ErgoPulse: Electrifying Your Lower Body With Biomechanical Simulation-based Electrical Muscle Stimulation Haptic System in Virtual Reality

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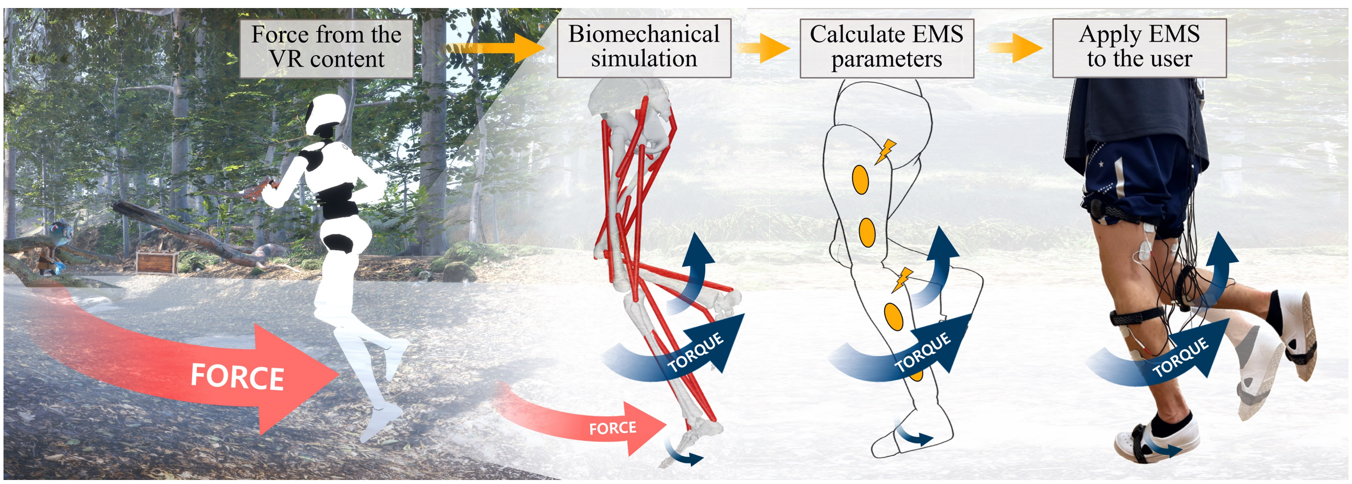

Figure 1: Graphical representation of ErgoPulse system, illustrating transformation of force feedback from virtual environment into joint torque via biomechanical simulation part of ErgoPulse system. This torque is subsequently translated into electrical muscle stimulation (EMS) parameters through EMS part of ErgoPulse system, which then delivers stimulation to user.

ABSTRACT

This study presents ErgoPulse, a system that integrates biomechanical simulation with electrical muscle stimulation (EMS) to provide kinesthetic force feedback to the lower-body in virtual reality (VR). ErgoPulse features two main parts: a biomechanical simulation part that calculates the lower-body joint torques to replicate forces from VR environments, and an EMS part that translates torques into muscle stimulations. In the first experiment, we assessed users' ability to discern haptic force intensity and direction, and observed variations in perceived resolution based on force direction. The second experiment evaluated ErgoPulse's ability to increase haptic force accuracy and user presence in both continuous and impulse force VR game environments. The experimental results showed that ErgoPulse's biomechanical simulation increased the accuracy of force delivery compared to traditional EMS, enhancing the overall user presence. Furthermore, the interviews proposed improvements to the haptic experience by integrating additional stimuli such as temperature, skin stretch, and impact.

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CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05
https://doi.org/10.1145/3613904.3642008

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; **Virtual reality**.

KEYWORDS

Virtual Reality, Haptic, Electrical Muscle Stimulation, Biomechanics, Simulation, Wearable Device

ACM Reference Format:

Seokhyun Hwang, Jeongseok Oh, Seongjun Kang, Minwoo Seong, Ahmed Elsharkawy, and SeungJun Kim. 2024. ErgoPulse: Electrifying Your Lower Body With Biomechanical Simulation-based Electrical Muscle Stimulation Haptic System in Virtual Reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 21 pages. https://doi.org/10.1145/3613904.3642008

1 INTRODUCTION

The advent of virtual reality (VR) technology has ushered in a new era in human-computer interaction, offering immersive experiences that blur the line between the physical and digital worlds [81]. In immersive VR environments, haptic feedback enables users to interact with virtual objects in a way that closely resembles real-life experiences [10, 13]. Haptic research in VR is primarily focused on reproducing the tactile sensations associated with hands or enabling users to feel the weight of virtual objects [31, 45, 50, 75, 94]. There have been significant advancements in haptic systems for the upper body. However, the significance of the lower body in real-world interactions, such as walking, running, kicking, and jumping, emphasizes the need for further research on lower body haptics [42, 91, 99]. In a virtual environment, the forces applied to the lower body during activities such as kicking a ball, pedaling a bicycle, or walking on different surfaces like wetlands, water, or mud, can be experienced.

Previous research has aimed to provide haptic feedback to the lower body of users in VR by using grounded mechanical devices in the initial stages [25, 38, 46, 77]. Although these devices could effectively simulate the sensation of walking on different textured solid surfaces, they do come with constraints, including large size, cumbersome installation, and limitations in supporting the free movement of users due to their fixed position on the ground [1, 26, 28, 42]. To address these challenges, recent studies have integrated haptic devices in the form of body-attached devices. These devices incorporate small actuators such as vibration motors [78, 80, 86], magnetic fluids [79, 99], and mini actuators [63, 91, 101]. This allows users to move freely while receiving haptic feedback through vibration or a simulated sensation of a liquid surface using magnetic fluids on the foot. However, body-attached devices cannot provide large-scale kinesthetic force feedback that affects the entire lower body, not just the feet, due to the limitations of the small actuators [42]. There have been several efforts to overcome these shortcomings, including the use of exoskeleton devices [63] or recent initiatives such as PropelWalker by Ke et al. [42], which involves attaching a propeller to the calf to deliver large-scale kinesthetic force feedback in the form of body-attached devices. Nonetheless, these approaches require large actuators and power to generate relatively large forces, leading to a technical trade-off involving increased noise and weight.

Conversely, electrical muscle stimulation (EMS) uses electrical impulses to induce muscle contraction, emulating the way our bodies naturally move our muscles. EMS has a distinct feature of being miniaturized as it stimulates muscles directly without the need for external actuators. Despite these advantages, there is a noticeable absence of research focusing on haptic devices using EMS with the goal of providing force feedback to the lower limbs. Existing studies have predominantly explored the use of small and lightweight EMS haptic devices for the upper body, such as *Possessed hand* [84], *ElectroCutscenes* [43], and *Muscle Propelled Force Feedback* [57]. In earlier studies, researchers effectively delivered haptic feedback to the upper body using EMS, without incorporating biomechanical simulation for determining the intensity and location of EMS. The intensity of EMS was adjusted on a binary scale of presence or absence, or on a ternary scale of none, weak, and strong [58–60, 70, 100]. Although Kim et al. [45], Kurita et al. [50], Rietzler et al. [75], and Lopes et al. [57] developed a system that adjusts the intensity of EMS based on force calculation, these systems are tailored for specific, predefined postures such as pushing objects or holding a smartphone. In most EMS haptic system studies, including those by the aforementioned authors, haptic stimuli were provided to users by using only one or two muscles, or by predefining muscles for specific basic postures associated with each action. This method of broadly adjusting stimulus intensity and location is particularly effective for upper body haptics because the upper body does not bear the body's weight and is activated in specific postures corresponding to content actions, such as holding an object or swinging a racket.

