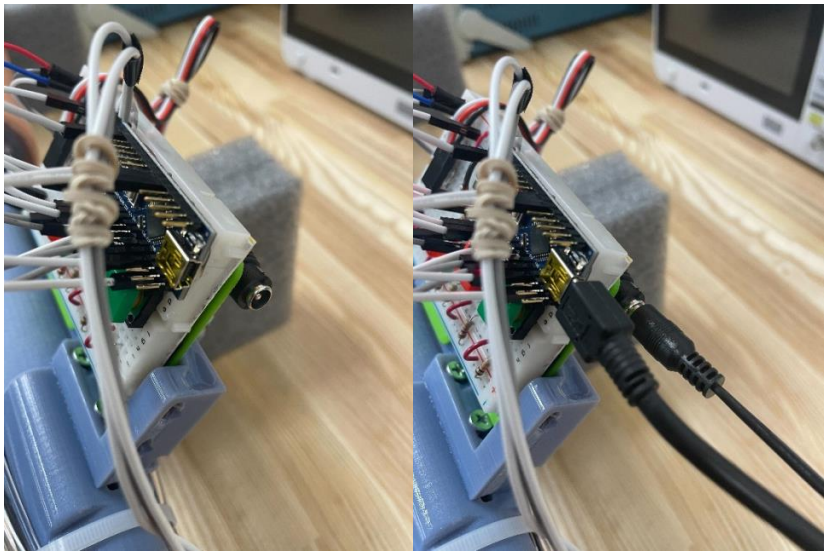


Figure 1. Powering up prototype with power adapter and USB cable

5. The four 1/16 in wire ropes seen in the image below can stiffen up or loosen up with by controlling a rotary-to-linear mechanism. Use green and red push buttons on the breadboard to do this. That is, the green button increases the tension of the ropes, and the red button loosens them up. See media file attached in the application.



Figure 2. 1/16 in Aluminum Wire Ropes

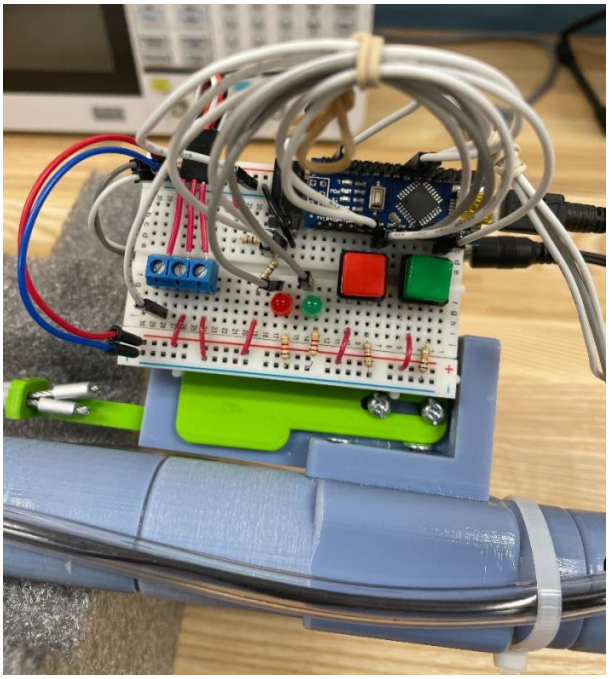


Figure 3. Circuitry of prototype. Use red and green buttons to manipulate ropes.

6. The rotary-to-linear mechanism consists of 3D printed parts and a 35 kg*cm servo motor. There is no major risks associated with these components. Nonetheless, do not manually interfere with them when manipulating our prototype.



Figure 4. Servo motor with rotary-to-linear mechanism

7. To power off our prototype, simply remove the power and the USB cables from the female jack and the microcontroller port, respectively.

8. Sanitize our prototype upon powering it off by applying sanitizing spray on the skin layers. This product is regularly available in the lab.

9. If while powering on/off or manipulating our prototype, an issue comes up, users will be required to unplug both the power adapter and the USB cable from their respective outlets and contact Marco Moran-Ledesma.

G. REFERENCES (if applicable)

[1] Donald A. Neumann, *Kinesiology of the Musculoskeletal System*. Elsevier, 2016.

[2] 35kg Servo Motor characteristics

(https://www.amazon.ca/gp/product/B099WKMHP8/ref=ppx_yo_dt_b_asin_title_o03_s00?ie=UTF8&psc=1)

C.2 Flex-Knee simulator

UNIVERSITY OF WATERLOO

Department of Management Sciences

(SAMPLE) STANDARD OPERATING PROCEDURE

A Standard Operating Procedure (SOP) is to be created to direct and guide researchers when performing study protocols, especially those that have the potential to cause harm (or increase risk) to a study participant such as those outlined as a controlled act in the Regulated Health Professions Act of Ontario (RHPA).

SOPs are to follow the Deming Cycle, a cycle that identifies "Plan-Do-Check-Act." A SOP is created to:

- outline the procedures that must be executed to effectively follow the study protocol and outline the resources/equipment needed (i.e., PLAN),
- provide detailed instructions for research staff of the steps that must be implemented and the training that must be completed (i.e., DO),
- clearly document the study protocol (i.e., CHECK), and
- aid with continuous improvement (i.e., ACT)

All SOPs are to be maintained and controlled by the Principal Investigator/Faculty Supervisor. The Principal Investigator/Faculty Supervisor is responsible for the current and approved versions.

SOPs are reviewed by the Office of Research Ethics reviewers and/or Research Ethics Committee members in conjunction with their review of the procedures section in the Form 101 or Form 104 (modification request).

Submit only new SOP's or those which have not been previously approved in conjunction with a prior application. In the procedures section of the 101 form or 104 form state the SOP name, date, and the previously approved ORE number, if applicable.

Title of SOP:

SOP created on: 01/13/2025 and **Ethics Clearance Received on:** pending

Revised on: [month/day/year] and **Ethics Clearance Received on**: [month/day/year or pending]

- Add additional "revised on" dates, as needed.
- Use tracking changes as needed to identify changes from a previous version.

SOP created by: Oliver Schneider, Associate Professor, Management Science and Engineering

Signature: 

Date: 2025/03/05

□ I acknowledge that as the principal investigator/faculty supervisor I am responsible for updating this SOP and notifying the ORE through a modification form (Form 104) if any of the procedures as outlined above change or require revision.

A. PURPOSE AND BACKGROUND

This Standard Operating Procedure (SOP) establishes guidelines to utilize safely and properly our *Interactive Artificial Knee* prototype, currently stored and ready for use in the Games Institute at the University of Waterloo. All researchers, from the "E-Campus – Kinesiology Education" study, are responsible for following this SOP.

B. PROCEDURES/STUDY PROTOCOL

Are there any controlled act(s) to be performed: Yes **X No**

Participants will be:

1) Presented with our prototype
2) Asked to familiarize with it (e.g., carry it, rotate it, touch it), and
3) Asked to perform tasks as if they were assessing the injury of a real human knee. To accomplish this, concretely, they will be performing the Valgus Stress Test [1].
    a. The following illustrations show a) a conventional Valgus test maneuver on a real patient and b) the way participants will be doing such maneuver on our prototype.



a)



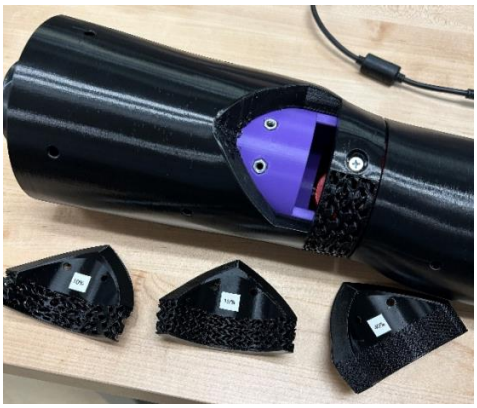
b)

4) Following the conclusion of the study, the researcher(s) will sanitize the entire prototype using wet disinfecting wipes.