However, providing force feedback to the lower limbs through EMS requires real-time calculation of the intensity and location of stimulation due to the complex leg movements involved in gait. During the gait movement, a person's lower limbs move the body forward while supporting its weight and maintaining balance. This process involves multiple muscles and joints that work in tandem in real-time [18, 52, 74]. For instance, in a virtual environment where a fast river needs to be crossed, the user's lower limbs are influenced by factors such as the force of the water flow, gravity, ground reaction, and the forces required for locomotion and maintaining balance. To apply the force generated by water flow to the calves and feet using EMS, the amount of force exerted on each lower limb and joint should be adjusted in real-time based on factors such as joint movements, user posture, and even position on the map. In such scenarios, real-time biomechanical dynamics calculations can determine the torque on each joint, which informs the intensity and location of the stimulation required to provide haptic forces on the user's lower limbs.

Therefore, we propose ErgoPulse, a system that combines biomechanical simulation and electrical muscle stimulation (EMS) to provide precise large-scale kinesthetic force feedback to the lower body while maintaining light weight, low power usage, and immediate response [59, 60, 70, 100]. When using EMS to provide force feedback to the lower limbs, ErgoPulse determines the intensity and location of stimulation in real-time while considering the complex movements of the lower body, as compared to upper body EMS haptic systems. ErgoPulse system consists of two main parts: 1) the biomechanical simulation part, which calculates the torques required at each of the user's lower limb joints to provide haptic force in the virtual environment, and 2) the EMS part, which produces these torques at each joint using personalized EMS and delivers them to the user. The biomechanical simulation part of ErgoPulse was created by combining two solutions: the open-source biomechanical simulation model, OpenSim [20], and the physics simulation solution, Nvidia PhysX engine, which is based on the Unity platform. The torque calculated by the biomechanical simulation part is then delivered to the user through the EMS part of ErgoPulse system. During this process, the EMS part personalizes the location and intensity of EMS for each user and delivers force feedback to the lower limbs by providing the calculated stimulus.

This paper discusses the design, implementation, and personalization of the ErgoPulse system, and presents the results of two experiments that were conducted to validate the system. The first experiment measures the discrimination threshold of haptic force intensity and direction that ErgoPulse can provide to users. In the second experiment, we created two simple gaming environments based on the results of E1 to measure user experience and immersion when applying ErgoPulse in an actual gaming environment. Additionally, we interviewed users to gather feedback on their experience with ErgoPulse system and discussed its contributions and limitations. This investigation reveals the impact of ErgoPulse system on the VR user's experience when enjoying content and provides guidance for improving the lower body EMS haptic system. We have addressed the following research questions through this study:

- What level of precision can users achieve in distinguishing the intensity and direction of haptic force applied to their lower body through the combination of biomechanical simulation and EMS?
- Can the use of a lower-body haptic device, based on biomechanical simulation and EMS, enhance the immersion of users experiencing VR content?
- What are the limitations of a system that delivers EMS haptic force to the lower body through biomechanical simulation, and how can these limitations be overcome?

2 BACKGROUND

2.1 Lower-limb Haptic System

The existing lower-limb haptic system can be categorized into two main types—grounded mechanical devices and body-attached devices. The former provides realistic haptic feedback to the lower limbs and are used to replicate various terrains and walking experiences in virtual environments. Grounded devices such as the 4-DOF leg-rehabilitation system [32], Active Leg Exoskeleton (*ALEX*) [7, 8], and *HapticWalker* [77] integrate mechanical structures to simulate realistic walking sensations. Iwata et al. developed *Gait Master* [35], which uses two on-foot mechanical platforms, allowing users to walk in different virtual terrains. Kim et al. utilized a cable-driven system with four-wire ropes to simulate reduced gravity on the Moon or the Mars [46]. These systems can accurately mimic the kinesthetic forces of walking in the real world, enhancing the sense of presence in VR by replicating various terrains, including flat and rugged ground. However, they are relatively large and require a stable base, which may limit portability and restrict the user's work or movement area [1, 26, 28, 42].

The body-attached devices are developed by primarily focusing on portability and direct interaction with the user's legs or feet. Devices such as *Level-Ups* [76] – foot-worn motorized stilts, and *Realwalk* [79] – in-shoe magnetorheological fluid can be worn directly on the user's body. Wang et al. introduced *Gaiters* [91], which can be worn on the calves, to provide dragging forces on the legs in VR. These devices provide unique experiences, such as the sensation of walking on snow or simulating different ground deformation and texture sensations. Their wearability enhances mobility, allowing a more natural interaction in the VR space. However, they often face challenges in simulating large-scale force feedback like buoyant and resistant forces induced by walking in various fluid mediums such as water, sand, and mud [42]. Additionally, the intensity provided by light actuators, such as vibrotactile actuators, may be limited, affecting the overall immersive experience [42].

2.2 EMS Haptic System

EMS generates signals that cause muscle contractions when positioned near the human muscles, using multiple electrode pads and a signal generator [62]. HCI researchers have studied EMS for its capability to offer distinct haptic feedback in VR settings [37, 45, 48, 58–60]. EMS enhances user experiences in simulations, such as VR games that simulate lightsaber duels [37], creating a more immersive VR perception, or generating sensations similar to fear and pain [48]. It can also simulate the sensation of physical impacts from virtual entities [58] or the weight of a virtual object [45, 59, 60]. Moreover, EMS feedback can be adjusted for a consistent perception of VR entities, and the repulsion design can provide haptic sensations similar to receiving a physical impact [60]. In the commercial sector, products like *TeslaSuit* have been developed, which use 80-channel electrodes to stimulate muscles throughout the entire body [14, 39].

Although previous studies have successfully integrated EMS in the haptic field, the magnitude and characteristics of the stimuli provided by EMS differ depending on the user's muscle characteristics and electrode placement [69]. Therefore, signal intensity should be calibrated based on the desired muscle response amplitude and duration, and electrode placement should be determined by anatomical landmarks to prevent unintended muscle reactions [89]. This personalization of EMS stimuli is used in haptic research to design an EMS response that aligns with user expectations and physiological limits, providing an immersive VR experience that is both comfortable and painless [69].

While EMS has the potential to be lightweight, use low power, and provide an immediate response, there has been limited research on the use of haptic stimulation from external forces to stimulate the lower body in VR contents [42]. Such feedback has been primarily used in coaching and medical rehabilitation fields. Lu et al. studied a haptic feedback mechanism for running, coaching, and injury prevention [61]. Phillips et al. evaluated an EMS system for assisting the gait of spinal injury patients [72]. Hassan, M. et al. introduced a wearable EMS device for running assistance [30]. Moreover, it has been used to control the path of pedestrians for adjusting walking directions according to navigation information [5].

The proposed ErgoPulse system optimizes muscle stimulation locations and intensity in real-time and considers the complex muscle and joint structure of the lower body in response to user movement. By analyzing the lower body's motion and load through a biomechanical-based computational algorithm, the system simulates the interactions of muscles and joints of lower body to provide force feedback in virtual environments that acts on the lower body.

2.3 Biomechanical Simulation

Biomechanical simulations have primarily been employed in rehabilitation studies, especially for analyzing patients' gait patterns and designing assistive devices [19, 44, 73, 90]. A commonly used tool for biomechanical simulation is OpenSim, an open-source biomechanics simulator with anatomical human musculoskeletal models [20]. These studies include Sousa et al. [19], who used OpenSim to validate the walking assistance performance of the hybrid neuroprosthesis controller proposed in their research, and Wang et al. [90], who analyzed ground reaction force data from patients during rehabilitation training using a lower limb rehabilitation robot with OpenSim.

Previous studies employing biomechanical simulations in VR have primarily aimed to provide engaging and motivational exercise experiences for rehabilitation patients [9, 15]. Mirelman et al. [65] conducted walking rehabilitation training for stroke hemiplegia patients within a VR environment and used biomechanical simulations to assess improvements in walking function through lower limb training with a robot-VR integrated system. Fusco et al. [27] combined lower-limb robotic therapy with VR visual feedback, demonstrating that this combination improved not only motor functions but also cognitive functions in patients. Demircan et al. [22] presented a pilot study on locomotion training that incorporated a wearable haptic feedback system with musculoskeletal models derived from OpenSim, similar to our system, and demonstrated a reduced risk of running injuries.

The aforementioned research on using biomechanical simulations in VR for rehabilitation training has demonstrated the ability to capture the kinematic characteristics of real users in a virtual environment. Therefore, in this study, we propose the system that calculates users' kinematic characteristics using haptic force data within the content to enhance the immersive haptic experience in a virtual environment.

3 IMPLEMENTATION

3.1 System Overview

ErgoPulse system proposed in this study consists of two parts–the **biomechanical simulation part** and the **EMS part**. The configuration of each part is shown in Fig. 2. To obtain real-time posture and joint angle data from users, we used the Perception Neuron Studio. This inertial measurement unit (IMU) based motion capture system uses 17 IMU trackers to measure user motion and is mainly utilized in the rehabilitation field [82, 92, 97]. These trackers are highly precise, offering a minimum resolution of 0.02 degrees and achieving static accuracy levels of 0.7 degrees for roll and pitch, and 2 degrees for yaw [66]. The collected data is then transferred to the biomechanical simulation part of ErgoPulse. For posture estimation, we collected motion capture calibration data such as the length between each joint, height, and gender. We also carried out a geometrical calibration using the calibration process through the Perception Neuron Studio.

Subsequently, ErgoPulse system uses motion capture and geometrical parameter data to calculate joint coordinate information for each of the user's joints in real-time, via inverse kinematics calculation through the Nvidia PhysX engine with Unity. Then, the system independently calculates the inverse dynamics in two different models (model 1 and 2 in Fig. 2) using the calculated joint coordinates to determine the total torque applied to each joint. However, only one (model 1 in Fig. 2) receives an additional force input from the content environment to calculate the user's joint torque. This model computes the joint torque with the force provided by the content, and the disparity in the joint torque calculated by the two models determines the torque that ErgoPulse needs to provide in order to deliver the haptic force in the content. Both models employ the ground reaction force for these calculations, which is measured by the OpenGo plantar pressure sensor from Moticon. This wireless sensor, designed as an insole, doesn't impede walking and captures the wearer's ground reaction force at 50 Hz, covering 65% of the entire foot area.

The biomechanical simulation component of ErgoPulse calculates the torque required for each joint and sends it to the EMS part of ErgoPulse. Then, ErgoPulse determines the equation for the torque-intensity relationship for each user, which specifies the intensity and location of the EMS needed to generate the calculated joint torque. To personalize the torque-intensity relationship for each user, ErgoPulse undergoes a personalization process, which is explained in detail in section 3.4. The calculated EMS location and intensity are transmitted to EMS hardware that can remotely control the intensity, thus providing force feedback to the user.

3.2 Biomechanical Simulation Implementation

As explained in the previous section, ErgoPulse conducts real-time torque estimation to accommodate the complex movements of the lower limbs, delivering haptic force feedback in response to the user's dynamic actions. In order to perform biomechanical simulation, ErgoPulse requires the construction of a body model that encompasses details about joint characteristics, including the degrees of freedom and movement attributes of each joint. Thus, we employed the *gait10dof18musc* model, which is utilized in the biomechanical simulation software OpenSim. The *gait10dof18musc* model is a lower-body model based on anatomical research on the lower limbs and knees by Delp et al. [21], Yamaguchi et al. [98], and Anderson et al [3, 4]. We used this model to extract information on the characteristics of each joint in the lower limbs and the connections between body segments. This model enables simulation of lower limb movements across ten degrees of freedom, including pelvis tilt, pelvis translation in the x and y directions, left and right hip flexion, left and right knee angle, left and right ankle angle, and lumbar extension (Fig. 3 (b)). Therefore, the biomechanical simulation in this study can calculate lower limb movements in a plane that includes forward, backward, upward, and downward directions relative to the user's pelvic orientation.

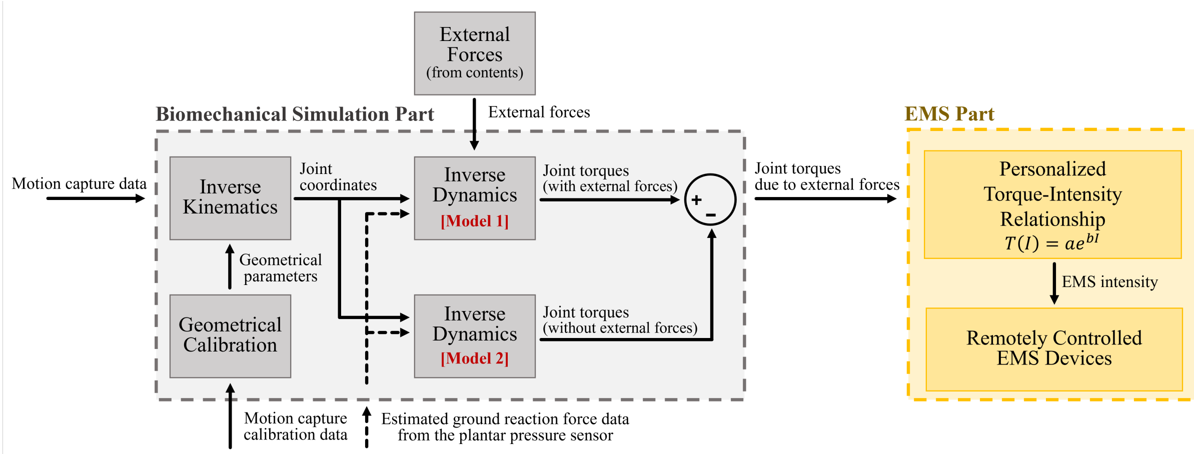


Figure 2: Schematic representation of ErgoPulse system

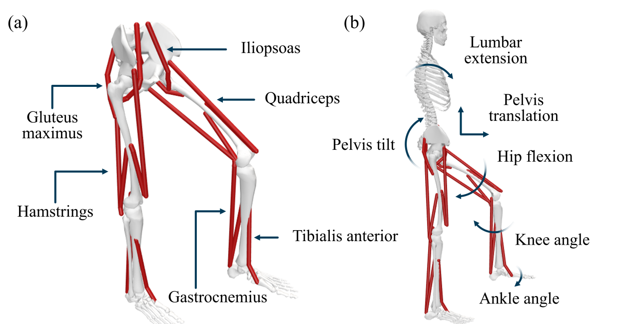


Figure 3: (a) Enumerated muscles utilized in *gait10dof18musc* biomechanical simulation model. (b) Illustration of 10 degrees of freedom of *gait10dof18musc* model