C. EQUIPMENT

- 1 Low- or Reduced- fidelity Knee Model







D. DESCRIPTION TO STUDY PARTCIPANTS

In this project we focus on the design and development of a reduced-fidelity haptic manikin modelled after the high-fidelity version. The goal is to create a model that is more cost-effective and easier to manufacture while retaining sufficient functionality for appropriate MCL injury evaluation. The integration of VR with this reduced-fidelity model aims to maintain an leveraging the high visual fidelity of the virtual environment to supplement and enhance the haptic feedback provided by the haptic model.

E. RISKS

There are no risks associated with this extremely passive physical artifact. Unlike its high-fidelity counterpart, there is no electricity involved.

F. SAFEGUARDS/SAFETY PROCEDURES

No person is allowed to manipulate our prototype until they receive a formal orientation from PhD candidate Marco Moran-Ledesma (ID: 20754624).

For added context, we have included multiple images showcasing the interior of our prototype and the hardware required for assembly. However, participants will not be expected to assemble anything. Below is the complete list of components used in our device:

- 2 acrylonitrile butadiene styrene (ABS) pipes.
- 1 universal joint 3D printed with polylactic acid (PLA) filament.
- 10 self-tapping screws.
- 3 leg-shaped members 3D printed with thermoplastic polyurethane (TPU).
- 2 layers of silicone, skin-like rubber [2], specifically Dragon Skin™ 10 NV (https://www.smooth-on.com/products/dragon-skin-10-nv/).









G. REFERENCES (if applicable)

[1] Aronson, P. A., Gieck, J. H., Hertel, J., Rijke, A. M., & Ingersoll, C. D. (2010). Tibiofemoral Joint Positioning for the Valgus Stress Test. *Journal of Athletic Training*, *45*(4), 357–363. https://doi.org/10.4085/1062-6050-45.4.357.

[2] Teyssier, M., Bailly, G., Pelachaud, C., Lecolinet, E., Conn, A., & Roudaut, A. (2019). Skin-On Interfaces: A Bio-Driven Approach for Artificial Skin Design to Cover Interactive Devices. *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, 307–322. https://doi.org/10.1145/3332165.3347943.

Appendix D

Ethics Protocols

D.1 TRAIN-KNEE Study Protocol

PROTOCOLS

#43571 - eCampus - Kinesiology Education

Protocol Information

Review Type	Status	Approval Date	Renewal Date
Expedited	**Approved**	**Feb 22, 2023**	**Apr 18, 2024**

Expiration Date	Initial Approval Date	Initial Review Type
May 10, 2024	**May 09, 2022**	**Expedited**

Feedback

Approval Comment

Renewal approved. Study may continue for 12 months - Asima

Protocol Renewal Form

Renewal form

What kind of application are you renewing?
Standard Application/Imported Record

What is the status of the study?

Participants have not yet been recruited

Have there been any delays/issues with recruitment?

No

Does your project involve research with Indigenous people?

No

Does the study involve the delegation of a controlled act? (e.g., venipuncture, ultrasound, x-ray, etc.)

No

Renewal Confirmation

By submitting this renewal application I am requesting to extend the study another 12 months

The following list outlines project changes that typically need to receive ethics clearance through an amendment to the project prior to implementing the change.

General Information

Only the Principal Investigator/Faculty Supervisor can submit the application. This acts as a signature indicating approval of the application.

Principal Investigator / Faculty Supervisor

Oliver Schneider

Department

Management Sciences and Engineering

Study title

eCampus - Kinesiology Education

General Questionnaire

Indicate the type of application you would like to complete

Standard application *

*** The Standard application is for faculty level research and thesis level research.**

**** The course project application is for single-term (non-thesis) course based research and can be completed by students or the course instructor**

Please confirm:

I understand that the type of applications listed above determine the form I am about to complete. If I have chosen the incorrect form I acknowledge that I may need to complete a new application.

People

University of Waterloo research team

Person

Oliver Schneider

Waterloo Department

Management Sciences and Engineering

Email Address

o2schnei@uwaterloo.ca

Phone

Researcher Role

Principal Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

OLIVER TCPS2_CORE_CERTIFICATE.PDF

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Person

Jennifer Roberts-Smith

Waterloo Department

Communication Arts

Email Address

j33rober@uwaterloo.ca

Phone

Researcher Role

Co-Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

JRS TCPS2_CORE_CERTIFICATE.PDF

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Person

Mark Hancock

Waterloo Department

Management Sciences and Engineering

Email Address

m2hancoc@uwaterloo.ca

Phone

Researcher Role

Co-Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

MARK TCPS2_CORE_CERTIFICATE.PDF

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Person

Emily Shiu

Waterloo Department

Psychology

Email Address

egshiu@uwaterloo.ca

Phone

Researcher Role

Research assistant

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

TCPS2_CORE_CERTIFICATE.PDF

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Person

Marco Moran Ledesma

Waterloo Department

Systems Design Engineering

Email Address

mamoranl@uwaterloo.ca

Phone

Researcher Role

Student investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

MARCO TCPS2_CORE_CERTIFICATE.PDF

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Do you have any investigators external to the University of Waterloo

No

General details

Is this new study related to any previous application?

No

What is the estimated start date and end date for the study?

Start Date

February 7, 2022

End Date

March 31, 2022

Does this research require approval from a UWaterloo departmental committee?

Not a department requirement

What is the level of the research to be conducted? Choose one.

Faculty, tenured, tenure track

Will this study involve Wilfrid Laurier University, Western University, Conestoga College or Local hospitals covered by the Tri-Hospital Research Ethics Board (Cambridge Memorial Hospital, Grand River Hospital and St. Mary's General Hospital)?

No

Has a version of this study been disapproved or rejected by any Research Ethics Board/Committee?

No

Special Instructions RE: Research During COVID-19 Pandemic
Are you proposing in this application a study that involves in-person (face-to-face) research activities either on-campus or off-campus?
Yes

Please follow the protocols for in-person research. If you have any questions please contact researchethics@uwaterloo.ca.

Study description

State your research question(s)

Using an artificial knee model augmented by haptic technology and design, how can the use of this knee model help foster student engagement as an e-learning tool, and how can it be improved?

Provide a clear, detailed description of the purpose, hypothesis, aim, and objectives of this study

This study will be conducted to refine the quality of an artificial knee model for use as a kinesiology learning and teaching tool. [Hypothesis?]

Provide background information, a rationale, and justification for conducting this study. Describe why the research is being done and what research has already been done in this area. Be sure to explain why this research is important.

Embodied learning activities, used in disciplines such as performing arts and physiology, require synchronous, in-person, physical instruction, currently completely unavailable for remote learners. Barriers to remote, embodied learning are especially great for learners with disabilities and learners in rural areas. The most advanced existing platforms enable limited, synchronous interaction with audio, visual, and textual media using internet video calling and chat in reliable, high speed networks. As such, they privilege able-bodied, visual and auditory learners in urban areas where high speed networks are accessible. To address these inequities, the next generation of remote learning platforms will need to support haptic technology (which engages the sense of touch via, e.g., vibration, force feedback, and temperature), among other things. To that end, we have built an artificial knee model which has haptic technology and VR capabilities to increase engagement in remote education students. This study is to assess the fidelity and quality of the haptic technology in the knee model in comparison to a real knee.