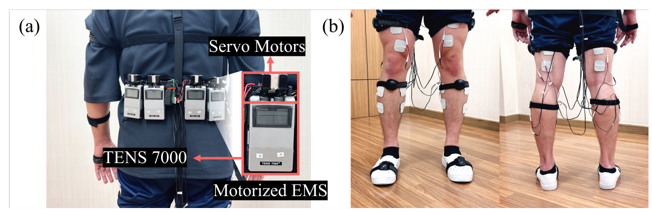


Figure 4: (a) Depiction of EMS device employed in study, accompanied by (b) image of participant outfitted with device.

The body model, derived from the previous process, is integrated into the ErgoPulse system and involves inverse dynamics calculations. The body model calculates the torque of each joint in accordance with the effects of gravity, ground reaction force, and, if applicable (model 1 of Fig. 2), the force from VR content exerted on the lower body. In this paper, the force acting on the content is provided within a plane that includes horizontal and vertical directions relative to the user's pelvic orientation which aligns with the degrees of freedom supported by the biomechanical simulation model. Therefore, the biomechanical simulation part of ErgoPulse can evaluate the torque applied to the user's joints in real-time using a physics-based simulation solution.

3.3 Hardware Implementation

ErgoPulse provides users with the calculated stimulation intensity through the EMS hardware. We used the TENS 7000 device to produce the EMS signal, which has passed medical safety inspections and can transmit an EMS of up to 100 mA. To ensure user safety, we used the signal-generating part of the TENS 7000 device without any modifications and motorized the intensity adjustment potentiometer to regulate the stimulation intensity, as shown in Fig. 4 (a). The motor utilized in this device has a resolution of 0.137 degrees and a speed of 60ms/60 degrees. Based on the results of the pilot test, participants generally found a range of stimulation within 20 degrees of the potentiometer to be comfortable. Considering the motor's performance, this equates to approximately 145 steps, allowing for the delivery of stimulation from the lowest to the highest level within a maximum delay of 20ms. ErgoPulse device, which controls the motorized potentiometer, enables quick wireless adjustment of the stimulation level through Wi-Fi communication. We used *Unity Profiler* to measure the end-to-end delay and found an approximate maximum delay of 65 ms. This includes motion capture ($\approx$ 15 ms), biomechanical simulation ($\approx$ 10 ms), Wi-Fi communications ($\approx$ 5 ms), the rise time of the motor-driven adjustment (< 20 ms), and muscle contraction delays ($\approx$ 15 ms).

In this paper, we deliver forces calculated within the degrees of freedom of the biomechanical simulation model to the lower body. Thus, excluding the iliopsoas and gluteus maximus located in the sensitive area among the muscles that produce joint movement within the targeted degrees of freedom, we attached the EMS to eight muscles: quadriceps, hamstrings, tibialis anterior, and gastrocnemius on both sides (Fig. 4 (b)). Therefore, ErgoPulse can control the left and right knee angle and the left and right ankle angle. To ensure safety, the stimulation and control parts are electrically isolated, and a switch that can shut down all devices at once is easily accessible to users.

3.4 Personalization Process of ErgoPulse EMS System

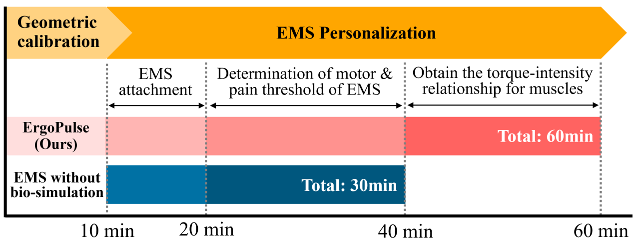


Figure 5: Comprehensive plot of the personalization process for the ErgoPulse and EMS without biomechanical simulation system.

This section introduces the personalization process for ErgoPulse. As mentioned previously, biomechanical simulation and EMS require a personalization process to consider individual factors such as height, weight, bone length, and musculoskeletal characteristics in order to calculate simulation results and provide stimulation. Personalization consists of two processes: 1) the **Geometric calibration process** involving measuring the user's body information for geometric calibration of biomechanical simulation, and 2) the **EMS Personalization process** for personalizing EMS to obtain the torque-intensity relationship (Fig. 5).

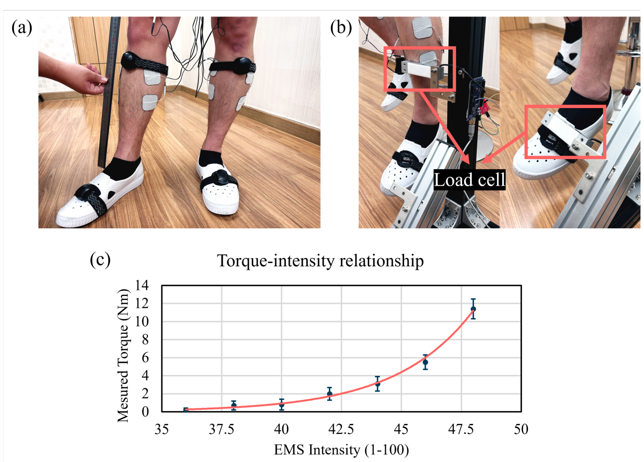


Figure 6: (a) Calibration procedure capturing inter-joint distances for participant. (b) Apparatus and methodology for quantifying torque relative to EMS intensity. (c) Sample data plotted against exponential fit.

First, in the **geometric calibration process**, we measured the distance between each joint of each user, as shown in Fig. 6 (a), to perform geometrical calibration of the biomechanical simulation. We entered the measured distances between joints into the calibration software for Perception Neuron Studio and calibrated it with the IMU sensor. Next, we used the Dempster biomechanical model [23] to estimate the weight of body parts, such as the foot, calf, thigh, pelvis, and torso. This model calculates the weight of each body segment as a percentage of the total body mass, which was measured using a scale. Thus, we established a biomechanical simulation model that is optimized for each user to calculate the required torque of each joint to produce the force felt in the content.