In a maximum of 250 words, provide a non-scientific lay language description that summarizes the project outlining the purpose, anticipated benefits, and basic procedures. Write this summary as if it would be read by members of the general public who are not familiar with academic terms or acronyms. Use language suitable for a media release.

Remote education helps make education accessible for those with disabilities or who live in rural areas. However, most of this remote education requires the student to have reliable, high-speed internet and restricts the majority of this learning to online lectures. Courses in disciplines such as kinesiology and physiotherapy suffer in this regard, as lessons are low-quality without the ability to feel and touch a physical human limb when learning how to make diagnoses. As such, the next generation of remote learning platforms will need to support haptic technology (which engages the sense of touch via, e.g., vibration, force feedback, and temperature), among other things. To that end, we have built an artificial knee model which has haptic technology and VR capabilities to increase engagement in remote education students. This study is to assess the fidelity and quality of the haptic technology in the knee model in comparison to a real knee.

What is the study design?

Qualitative analysis, mixed method

Is this a pilot study?

No

Sample Size

What is the expected sample size? Outline the number of participants anticipated to take part in the study.

20

Was a formal sample size calculation completed?

No

Provide a rationale for the number of participants specified

20 participants is common in HCI for large effect sizes (which we usually encounter in classic HCI)

Study sites

Where is this study taking place?

University of Waterloo

Are there any permissions required to conduct this study on campus?

No

Funding

Is the study funded/will it be funded?

Yes

Funding
List all funding sources that are new or ongoing

Funding status

New funding

Funding source is

Tri-agency / Canadian Government sponsor

Canadian Government agency

Other

Program name if applicable

eCampus Ontario Virtual Learning Strategy

Work-order or award number, if known

10001-11221-1575-XXX-50030

What is the period of funding

Funding from

April 1, 2021

Funding to

March 31, 2022

Conflict of interest

Are there any potential, perceived, or actual financial or non-financial conflicts of interest of the research team in undertaking the proposed research?

No

Benefits

Are there direct benefits of the proposed research to the study participants?

No

What are the scientific and/or scholarly benefits of the proposed research?

This research will further inform the potential of technology (haptics/VR augmented artificial models) in the role as teaching tools and learning aids, especially for remote learning.

Participants

Participant general categories

University of Waterloo staff and/or faculty
Adults (age 18-64 years)

Describe the sample in detail and list any specific inclusion/exclusion criteria for the study

Faculty members in the Department of Kinesiology with expertise in knee biomechanics and injury diagnosis and/or local physiotherapists.

If you are excluding people on certain characteristics provide a justification for the exclusion.

This study will collect responses on the quality and fidelity of our artificial knee model in comparison to a real knee. To that end, we need qualitative opinions from participants who are experts in knee biomechanics or injury diagnosis.

Will a screening process be used to determine eligibility in the study based on the inclusion and/or exclusion criteria identified above?

No

Recruitment

Identify from where/what sources potential participants will be recruited.

Through email/internet (e.g., social media networks)
Other

Indicate what email listing, internet site or network you intend to recruit from

Will directly contact Kinesiology faculty and local physiotherapists.

Provide details on your other recruitment source

Faculty members and physiotherapists may invite and recommend other faculty members and/or physiologists whom they believe would be interested in participating in the study.

What recruitment materials will be used?

Email script
Other
Social media

Describe how social media will be used

Social media posts will be used to advertise the study. Social media platforms to be used: Twitter, Slack, Discord, Facebook, Messenger, Instagram, Reddit.

Describe the other recruitment materials

Word of mouth

Upload your recruitment materials

Upload your recruitment materials

RECRUITMENT EMAIL 2021-10-29.DOCX

Study group

Email

Upload your recruitment materials

RECRUITMENT - SOCIAL MEDIA 2022-01-21.DOCX

Study group

Social media

Will potential participants be recruited through pre-existing relationships with members of the research team (e.g., employees, students, or patients of research team, acquaintances, own children or family members, colleagues, etc.)?

No

Methods and procedures

Which of the following will be conducted for this study?

Surveys/questionnaires

One-on-one interviews

Observation

How will the survey(s) or questionnaire(s) be administered?

In-person - Computer-administered or web/online

How will the one-on-one interviews be conducted?

In-person

Will quotations be used in the write-up of the study

Yes

What type of quotations will be used?

Anonymous

What type of observations are planned?

Participant observation (where the researcher engages in, and observes, the action; participant knows they are being observed)

Will the people being observed have an expectation of privacy?

No

Explain why there will not be an expectation of privacy

Observations of the participants will be made while they are interacting with the knee prototype in front of the researchers.

For each of the procedures indicated above, provide a detailed, sequential description of how they will be used in the study.

After agreeing to participate, participants will be brought into a lab room at the Games Institute. They will be asked to provide consent to proceed. (They will also be given the option to provide one consent before scheduling a study appointment.) Participants will then be presented with the artificial knee model and be asked to interact with it and perform certain tasks as if they were assessing the injury of a real, human knee (e.g. performing the Valgus test). After the interaction, they will be asked a few interview questions about their experience with using the prototype (e.g. how does the weight feel in comparison to a real human knee). Some non-predetermined questions may also be asked over the course of the interview to probe participants' responses further. Video and/or audio recordings may be made upon consent by the participants. Participants' faces will be anonymized (either cropped or blurred) with a video editor before being stored.

Please upload any study materials related to the procedure(s)

Study material

INTERVIEW GUIDE 2021-10-27.DOCX

Does the study involve the administration or use of an approved drug or natural health product?

No

Will you be collecting any biological specimens?

No

Will you be creating or contributing to a bio-bank, bio-repository, registry, as part of the study?

No

Will you be doing any genetic testing or analysis?

No

Incidental and secondary findings

See Guideline for reporting incidental and secondary findings to study participants

Are any of the methods or procedures used likely (i.e., a real possibility and probability) to reveal an incidental finding (i.e., discoveries made in the course of research but that are outside the scope of the research and/or results that are outside the original purpose for which a test or procedure was conducted)?

No

Are any of the methods or procedures used likely to reveal a secondary finding (i.e., findings that are not the primary target of the test or procedure; rather, it is an additional result that is actively sought)?

No

Equipment use

Will there be any equipment used as part of this study?

Yes

Please list all equipment being used in this study

Full name of device or equipment

Artificial Knee Model

What type of device or equipment is this

equipment or device that has been created or built and/or modified by the researchers to be used with participants

Has this equipment or device been used in a previous study?

No

Upload a copy of the assessment form, if already approved by the Safety Office

SCHNEIDER - KNEE MODEL DEVICE SAFETY - MARCH 21, 2022.PDF

Upload your team's SOP, for the equipment or device.

SOP_TEMPLATE_20220420+OS.PDF

Full name of device or equipment

Silicone-based artificial skin (Ecoflex and DragonSkin)

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Is this a medical device?

No

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Attach the other supplementary information (e.g., user manual)

SAFETY DATASHEET - SMOOTH ON PRODUCTS.PDF

Deception

Does the study involve deception or partial disclosure?

No

Risks and safeguards

Considering each method or procedure to be used in this study, indicate if participants might experience any of the following risks or harms

No known or anticipated risks

Outline the criteria for stopping the study early due to safety concerns/other issues.

Aside from the known risks of COVID-19 (which are being addressed with the Safety plan), there are no other known risks to this study.

Privacy

Will demographic and/or background information be asked of participants? If so, ensure that the demographic questions have been uploaded in the methods section.

No

Participant identification

Participants will be identified by an assigned subject number.

If applicable how will the key/list that links participants' codes with their actual name and/or consent forms be stored and protected?

N/A

Are there any limitations to the promise of confidentiality?

No

Will any study data be leaving the University of Waterloo, the province, or country (e.g., member of research team is located in another institution, province, or country, etc.)?

No

Will any collected data or information be entered into a database for future use?

No

Are there other members of the research team who are not named on this application (e.g., co-op students, research assistants, or other temporary personnel) who may carry out specific tasks involved in your study?

No

Will individual participant identities be confidential in the publication or release of the study findings?

Yes

Data storage

What type(s) of data will be collected for this study?

Audio-recordings
Video-recordings
Electronic files

If identifiable features are captured, ensure this is described as part of the procedures section

---

For each type of information collected, identify where the data will be stored

All electronic data will be stored in password-protected personal computers owned by researchers. Later as the university reopens, these data will be transferred to a secure local computer in the Games Institute using a flash drive. Multiple steps will be taken to ensure the anonymity of participants and confidentiality of data. First, the data files of each participant will be stored on a password-protected computer (recording, keypress, and questionnaire data), with a unique subject code consisting of letters and numbers; participant names will not be attached to the data (data will not be linked to the contact information in any way). Only researchers associated with the study will have access to the locked cabinet and computer. In the release of findings (either during presentations or written reports) only group data is discussed. Identifying information about individual participants is never released or associated with individual data. Data may be deposited in an online public repository/database. Data will be de-identifed (i.e. data such as names, student numbers, and certain identifying demographic information removed) prior to submission to the repository/database and will be presented in aggregate form in online publications.

For each type of data collected, identify the minimum retention period

Data collected during this study will be retained for a minimum of 7 years. Audio and video files will be deleted once transcribed and no longer required unless participants have signed the audio and/or video release forms indicating consent to allow recordings to be used for external presentation purposes.

Data Management

Are there plans to link the data collected with other data sets, databases, or registries?

Unsure at this time

The Tri-Agency Open Access Policy on Publications and some journals are requesting that research data be provided to an open access repository to promote the availability of findings, to enhance transparency and share with the widest possible audience.

Do researchers plan to make the anonymized data-set available in an online repository?

Unsure at this time

Do you have a data management plan?

Yes

Consent and Withdrawal

What member(s) of the research team will be responsible for obtaining informed consent?

Emily Shiu, Marco Moran-Ledesma

Is there a relationship between the potential participant(s) and the person obtaining consent?

No

How will consent be obtained

Written signature on a consent form

Upload Information and Consent Materials

Upload Information and Consent Materials

CONSENT FORM 2022-02-08.DOCX

Study group

Do you anticipate that you will need to make special accommodations for your participant group?

No

Do you anticipate needing to put in place any special procedures when obtaining informed consent?

No

Will consent need to be re-documented throughout the life of this study?

No

Describe how participants will be informed of their right to withdraw from the study.

Participants will be informed that they can withdraw from the study at any time without penalization, and their data will not be used. Participants will also be informed that they can decline to answer any questions they do not wish to answer.

Outline what will be done with the participant's data if they withdraw from the study.

If the participant has completed a sufficient amount of the study for analysis, their data will be included (unless the withdrawing participant has requested that this not be the case). If the participant has not completed a sufficient amount of the study for analysis, their data will not be analyzed.

Will any individuals taking part in this study be unable to provide their own informed consent?

No

Remuneration

Will there be remuneration provided to show appreciation for a participant's time, effort, skills, etc. to take part in the study?

Yes

Type of remuneration

Gift card

Identify the retailer(s) and dollar amount

$50 (Amazon)

If a participant withdraws from the study will remuneration be pro-rated?

No, participants will receive maximum remuneration

Will participants incur any expenses by participating in the study?

No

Feedback and Appreciation

How will you show appreciation to participants for taking part in the study?

Participants will receive a feedback letter after completing the study that will thank them for their participation and provide further information about the study.

When will feedback/appreciation be provided to participants (e.g., immediately after the session, at the end of a survey, mail results at time X.)?

Feedback letter will be made available at the completion of the study.

Upload Feedback/Appreciation materials

Upload Feedback/Appreciation materials

FEEDBACK LETTER 2022-01-22.DOCX

Study group

How can participants learn about the study results/obtain a summary of the findings if interested?

The participants will be informed in the feedback letter that if they wish to learn more about the study, that the names and email of the principal and student investigators will be present on the feedback letter and can contact them if they so choose. As for their own data, they will be reminded that after they complete the study that all information regarding them will be de-identified. Making it impossible for the researchers to identify them.

Other Details

Provide any other information relevant to this study you wish to explain to the Research Ethics Board reviewers or to the staff in the Office of Research Ethics.

N/A

Other Attachments

Upload any additional study documents

Attachments

Attachment

EC1-1303-HAPTIC LAB GENERAL USAGE SAFETY PLAN-FINAL.PDF

Name

Attachment Type

Comments

Attestation

As the Principal Investigator/Faculty Supervisor/Local Investigator, I attest to the following:

- I will ensure all co-investigators, collaborators, and student investigators listed on this application have reviewed the application contents and will conduct the study according to the application/protocol.
- I am aware that any changes made to the research must be reviewed and provided clearance before the changes are implemented. Change requests (i.e., an amendment) are to be submitted through the system. I am also aware ethics clearance for this study is valid for only 12 months unless I renew the study prior to the ethics clearance expiry date. If an annual renewal report is NOT submitted through the system prior to the expiry date, the study will be suspended, all work on the study must stop, and Research Finance will be notified which will result in a hold being put on the funds associated with this study.
- I agree to comply with the Tri-Council Policy Statement (TCPS2) for conducting research with human participants and with University of Waterloo policies and guidelines when conducting this study (e.g., statement on human participant research, IST policies, etc.).
- I confirm I have read the University of Waterloo Research Integrity guidelines and I agree to comply with the policies and guidelines of my profession or discipline regarding the ethical conduct of research involving humans.

By submitting this application I agree to the above attestations and will ensure the research is conducted accordingly

Only the Principal Investigator/Faculty Supervisor can submit the application. This acts as a signature indicating approval of the application.

This is the end of the application form. Click submit in the right menu if you are ready to send it to the Research Ethics Office.

D.2 Flex-Knee Study Protocol

PROTOCOLS

#47288 - Enhancing Physiotherapy Training with a Reduced-Fidelity Haptic Manikin in Virtual Reality

Protocol Information

Review Type	Status	Submission Number	Approval Date
Expedited	**Approved**	**4**	**Mar 20, 2026**

Renewal Date	Expiration Date	Initial Approval Date	Initial Review Type
Apr 06, 2027	**Apr 29, 2027**	**Apr 28, 2025**	**Expedited**

Feedback

Approval Comment

Renewal approved. Study may continue for another 12 months- JE

Protocol Renewal Form

Renewal form

What kind of application are you renewing?

Standard Application/Imported Record

What is the status of the study?

Participants are being recruited or participation is ongoing

Approximately how many participants are left to recruit?

10-20

In the past 12 months, have any participants withdrawn from the study?

No

In the past 12 months, have any of the following issues occurred, but have not been reported to Research Ethics?

No unreported events/changes

Does your project involve research with Indigenous people?

No

Does the study involve the delegation of a controlled act? (e.g., venipuncture, ultrasound, x-ray, etc.)

No

Renewal Confirmation

By submitting this renewal application I am requesting to extend the study another 12 months

The following list outlines project changes that typically need to receive ethics clearance through an amendment to the project prior to implementing the change.

General Information

Only the Principal Investigator/Faculty Supervisor can submit the application. This acts as a signature indicating approval of the application.