Next, in the **EMS Personalization process**, we personalized EMS to calculate torque, as the correlation between EMS intensity and the torque generated by a participant's muscles varies based on musculoskeletal features [69]. Therefore, we obtained a torque-intensity graph for each participant using the following method. To ensure a clear sense of stimulation within a safe range, the EMS equipment used for haptic stimulation should apply stimulation between the intensity of the motor threshold (I_{MT}), which is the minimum intensity required to trigger muscle contraction force, and the pain threshold (I_{PT}), which is the minimum intensity that causes pain to the user. Therefore, the available EMS stimulation area is included in the acceleration region of the entire torque-stimulation intensity graph, which possesses a sigmoid function form [6, 12, 50, 55]. Thus, we can represent the relationship between the torque (T) and the stimulation intensity (I) with the exponential function (Eqn. 1) [53], which consists fitting parameters a and b:

$$T(I) = ae^{bI}(I_{MT} \le I \le I_{PT}) \tag{1}$$

To establish the minimum and maximum intensity of EMS stimulation (I_{MT} and I_{PT}), we mapped the EMS intensity to a scale of 0-99 and gradually increased the intensity by one increment, starting at zero. Next, to establish the torque-intensity relationship in this range, we partitioned the area between I_{MT} and I_{PT} into seven equal parts. We then measured the torque generated at each EMS intensity using the load cell of the device shown in Fig. 6 (b). To minimize personalization errors, we measured the torque at the same EMS intensity three times and calculated the average torque. We used Eqn. 1 to customize the torque-intensity relationship for each of the eight muscles providing EMS for each participant, yielding eight graphs similar to Fig. 6 (c) for each user. ErgoPulse utilizes this relationship to determine the appropriate EMS intensity needed to produce torque, as determined through biomechanical simulation.

The ErgoPulse EMS system's **geometric calibration process** requires approximately 10 minutes to complete, and its **EMS personalization process** takes around 50 minutes, resulting in a total time investment of approximately one hour. The **EMS personalization process** consists of three detailed steps: attaching the EMS (≈ 10 minutes), determining the motor and pain threshold of the EMS (≈ 20 minutes), and obtaining the torque-intensity relationship for each muscle (≈ 20 minutes) (Fig. 5). In contrast, EMS systems that do not utilize biomechanical simulations only require a two-step process: attaching the EMS and determining the motor and pain threshold of the EMS, necessitating a total time of about 30 minutes. Consequently, due to the meticulous personalization required for precise biomechanical stimulation, our ErgoPulse system requires an additional 30 minutes of setup time compared to conventional

EMS systems. The personalization parameters retain their validity as long as the electrodes remain affixed to the user. Therefore, after personalizing the EMS for one participant, we maintained the electrodes in place until the end of all experiments to preserve the validity of the personalization process.

4 EXPERIMENT 1: LIVE-USER EVALUATION - DISCRIMINATION THRESHOLD OF ERGOPULSE SYSTEM (E1)

ErgoPulse system interprets the dynamics of a rigid body through biomechanical simulation, calculating the torque at each joint to provide force feedback applied to the lower limbs through EMS. In order to create engaging content with ErgoPulse that provides different intensities and directions of force, we need to ensure that users can distinguish the system's force feedback while developing content or applications. Therefore, we conducted a study using a two-alternative forced-choice (2AFC) paradigm [2, 17, 54] to determine the smallest differences in intensity and direction that a user with ErgoPulse can distinguish while walking freely.

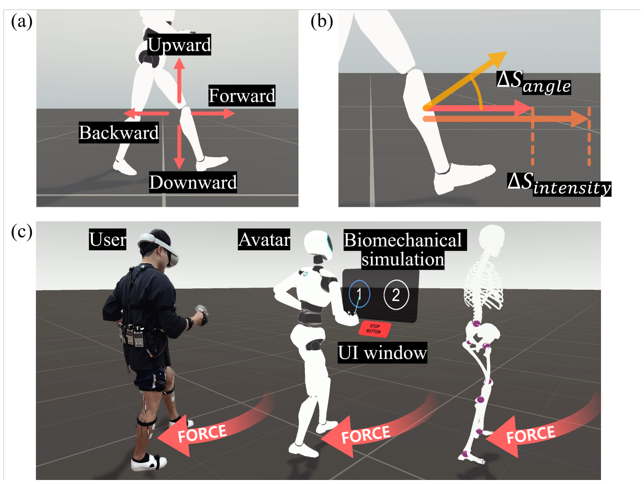


Figure 7: (a) Quartet of reference directions, complete with their respective labels. (b) Example diagram indicating the $\Delta S_{intensity}$ and ΔS_{angle}. (c) Concept diagram of E1: The user's real-time movement is transmitted to the avatar and biomechanical simulation. The force selected by the user is then provided to the user through ErgoPulse calculation.

4.1 Evaluation Setup

In this paper, we adopted the 2AFC paradigm, previously employed in studies by Allin et al [2]., Cui et al. [17], and Lee et al. [54], to measure the discrimination thresholds of the haptic system. The participants were presented with two stimuli. One offered a reference force feedback (S), while the other imparted a test force feedback ($S \pm \Delta S$) (Fig. 7 (b)). In the intensity discrimination threshold experiment, a force that is either greater or smaller than the reference force by $\Delta S_{intensity}$ (Fig. 7 (b)) was presented for the test force feedback. In the direction discrimination threshold test, the test feedback delivered a force that differed by an angle of ΔS_{angle}, (Fig. 7 (b)) either in the clockwise or counterclockwise direction relative to the reference force in global space, to assess participants' ability to detect changes in the force direction.

The order of the two options and the value of ΔS were always randomized, and the participants needed to identify which of the two stimuli was stronger, or which rotated in the clockwise or counterclockwise direction. If participants could perfectly distinguish between the two stimuli, the accuracy rate would converge to one. Conversely, if they could not differentiate at all, randomly selecting between the two choices would result in an accuracy rate of 0.5. Based on previous research, we fitted participants' accuracy rates to a Weibull function psychometric curve [2, 17, 54], measuring discrimination thresholds at the 75% accuracy level.

First, the discrimination threshold for intensity was evaluated in four reference directions: forward, backward, up, and down (Fig. 7 (a)). In this experiment, the intensity of the reference force feedback (S) was set to 50% of the maximum intensity, which participants found comfortable. The $\Delta S_{intensity}$ values were randomly chosen from among ±5%, ±15%, ±25%, ±35%, and ±50% of the maximum intensity. In each session, the total occurrences of each selected $\Delta S_{intensity}$ are equal. Participants responded to 20 trials of 2AFC tasks, each for one reference force feedback direction, resulting in a total of 80 trials of 2AFC responses across the four directions.

Second, direction discrimination thresholds, similar to the intensity discrimination thresholds, were also assessed for the same four reference directions S - forward, backward, up, and down (Fig. 7 (a)). The intensity was set to half the maximum stimulus intensity that participants found comfortable. ΔS_{angle} was randomly selected from angles of ±10°, ±20°, ±30°, ±45°, and ±60°, either in the clockwise or counterclockwise direction. In each session, the total occurrences of each selected ΔS_{angle} are equal. Participants responded to 20 trials of 2AFC tasks, each for one reference force feedback direction, resulting in a total of 80 trials of 2AFC responses across the four directions.

Procedure. Participants completed the personalization process described in Section 3.4 before taking part in the experiment. After personalizing their settings, participants put on the Oculus Quest 2 headset and received a brief introduction on how to use it. Once the experiment began, participants were free to walk around the environment shown in Fig. 7 (c), with an UI window displayed in front of them. Participants used the controller to interact with the UI window, switching between the two stimuli, and answering the 2AFC task. Participants were given sufficient rest time between experiments, and if anyone felt discomfort and requested to stop, all stimuli were immediately halted. All participants were healthy adults, suitable to wear head mounted displays, and were free from any neurological diseases, cardiovascular disorders, central-nervous-system abnormalities, or sensitive skin. Nine participants (age range: 20–27, M = 23.8, SD = 2.43, 6 males, 3 females) were engaged in the study. Among these participants, one had no prior experience with EMS, while eight had experience using EMS in physical therapy devices. The study was approved by the Institutional Review Board.