Principal Investigator / Faculty Supervisor

Oliver Schneider

Department

Systems Design Engineering

Study title

Enhancing Physiotherapy Training with a Reduced- Fidelity Haptic Manikin in Virtual Reality

General Questionnaire

Indicate the type of application you would like to complete

Standard application

Please confirm:

I understand that the type of applications listed above determine the form I am about to complete. If I have chosen the incorrect form I acknowledge that I may need to complete a new application.

People

Research team members based at the University of Waterloo.

Ensure **all** information in this table is completed.

Person

Oliver Schneider

Waterloo Department

Management Science and Engineering

Email Address

o2schnei@uwaterloo.ca

Phone

Researcher Role

Principal Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 2022 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 2022 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

tcps2_core_certificate_2024-02-04.pdf

Ensure **all** information in this table is completed.

Person

Mark Hancock

Waterloo Department

Management Science and Engineering

Email Address

m2hancoc@uwaterloo.ca

Phone

Researcher Role

Co-Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 2022 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 2022 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

Hancock_tcps2_core_certificate_2022.pdf

Ensure **all** information in this table is completed.

Person

Robert Burns

Waterloo Department

Kinesiology and Health Sciences

Email Address

rwburns@uwaterloo.ca

Phone

Researcher Role

Co-Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 2022 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 2022 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

tcps2_core_certificate- R Burns.pdf

Ensure all information in this table is completed.

Person

Marco Moran Ledesma

Waterloo Department

Systems Design Engineering

Email Address

mamoranl@uwaterloo.ca

Phone

Researcher Role

Student investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 2022 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 2022 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

tcps2_core_certificate.pdf

Do you have any investigators external to the University of Waterloo?

No

General details

Is this new study related to any previous application?

Yes

Previous UWaterloo ORE/Kuali #

43571

What is the estimated start and end date for the study?

Start Date (Date you anticipate beginning the recruitment of participants)

April 1, 2025

End Date (Date you expect the study will end, for example, the date when there will be no further contact with participants or when the data analysis will be completed for US funded research)

August 31, 2025

Does this research require approval from a UWaterloo departmental committee?

Not a department requirement

What is the level of the research to be conducted? Choose one.

PhD dissertation research

Will this study involve local hospitals covered by the Waterloo Wellington Research Ethics Board (WWREB) (established by Cambridge Memorial Hospital, Grand River Hospital and St. Mary's General Hospital)?

No

Has a version of this study been disapproved or rejected by any Research Ethics Board/Committee?

No

Study description

State your research question(s).

How can a reduced-fidelity version of our high-fidelity knee model replicate its effectiveness in enabling users to perform the Valgus test and simulate various MCL injury conditions? Secondary RQs: Can practitioners distinguish between healthy and unhealthy MCL conditions when using a lower-fidelity manikin and a realistic VR model? Do factors such as 1) the soft tissue materials (structure) and 2) the type of joint used affect their ability to differentiate healthy and unhealthy conditions? For low-fidelity model with no VR study with the KIN 491 students, we add the following: How feasible is it to deploy a low-cost knee model in classrooms as a supplemental tool to learn manual tests? How do novice practitioners/students perceive the usefulness of our knee model and its potential integration into their learning environments (classrooms, labs)? Are they able to correctly perform the Valgus test on our model after only one lecture/lab session?

Provide a clear, detailed description of the purpose, hypothesis, aim, and objectives of this study.

This study aims to explore how an immersive virtual reality (VR) environment can compensate for reduced haptic fidelity in a simulated knee examination. By integrating VR with a lower-fidelity physical knee model, we seek to determine whether practitioners can still accurately perform the Valgus test and assess medial collateral ligament (MCL) injuries. We hypothesize that an immersive VR environment, when paired with a low-fidelity knee model, will allow users to effectively distinguish between healthy and injured MCL conditions. We expect that VR will provide sufficient visual information to compensate for the limitations in physical realism. The aim of this study is to develop an accessible (affordable) training platform for novice practitioners and educators to evaluate knee injuries. This approach offers several benefits, including increased accessibility for institutions with limited budgets, consistent and standardized training, and the potential for remote learning. It enables students to gain hands-on experience in a controlled, repeatable setting without relying on expensive simulators or injured patients.

Provide background information, a rationale, and justification for conducting this study. Describe why the research is being done and what research has already been done in this area. Be sure to explain why this research is important.

The diagnosis of knee injuries requires the hands-on manipulation and palpation of a patient's knee to assess the degree of injury. Current instructional methods for physiotherapy and medical students in learning knee injury diagnosis asks them to practice these hands-on techniques on the healthy knees of their class partners. But, they often do not have the opportunity to experience feeling the difference in ligament tensions of real knee injuries. This leaves future clinicians and doctors with a large gap in knowledge until they are able to access such an opportunity. To that end, we have designed and built an artificial knee model with haptic technologies. This model can be adjusted to simulate the difference in tactile feedback of a healthy knee compared to a knee with a Grade 1, 2, 3, or 4 injury in the Medial Collateral Ligament. This study will assess whether the simulated injuries in our model accurately replicate the feeling of real knee injuries such that clinicians are able to make diagnoses accurate to the intended simulation. The study will also assess clinicians' overall opinions of the haptic fidelity of the knee model itself, as well as kinesiology instructors' opinions and feedback of the knee model's utility as a teaching tool.

In a maximum of 250 words, provide a non-scientific lay language description that summarizes the project outlining the purpose, anticipated benefits, and basic procedures. Write this summary as if it would be read by members of the general public who are not familiar with academic terms or acronyms. Use language suitable for a media release.

Knee injuries require a doctor or therapist to prod and touch a patient's knee to feel small differences in tension compared to a healthy knee. Unfortunately, medical and physiotherapy students are usually unable to experience these differences in tension while in school, since they are often only practicing on the healthy knees of their classmates. Because of this, there is a need for a tool that can consistently replicate these tactile feelings in injured knees for students to gain the needed experience. To that end, we built an artificial knee model that can be used as a teaching tool. The tension in this knee model is designed so that it can simulate what a knee with a Grade 1-4 injury would feel like in a real knee. In this study, we plan to verify that our knee can accurately do so such that it can be used as a teaching tool for future clinicians. We plan to ask currently practicing clinicians to perform an assessment for an injury in our knee model to see if they are able to correctly do so according to the intended simulation. Finally, we also plan to ask for opinions and feedback on how it could be used as a teaching tool.

What is the study design?

Mixed method

Is this a pilot study?

No

Sample Size

What is the expected sample size? Outline the number of participants anticipated to take part in the study.

25

Was a formal sample size calculation completed?
See Statistics Help Desk for support in calculating sample sizes.
No

Provide a rationale for the number of participants specified

We will conduct a within-participants experiment, utilizing repeated measures analysis of variance (ANOVA) and post-hoc pairwise comparisons to assess participants' perceptions of multiple MCL conditions. To determine an appropriate sample size, we conducted a power analysis using G*Power software (Cohen, 1992). The analysis indicates that a minimum of 23 participants is required to achieve a statistical power (1−β) of 0.80, with a medium effect size (f) of 0.25 and a significance level (α) of 0.05. This sample size ensures a sufficient likelihood of detecting meaningful differences between conditions while balancing feasibility. Given that our study involves specialized participants (i.e., undergraduate students in the Kinesiology program who have completed the KIN 140L course), this number is both practical and representative of our target population.

Study sites

Where is this study taking place?
On a University of Waterloo campus

Are there any permissions required to conduct this study on campus?

No

Funding

Is the study funded/will it be funded?

Yes

Funding
List all funding sources that are new or ongoing

Funding status

Ongoing funding

Funding source is

Tri-agency / Canadian Government sponsor

Industry partner/sponsor name

Canadian Government agency

NSERC - Natural Sciences and Engineering Research Council of Canada

Charitable foundation

Other Charitable foundation name

Internal UWaterloo funding source

US federal funds

Other US federal funds sponsor

Other funding source

Program name if applicable

NSERC Discovery - RGPIN-2024-05124

Work-order or award number, if known

What is the expected period of funding

What is the period of funding

Funding from

March 1, 2024

Funding to

March 31, 2029

Funding status

Ongoing funding

Funding source is

Internal UWaterloo funding

Industry partner/sponsor name

Canadian Government agency

Charitable foundation

Other Charitable foundation name

Internal UWaterloo funding source

CTE LITE Seed Grant

US federal funds

Other US federal funds sponsor

Other funding source

Program name if applicable

CTE LITE Seed Grant

Work-order or award number, if known
11000-10403 201

What is the expected period of funding

What is the period of funding

Funding from
January 1, 2025

Funding to
December 31, 2025

Conflict of interest

Are there any potential, perceived, or actual financial or non-financial conflicts of interest of the research team in undertaking the proposed research?
No

Benefits

Are there direct benefits of the proposed research to the study participants?
No

What are the scientific and/or scholarly benefits of the proposed research?

This research will further inform the potential of technology (haptics-augmented artificial models) in the role of teaching tools and learning aids

Participants

Participant general categories

University of Waterloo undergraduate and/or graduate students
University of Waterloo staff and/or faculty

Are you conducting research in classes with students as your participants to evaluate a teaching method or object?

No

Describe the sample in detail and list any specific inclusion/exclusion criteria for the study

Faculty members in the Kinesiology department, certified physiotherapists and athletic therapists, and undergraduate students who have completed the KIN 140L course, as it provides exposure and practical training in the management of injuries in an athletic population, including MCL injuries. For low-fidelity model with no VR study, undergraduate students enrolled in the KIN 491 course.

If you are excluding people on certain characteristics provide a justification for the exclusion.

Since there is a VR component, people with visual impairments, people with audio impairments, people with balance impairments, and people with medical implants will not be eligible to participate. If people listed in the exclusion criteria use the HTC Vive (our intended VR headset), they might experience health problems indicated in the HTC Vive Safety and Regulatory Guide file (attached in the "Equipment Use" section).

Will a screening process be used to determine eligibility in the study based on the inclusion and/or exclusion criteria identified above?

Yes

Is a screening questionnaire to be used?

No

How is the screening to be conducted?

We will rely on self-report/self-exclusion. The recruitment material will include the risks associated with participating in the study, and before the study takes place, participants will be given the information again.

When is the screening to be conducted in relation to other study procedures (i.e., consent)?

During the sign-up for the experiment.

What are individuals told if they do not meet the eligibility criteria?

The eligibility criteria will be made clear in the recruitment materials. If participants still come to the study and they do not meet the criteria, then they will be kindly told they do not qualify and advised against participating since the risks associated could affect their health.

What will be done with the information or data collected if an individual is deemed ineligible to participate in the study?

There is no data collected during the screening process.

Recruitment

Identify from where/what sources potential participants will be recruited. If your participants are part of an organization/group please see guidance for conducting research when participants are part of an organization or group and incorporate this information into the methods section.

University of Waterloo campus (e.g., SLC, Engineering Foyer, laboratories)
Through email/internet (e.g., social media networks)

Where on campus do you intend to recruit?

SLC, Health Science buildings For low-fidelity model with no VR study, we will recruit students in the KIN 491 course on the week of September 22, 2025. Participation is voluntary and has no impact on their grade.

Indicate what email listing, internet site or network you intend to recruit from

We intend to recruit participants through the email listings commonly used by the Faculty of Health. Specific channels will be determined in consultation with the department.

What recruitment materials will be used? See sample recruitment materials.

Email script

Verbal script

Posters

Upload your recruitment materials

Upload your recruitment materials

Recruitment email 2025-01-13.pdf

Study group

Participants

Upload your recruitment materials

Recruitment Poster_2025-01-13.pdf

Study group

Participants

Upload your recruitment materials

Verbal script_noVR_2025-09-16.pdf

Study group

Verbal script

Will potential participants be recruited through pre-existing relationships with members of the research team (e.g., employees, students, or patients of research team, acquaintances, own children or family members, colleagues, etc.)?

Yes

Outline the relationship between the researchers and potential participants (e.g., professor-student, colleagues)

A member of our research team is the instructor for the KIN 140L course and may assist in spreading the word. However, BEFORE ANY CONCERNS ARISE, our participation criteria explicitly state that only undergraduate students who HAVE COMPLETED KIN 140L are eligible. As a result, there is no conflict of interest. This approach ensures voluntariness and prevents undue influence or manipulation. For low-fidelity model with no VR study: a member of our research team is the instructor for the KIN 491 course. He and the student investigator will invite students to participate.

Could this relationship compromise the potential participant's freedom to decline participation?

No

Explain

NO, this relationship does not compromise a potential participant’s freedom to decline participation. All eligible participants will have already completed KIN 140L before being recruited, meaning there is no academic influence or power imbalance that could pressure them into participating. Their decision to join the study is entirely voluntary, with no impact on their past or future coursework. Participation is VOLUNTARY and has no impact on people's grade, so there is no conflict of interest. This approach ensures voluntariness and prevents undue influence or manipulation.

Methods and procedures

Which of the following will be conducted for this study?

Surveys/questionnaires

Observation as described in TCPS 2 Chapter 10

How will the survey(s) or questionnaire(s) be administered?

In-person - Computer-administered or web/online

Will quotations be used in the write-up of the study

Yes

What type of quotations will be used?

Anonymous

What type of observations are planned?

Participant observation (where the researcher engages in, and observes, the action; participant knows they are being observed)

Will the people being observed have an expectation of privacy?

No

Explain why there will not be an expectation of privacy

Participants will be informed that their faces will NOT be videotaped. We will record video footage of participants interacting with our two knee models. The camera will be positioned to capture only their hands, waist area, and the knee model they are using.

For each of the procedures indicated above, provided a detailed, sequential description of how they will be used in the study. Provide one or more paragraphs describing how you are recruiting participants, obtaining consent, what participants are asked to do, and how the research team will be using the collected data.

1. Participants are given a verbal introduction about the purpose of the study. 2. Participants complete a consent form (attached below). 3. Participants are given a brief explanation of the two knee models they will be using during the study. 4. Participants are given a brief explanation of the Virtual Reality equipment and hand tracking device they will be wearing during the study. 5. Participants are instructed to wear the headset and put on the hand tracking device (glove with sensors) and view our virtual environment, which includes only a highly accurate digital model of a human. 6. Participants execute the following four interaction conditions in a randomized order: VR + high-fidelity model, No VR + high-fidelity model, VR + low-fidelity model, No VR + low-fidelity model. 6a) In each condition, participants perform the Valgus test on the model 8 times and verbally classify each test as either an "injured" or "healthy" MCL condition based on their perception. The student investigator records their answer in a spreadsheet. In each of the 8 trials, the student investigator adjusts the knee model to a specific injury condition, which the participant will be unaware of. While the participant knows that something is being modified, they do not know whether the condition being set is healthy or injured. 6b) After each condition, participants fill in a custom-made computer-administered questionnaire. 7. Participants will be paid, given a feedback letter, and thanked. For low-fidelity model with no VR study ONLY: To save time, we will have three versions of the low-fidelity model available; two will be configured as injured and one will be configured as healthy. 1. Participants are given a verbal introduction about the purpose of the study and about the knee model during the KIN 491 lab hrs (5 minutes). See the verbal script in the Recruitment section. 2. The student investigator will have the knee models set up in the lab and will invite students to informally interact with them. This will happen during a scheduled pause in the KIN 491 lab. 3. There will be a QR code available next to the knee models. Those interested in participating will be invited to scan. The QR will direct them to the consent form (attached below) and to a link to schedule a time slot immediately after the lab or later. Those sessions will happen in the same room in the BMH building. 4. When they arrive, participants are given again a brief explanation of the knee model they will be using during the study. 5. Participants in a randomized order perform the Valgus test on each model and verbally classify each as either an

"injured" or "healthy" MCL condition based on their perception. The student investigator records their answers in a spreadsheet. The participant will be unaware of how each model is configured. 6) Participants fill in computer-administered questionnaires: Questionnaire_noVR_2025-09-04 and HX_questionnaire_noVR_2025-09-08. 7. Participants will be paid, given a feedback letter, and thanked.