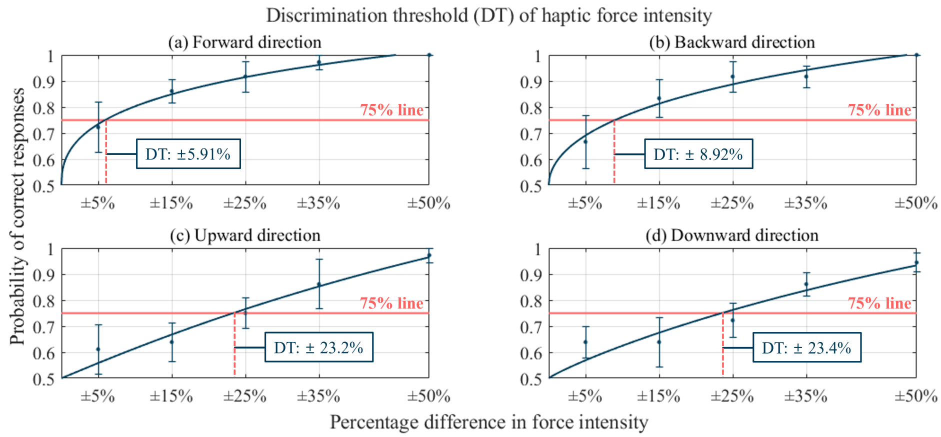


Figure 8: Graphical representation of discrimination threshold for haptic force intensity. X-axis delineates the $\Delta S_{intensity}$ values, while y-axis plots participant accuracy. Standard error is also depicted, with 75% accuracy threshold highlighted in red.

4.2 Results and Discussion

4.2.1 Discrimination Threshold of Haptic Force Intensity. The results of the intensity discrimination threshold experiment are presented in Fig. 8. The x-axis represents the value of $\Delta S_{intensity}$ applied to the participants through 2AFC, while the y-axis shows the accuracy rate of their responses, with the standard error indicated. The accuracy of the participants' responses was fitted to the Weibull function psychometric curve according to prior research [2, 17, 54]. Based on the fitted graph for each direction, the calculated discrimination thresholds are as follows: Forward: ±5.91%, Backward: ±8.92%, Upward: ±23.2%, Downward: ±23.4% of the maximum force. These results indicate that when a force is provided with a difference equivalent to the measured discrimination threshold, ErgoPulse can deliver distinguishable force intensities to users with 75% accuracy. The results confirm that the perceived resolution of haptic force intensity provided by ErgoPulse is higher when the force is in horizontal directions to the ground, such as forward and backward. In contrast, the forces in vertical directions to the ground, such as upward and downward, are perceived with relatively less sensitivity to intensity. Therefore, to enable users to experience variations in force intensity in the content, the difference should exceed the discrimination threshold mentioned above, which is larger for the vertical direction compared to the horizontal ones.

4.2.2 Discrimination Threshold of Haptic Force Direction. The results for the direction discrimination threshold measurement are shown in Fig. 9. The x- and y-axes indicate the angle of ΔS_{angle} provided in the 2AFC and the accuracy rate of participant responses, with the standard error denoted, respectively. The measured discrimination threshold of ErgoPulse for each direction is as follows: Forward: ±35.4°, Backward: ±27.1°, Upward ±15.2°, and Downward ±15.3°. Through the results, we can deduce that if a difference in angle corresponding to the measured discrimination threshold is provided, users can perceive the difference in force direction with 75% accuracy. Based on these findings, it can be inferred that users are more sensitive to distinguishing the direction of force in vertical directions (Forward/Backward) compared to horizontal directions (Upward/Downward). Therefore, to enable users to perceive directional differences in force during content, the force should be rotated by an angle larger than the discrimination threshold, which is higher for the horizontal direction than for the vertical direction.

4.2.3 Discussion. Based on our discrimination threshold experimental results, we observed that the perceived resolution of ErgoPulse's force intensity and direction is not consistent across all directions. Participants were more sensitive to changes in haptic force intensity in directions horizontal to the ground (Forward/Backward) than in vertical directions (Upward/Downward). Conversely, they were more sensitive to changes in the direction of the haptic force in vertical directions compared to horizontal directions. We could identify the reasons for these directional differences in perceived force resolution with two factors – gravity affecting the lower limbs [83] and anisotropy in human force perception [87, 88].

According to Takahashi et al.'s previous research, applying external forces caused the distortion of human perception of force [83]. In our study, we found that the direction of gravity, which aligns with the vertical direction, can distort the accuracy of force intensity perception, resulting in lower resolution in vertical directions. Additionally, we found observational studies that suggest the human body has an inherent anisotropy in perceiving force intensity and direction [87, 88]. These studies proposed that the range of movement in the human body exhibits anisotropy due to its structural characteristics, and this kinematic anisotropy induces anisotropy in force perception. We speculate that in our experiments with the ErgoPulse system, these distortions manifested as variations in the discrimination threshold based on the reference force direction.

Through E1, we measured the discrimination threshold of the ErgoPulse system and confirmed that the resolution of the haptic force on the lower body varies depending on its direction. Based on the observations in this paper, ErgoPulse allow users to perceive more subtle differences in intensity in vertical directions, along with more precise angular differences in vertical directions due to gravity

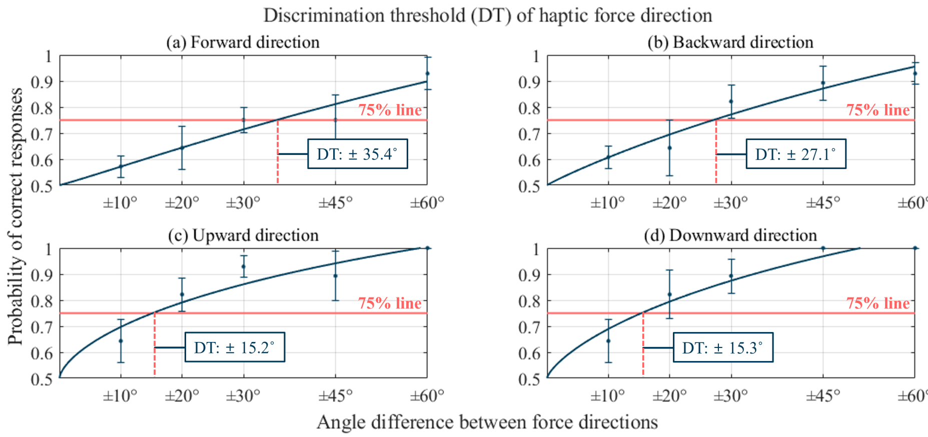


Figure 9: Graphical representation of discrimination threshold for haptic force direction. X-axis delineates ΔS_{angle} values, while y-axis plots participant accuracy. Standard error is also depicted, with a 75% accuracy threshold highlighted in red.

and anatomical anisotropies of the human body. In the next section, we created a demo application using the discrimination threshold obtained through E1. We analyzed whether users can receive the appropriate direction and intensity of stimuli when using ErgoPulse in game content, as well as the influence of ErgoPulse on the content experience.