Please upload any study materials related to the procedure(s)

Study material

Custom-made questionnaire_v1_2025-02-13.pdf

Study material

Demographics_Questionnaire_2025_04_25.pdf

Study material

Questionnaire_noVR_2025-09-04.pdf

Study material

HX_questionnaire_noVR_2025-09-08.pdf

Does the study involve the administration or use of an approved drug or natural health product?

No

Will you be collecting any biological specimens?

No

Will you be creating or contributing to a bio-bank, bio-repository, registry, as part of the study?

No

Will you be doing any genetic testing or analysis?

No

Incidental and secondary findings

See Guideline for reporting incidental and secondary findings to study participants

Are any of the methods or procedures used likely (i.e., a real possibility and probability) to reveal an incidental finding (i.e., discoveries made in the course of research but that are outside the scope of the research and/or results that are outside the original purpose for which a test or procedure was conducted)?

No

Are any of the methods or procedures used likely to reveal a secondary finding (i.e., findings that are not the primary target of the test or procedure; rather, it is an additional result that is actively sought)?

No

Equipment use

Will there be any equipment used as part of this study?

Yes

Please list all equipment being used in this study

Full name of device or equipment

HTC Vive Safety

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Describe this other type of device or equipment

Is this a medical device?

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Provide ORE # and name of study

Are you making any changes to how the equipment or device will be used in this study?

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

No Attachment

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

HTC - Safety and Regulatory Guide.PDF

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

No Attachment

Full name of device or equipment

HTC Vive Manual

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Describe this other type of device or equipment

Is this a medical device?

No

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Provide ORE # and name of study

Are you making any changes to how the equipment or device will be used in this study?

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

No Attachment

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

HTC Vive_UserManual_20190217.pdf

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

No Attachment

Full name of device or equipment

High-fidelity Knee Model

What type of device or equipment is this

equipment or device that has been created or built and/or modified by the researchers to be used with participants

Describe this other type of device or equipment

Is this a medical device?

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Yes

Provide ORE # and name of study

43571

Are you making any changes to how the equipment or device will be used in this study?

No

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

Schneider - Knee Model Device Safety - March 21, 2022 (1).pdf

Select how you will be providing more information on the device/equipment

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

No Attachment

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

SOP_Template_20220420+os.pdf

Full name of device or equipment

Silicone-based artificial skin (Ecoflex and DragonSkin)

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Describe this other type of device or equipment

Is this a medical device?

No

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Provide ORE # and name of study

Are you making any changes to how the equipment or device will be used in this study?

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

No Attachment

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

Safety Datasheet - Smooth ON products.pdf

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

No Attachment

Full name of device or equipment

OptiTrack motion capture system

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Describe this other type of device or equipment

Is this a medical device?

No

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Provide ORE # and name of study

Are you making any changes to how the equipment or device will be used in this study?

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

No Attachment

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

Optitrack.pdf

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

No Attachment

Full name of device or equipment

Optitrack Active Markers for Hand Tracking

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Describe this other type of device or equipment

Is this a medical device?

No

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Provide ORE # and name of study

Are you making any changes to how the equipment or device will be used in this study?

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

No Attachment

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

Optitrack - Active Markers.pdf

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

No Attachment

Full name of device or equipment

Low-fidelity Knee Model

What type of device or equipment is this

equipment or device that has been created or built and/or modified by the researchers to be used with participants

Describe this other type of device or equipment

Is this a medical device?

This device is a

What is the medical device establishment or active licence number? See Health Canada Medical Devices Licence Listings

Has this equipment or device been used in a previous study?

Yes

Provide ORE # and name of study

43571

Are you making any changes to how the equipment or device will be used in this study?

No

Describe the changes

Upload a copy of the assessment form, if already approved by the Safety Office

Schneider - Low Fidelity Knee Device - Feb 24 2025.pdf

Select how you will be providing more information on the device/equipment

Upload your team's SOP

No Attachment

Attach the other supplementary information (e.g., user manual)

No Attachment

Enter the ORE # where this SOP was previously used

Upload this SOP

No Attachment

Please ensure your SOP explains the following:

Upload your team's SOP, for the equipment or device.

LOW-FIDELITY-DEVICE_SOP_Template_2025-01-13+os.pdf

Deception

Does the study involve deception or partial disclosure?

No

Risks and safeguards

Considering each method or procedure to be used in this study, indicate if participants might experience any of the following risks or harms

Other risks or harms (e.g., risks that go beyond the individual and may involve the interests of communities, societies or other groups)

Risk details

For each risk identified above, please add additional details describing that risk

Describe the risks or harm

Motion sickness is a syndrome characterized by symptoms such as nausea and vomiting, pallor, sweating, headache, dizziness, malaise, increased salivation, apathy, drowsiness, belching, hyperventilation, and stomach awareness. Symptoms can be triggered by externally imposed motion or by implied self-motion from a moving visual field, such as in a cinema or a Virtual Reality (VR) environment. Although there is no universally accepted explanation for why people experience motion sickness, a common understanding is that it results from a mismatch between sensory inputs, particularly between the visual and vestibular systems. For instance, in the case of VR, individuals often experience symptoms due to visual motion without corresponding physical movement. To help alleviate motion sickness symptoms, some individuals find relief through non-drug remedies. Ginger, for example, is a commonly known natural remedy for nausea. As a comfort measure, researchers will offer participants the choice of ginger or peppermint tea. Overall, our VR environment will be designed to minimize any mismatch between visual motion and the participant's actual motion. Nevertheless, in the event that a participant experiences motion sickness, the non-drug procedures described above will be followed, along with other comfort measures such as offering water and providing a place to lie down. It must be emphasized that no medications will be administered in this study. Reference Murdin, L., Golding, J., & Bronstein, A. (2011). Managing motion sickness. The BMJ: leading general medical journal, 1213–1217.

Are any of the risks or harms identified above greater than those the participants might encounter in their everyday life?

No

A determination will be made, upon receipt of the application, if the research can be reviewed by delegated review or must be reviewed by one of the two Research Ethics Boards.

Describe the safeguards (or procedures) to be put in place to mitigate each of the risks or harms identified above.

- Give peppermint/ginger tea to the participant - Stop the study - Call UWaterloo Health Services

For the risks or harms identified above, is there any monitoring that will need to be undertaken during the study?

Yes

Describe what monitoring is needed, for how long, and how this will be undertaken.

Be aware and observe the participant's behavior at all times. The participant might report motion sickness while the VR headset is ON and displaying VR content.