5 EXPERIMENT 2: LIVE-USER DEMOS - EXAMINING ERGOPULSE SYSTEM'S EFFECT ON USER CONTENT EXPERIENCE (E2)

In Experiment 1, we determined the discrimination threshold of the intensity and direction of the haptic force that ErgoPulse can apply to users. In this section, we evaluated the ErgoPulse system through two demonstration contents: *Rainforest Treasure Hunt* and *Soccer Goal Challenge* (Fig. 10), to measure 1) the degree of accuracy with which it can provide virtual forces in each game content, and 2) how much it can improve user presence when applied to game content.

In this study, we classified the forces that can act on the user's lower limbs in content into two main categories: continuous force and impulse force. Continuous force situations involve forces continuously acting on the lower limbs for a prolonged period. Examples of such situations include experiencing a continuous flow of water, buoyancy in water, strong winds, or dealing with drag resistance in a swamp. In this situation, the user's lower limbs continuously move during the applied haptic force, and the intensity and location of muscle stimulation are adjusted in real-time to provide prolonged force feedback. On the other hand, when there is an impulse force, a force is applied to the lower limbs for a brief period of time, such as when kicking a ball or accidentally hitting a stone with the foot. In this scenario, the intensity and location of the stimulus are determined by the user's current posture, joint angular velocity, and angular acceleration.

We designed demo contents to observe the accuracy of force provision by ErgoPulse and the differences in user experience according to each situation by providing two different types of forces

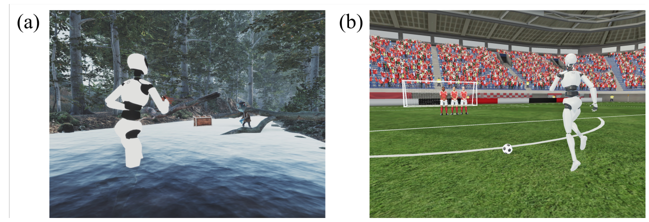


Figure 10: (a) Snapshot of participant engaged in "*Rainforest Treasure Hunt*" and (b) "*Soccer Goal Challenge*".

in separate demos. In the first demo, "*Rainforest Treasure Hunt*," we designed game content featuring rainforest terrains where continuous force is applied, influenced by the validation environments of Son et al.'s *Realwalk* [79], Wang et al.'s *Gaiters* [91], Ke et al.'s *PropelWalker* [42], and Han et al.'s *GroundFlow* [29]. In the second demo, "*Soccer Goal Challenge*," we created a soccer ball-kicking gaming environment that enables users to encounter impulse force, aligning with the validation settings presented in Wang et al.'s *Gaiters* [91], Lopes et al.'s *Impacto* [58], and Masuda et al.'s *exoskeletal lower limb force-feedback device* [63].

In our study, we introduced participants to three distinct haptic stimulation conditions, as illustrated in Fig. 11. The first condition was a control condition where participants wore the device but no EMS was provided (denoted as **NonEMS**). In the second condition, EMS was applied; however, it did not involve calculations from biomechanical simulations. Instead, a constant stimulation intensity was used, set at half the maximum level deemed comfortable by each participant (denoted as **NonBioSim**). The third condition, denoted as **ErgoPulse**, applied haptic force feedback via EMS, calculated through biomechanical simulation. Particularly, by comparing the NonBioSim and ErgoPulse conditions, we examined whether EMS calculations via ErgoPulse's biomechanical simulation could enhance the accuracy of the haptic force provided in the virtual environment and improve the user's content experience.

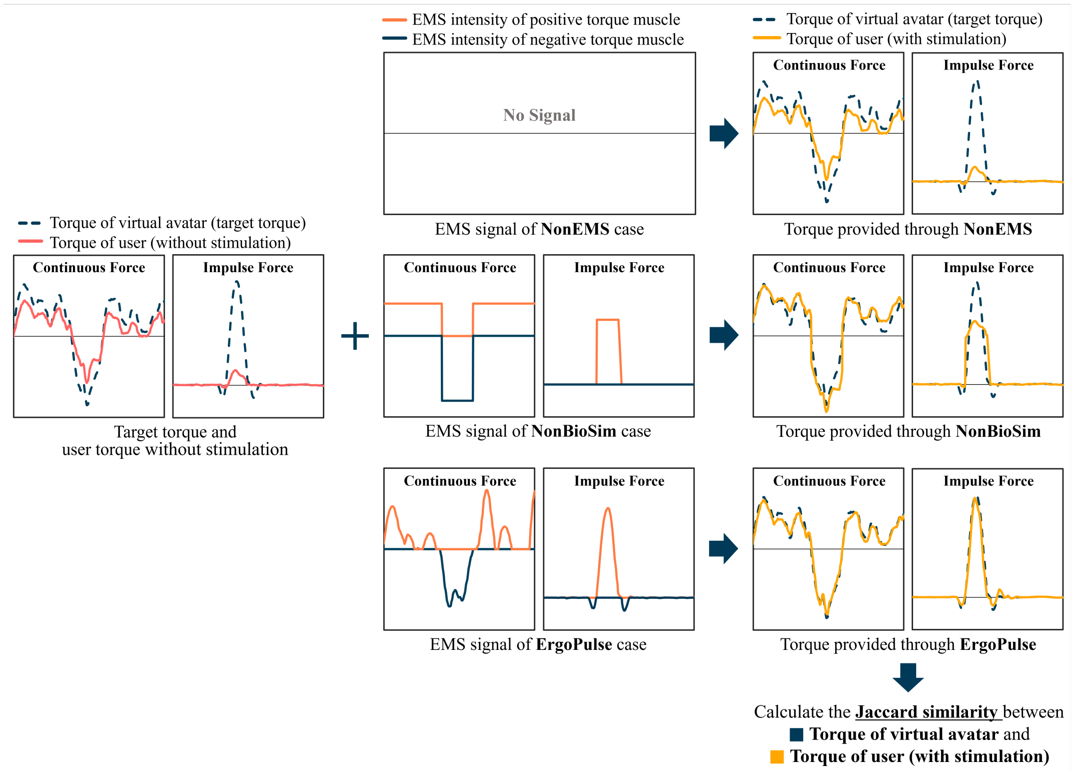


Figure 11: Time-dependent torque and standard EMS response for the three conditions (NonEMS, NonBioSim, ErgoPulse). It shows the torque values and corresponding EMS graphs in both continuous force and impulse force environments, along with the changes in user torque when stimulation is applied.

Through two types of content and three stimulation conditions, we explored whether ErgoPulse can accurately provide both types of forces in each environment and whether it induces varied user experiences based on the distinct characteristics of forces. These demos were designed in accordance with the discrimination thresholds analyzed in E1, and the specifics of each are explained below.

5.1 Evaluation Setup

5.1.1 Content Implementation.

Application 1: Rainforest Treasure Hunt. The first demo application is a game where users explore a rainforest environment, as depicted in Fig. 10 (a), in search of treasures that they can offer on an altar. In this game, players traverse various terrains within the rainforest, including dry land, swamps, and flowing rivers, while using their controllers to find treasures and defeat small monsters. Throughout the *rainforest content*, players experience continuous force feedback. The intensity and direction of this force feedback vary based on factors such as the strength of the river current, the speed of their leg movements, the buoyancy, drag resistance, and the viscosity of the fluid in the virtual environment. The direction of the haptic feedback also changes according to factors such as the direction of the river's flow, the user's body position, and the angle of their legs. We used Nvidia PhysX to calculate the force generated by the user's interactions with the virtual environment. Subsequently, we mapped this force to the nearest intensity and directional level based on the discrimination threshold results obtained in E1. This approach ensures that players can perceive and distinguish different force feedback based on their in-game actions and posture. The game ends when the player defeats all monsters and places all treasures on the altar successfully. On average, each game session lasts approximately five minutes.