For the risks or harms identified above, is there any monitoring that will need to be undertaken following the study conclusion?

No

Describe what monitoring is needed, for how long, and how this will be undertaken.

Outline the criteria for stopping the study early due to safety concerns/other issues.

N/A

Privacy

Will demographic and/or background information be asked of participants? If so, ensure that the demographic questions have been uploaded in the methods section.
See TCPS2, Chapter 5, Privacy and Confidentiality, and Waterloo's guideline on securing human research participant information and data.

Yes

What demographic/background information will be collected?

Age
Gender
Occupation
Other

Describe what “other” demographic/background information will be collected.

Height, weight, and dominant hand

Will demographic/background information be collected separately from names and other identifying information?

Yes

Participant identification - If applicable, include how participants will be referenced in study results.

Participants will be identified by an assigned subject number.

If applicable how will the key/list that links participants’ codes with their actual name and/or consent forms be stored and protected? Also, outline how long the key/list will be stored.

N/A

Are there any limitations to the promise of confidentiality?

No

Will any study data be leaving the University of Waterloo, the province, or country (e.g., member of research team is located in another institution, province, or country, etc.)?
See Waterloo’s guideline on securing human research participant information and data.

No

Will any collected data or information be entered into a database for future use?

No

Are there other members of the research team who are not named on this application (e.g., co-op students, research assistants, or other temporary personnel) who may carry out specific tasks involved in your study?

No

Will individual participant identities be confidential in the publication or release of the study findings?

Yes

Data storage

What type(s) of data will be collected for this study?

Video-recordings

If identifiable features are captured, ensure this is described as part of the procedures section

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For each type of information collected, identify where the data will be stored. Specify the physical location (e.g., personal computer, UW server, server in US, a Cloud, a Google Drop box). Describe how it will be secured to protect privacy and confidentiality (e.g., encrypted).
* Best practices are to de-identify the data at the earliest possible time.
See Waterloo's guideline on securing human research participant information and data.

Multiple steps will be taken to ensure the anonymity of participants and the confidentiality of data. All data files (including recordings, keypresses, and questionnaire responses) will be stored on a password-protected computer and associated only with a unique subject code consisting of letters and numbers. Participant names, student numbers, or any direct identifiers will not be collected or linked to the data in any way. Only researchers associated with the study will have access to the locked cabinet and password-protected computer. In any release of findings (e.g., presentations or written reports), only group-level data will be reported, and no identifying information about individual participants will be disclosed. Data will not be deposited in any public repository or database.

For each type of data collected, identify the minimum retention period.
See Guideline on data retention and how long researchers should keep their data.

Data collected during this study will be retained for a minimum of 7 years. Audio and video files will be deleted once transcribed and no longer required unless participants have signed the audio and/or video release forms indicating consent to allow recordings to be used for external presentation purposes.

Data Management

Are there plans to link the data collected with other data sets, databases, or registries?

No

The Tri-Agency Open Access Policy on Publications and some journals are requesting that research data be provided to an open access repository to promote the availability of findings, to enhance transparency and share with the widest possible audience.

Do researchers plan to make the data-set available in an online repository/archive?

No

Do you have a data management plan? See the Library Research Data Management: Get Started guide.

Yes

Consent and Withdrawal

What member(s) of the research team will be responsible for obtaining informed consent?

Marco A Moran-Ledesma

Is there a relationship between the potential participant(s) and the person obtaining consent?

No

How will consent be obtained

Written signature on a consent form

Upload Information and Consent Materials - See resources and samples for creating information consent letters. Refer to the guide for creating an information consent letter on this webpage.

Upload Information and Consent Materials

Consent Form_v1_2025-02-13.pdf

Study group

Participants

Upload Information and Consent Materials

Consent Form_noVR_2025-09-04.pdf

Study group

Participants

Do you anticipate that you will need to make special accommodations for your participant group?

No

Do you anticipate needing to put in place any special procedures when obtaining informed consent?

No

Will consent need to be re-documented throughout the life of this study?

No

Describe the participants rights and processes for withdrawing consent.

Participants will be informed that they can withdraw from the study at any time without penalization, and their data will not be used. Participants will also be informed that they can decline to answer any questions they do not wish to answer.

Outline what will be done with the participant's information (data, samples, etc.) if they withdraw from the study.

If the participant has completed a sufficient amount of the study for analysis, their data will be included (unless the withdrawing participant has requested that this not be the case). If the participant has not completed a sufficient amount of the study for analysis, their data will not be analyzed.

Will any individuals taking part in this study be unable to provide their own informed consent?

No

Remuneration

Will there be remuneration provided to show appreciation for a participant's time, effort, skills, etc. to take part in the study?

Yes

Type of remuneration

Gift card

Identify the retailer(s) and dollar amount

$40; choice of Amazon.ca, Starbucks, or Indigo For low-fidelity model with no VR study, $10; choice of Amazon.ca, Starbucks, or Indigo

If a participant withdraws from the study will remuneration be pro-rated?

No, participants will receive maximum remuneration

Will participants incur any expenses by participating in the study?

No

Feedback and Appreciation

How will you show appreciation to participants for taking part in the study?

Participants will receive a feedback letter after completing the study that will thank them for their participation and provide further information about the study.

When will feedback/appreciation be provided to participants (e.g., immediately after the session, at the end of a survey, mail results at time X.)?

Feedback letter will be made available at the completion of the study.

Upload Feedback/Appreciation materials

Upload Feedback/Appreciation materials

Feedback Letter_v1_2025-02-13.pdf

Study group

Participants

Upload Feedback/Appreciation materials

Feedback Letter_noVR_2025-09-04.pdf

Study group

Participants

How can participants learn about the study results/obtain a summary of the findings if interested?

The participants will be informed in the feedback letter that if they wish to learn more about the study, that the names and email of the principal and student investigators will be present on the feedback letter and can contact them if they so choose. As for their own data, they will be reminded that after they complete the study that all information regarding them will be de-identified. Making it impossible for the researchers to identify them.

Other Details

Provide any other information relevant to this study you wish to explain to the Research Ethics Board reviewers or to the staff in the Office of Research Ethics.

N/A

Other Attachments

Upload any additional study documents.

Attachments

Attestation

As the Principal Investigator/Faculty Supervisor/Local Investigator, I attest to the following:

- I will ensure all co-investigators, collaborators, and student investigators listed on this application have reviewed the application contents and will conduct the study according to the application/protocol.
- I am aware that any changes made to the research must be reviewed and provided clearance before the changes are implemented. Change requests (i.e., an amendment) are to be submitted through the system. I am also aware ethics clearance for this study is valid for only 12 months unless I renew the study prior to the ethics clearance expiry date. If an annual renewal report is NOT submitted through the system prior to the expiry date, the study will be suspended, all work on the study must stop, and Research Finance will be notified which will result in a hold being put on the funds associated with this study.
- I agree to comply with the Tri-Council Policy Statement (TCPS2) for conducting research with human participants and with University of Waterloo policies and guidelines when conducting this study (e.g., statement on human participant research, IST policies, etc.).
- I confirm I have read the University of Waterloo Research Integrity guidelines and I agree to comply with the policies and guidelines of my profession or discipline regarding the ethical conduct of research involving humans.
- Proper safeguards as to confidentiality and security of data will be maintained and data will be securely stored in accordance with University of Waterloo standards and applicable privacy legislation.

By submitting this application I agree to the above attestations and will ensure the research is conducted accordingly

Only the Principal Investigator/Faculty Supervisor can submit the application. This acts as a signature indicating approval of the application.

This is the end of the application form. Click submit in the right menu if you are ready to send it to the Research Ethics Office.