Application 2: Soccer Goal Challenge. The second demo application simulates a soccer field environment, as shown in Fig. 10 (b). The application simulates a free-kick scenario in soccer, where the goal is to kick the ball into the goal without being blocked by randomly positioned defenders, and the players can select from three balls of different weights. The players experience the impact of hitting the ball, which varies in both strength and direction based on factors such as the direction and speed of the foot, the position and angular velocity of the joint, and the weight of the ball. Therefore, unlike in Application 1, they encounter instantaneous impulse stimuli. We utilized the discrimination threshold findings from E1 to segment the haptic forces delivered to the players, ensuring that players experience distinct forces corresponding to different situations. Each game consists of ten kicks per user, with a playtime of approximately five minutes.

5.1.2 Haptic Force Accuracy Measurement Setup. To analyze how accurately the biomechanical simulation-based EMS of ErgoPulse can support the virtual forces experienced by an avatar in VR content, we conducted an analysis using Jaccard similarity [36].

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|} = \frac{|A \cap B|}{|A| + |B| - |A \cap B|} \quad (2)$$

Jaccard similarity $J(A,B)$ is a set-based similarity measurement method that determines the intersection of two sets A and B divided by the size of their union (Eqn. 2). Therefore, Jaccard similarity has a value between 0 and 1, with values closer to 1 indicating higher similarity between two sets. In this experiment, we analyzed the comparison of two sets of torque values: 1) the torque values acting on each joint of the real user, influenced by the provided EMS, and 2) the torque values calculated for the virtual forces experienced by the avatar in the content (target torque) (Fig. 11).

We calculated the Jaccard similarity between two sets, the user torque in the EMS condition and the target torque of the VR avatar, under three conditions: NonEMS, NonBioSim, and ErgoPulse. We recorded the EMS intensity provided to each muscle in real-time and used the torque-intensity graph obtained through the personalization process in Section 3.4 to calculate the magnitude of torque each joint received from EMS. Simultaneously, a separate biomechanical simulation, operating independently, produced a series of target torque values for each joint of the avatar as it encountered forces within the content. The torque values and EMS intensities were recorded at 30 Hz, and we created pairs of torque sets at 5-second intervals (i.e., each set containing 150 data points, calculated as 5 sec * 30 Hz). Using each of these 5-second pairs, we calculated the Jaccard similarity according to Eqn 2, and this process was repeated every 5 seconds until the end of the content to measure how accurately the user torque in each condition followed the avatar's target torque.

5.1.3 User Presence and Experience Evaluation Setup. We used the Witmer-Singer presence questionnaire [95] to assess the user's level of presence in different environments and conditions. This questionnaire comprises a total of 32 items and employs a 7-point Likert scale to collect responses from participants. For a detailed understanding of our survey and assessment criteria, we have included the full set of questionnaire items used in our experiment in the appendix A. The questionnaire categorizes the user's sense of presence into four factors as follows:

- **Control Factor**: This factor assesses the user's capability to interact with and manage elements within the virtual environment. It examines the level of immediate responsiveness of the environment to the user's actions and the extent of control that the user perceives. A greater sense of control can amplify the user's feeling of being present.
- **Sensory Factor**: This factor evaluates the sensory information provided by the virtual environment in terms of quality and consistency. This includes the level of engagement provided by the visual, auditory, and tactile experiences. The more convincing and encompassing these sensory inputs are, the more present a user is likely to feel.
- **Distraction Factor**: This factor evaluates the degree to which distractions disrupt the user's experience within the virtual environment. Distractions may impede the user's immersion and diminish their sense of presence. These distractions include external factors, such as noise from the physical environment, as well as internal factors, such as discomfort or awareness of the equipment being used.
- **Realism Factor**: This factor assesses the extent to which the virtual environment is realistic for the user. It is the degree to which the environment mirrors real-world experiences and behaviors. The more realistic the environment, the more likely the user is to feel immersed in it.

Furthermore, we conducted open-ended interviews to investigate the detailed user experiences. The structure of the interview questions is as follows:

- How did the haptic feedback provided by ErgoPulse affect your experience of enjoying the content?
- How closely did the haptic feedback from ErgoPulse resemble a real-life experience?
- Which elements of the content did you find particularly immersive? Or were there any elements that prevented immersion?

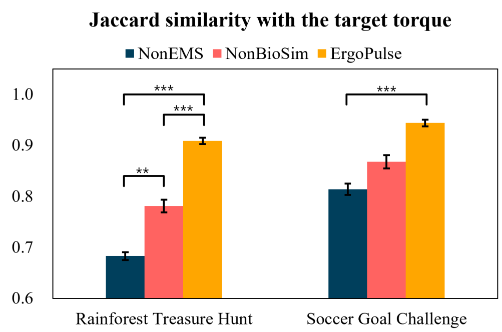
All participants were recruited under the same participant conditions as in E1, and the study was conducted with a total of 12 participants (age range: 20–30, $M = 24.0$, $SD = 2.73$, 8 males, 4 females). Among these participants, three had no prior experience with EMS, while nine had experience using EMS in physical therapy devices. However, none of the participants had previously used EMS for haptic stimulation. All experimental conditions were randomized using a Latin-square design. Before the experiment began, all participants completed the personalization process outlined in Section 3.4 and were instructed to take sufficient breaks between experiments. To ensure the validity of EMS personalization, participants maintained the same electrode placement for the personalization process and the entirety of E2. The study received approval from the Institutional Review Board.

5.2 Results and Discussion

Table 1: Results of one-way RM ANOVA from Jaccard similarity in "*Rainforest Treasure Hunt*" and "*Soccer Goal Challenge*". Significance levels are indicated: $^{**}p < .01$, $^{***}p < .001$.

RM ANOVA	Bonferroni post-hoc	
Rainforest content		
$F(2, 22) = 45.315$	N.EMS - N.BioSim	$p = .001^{**}$
$p < .001^{***}$	N.EMS - ErgoP	$p < .001^{***}$
	N.BioSim - ErgoP	$p < .001^{***}$
Soccer content		
$F(2, 22) = 9.766$	N.EMS - N.BioSim	$p = .143$
$p < .001^{***}$	N.EMS - ErgoP	$p < .001^{***}$
	N.BioSim - ErgoP	$p = .090$

5.2.1 Accuracy of provided haptic force by ErgoPulse. The results of the Jaccard similarity analysis are presented in Fig. 12 and Table. 1. We compared the accuracy of the generated torque by analyzing the similarity between 1) the torque sets of each joint of the user, influenced by the provided EMS and 2) the torque sets of the



		Rainforest Treasure Hunt	Soccer Goal Challenge
NonEMS	*M*	0.633	0.764
	SE	0.016	0.023
NonBioSim	*M*	0.731	0.818
	SE	0.025	0.026
ErgoPulse	*M*	0.859	0.894
	SE	0.012	0.013

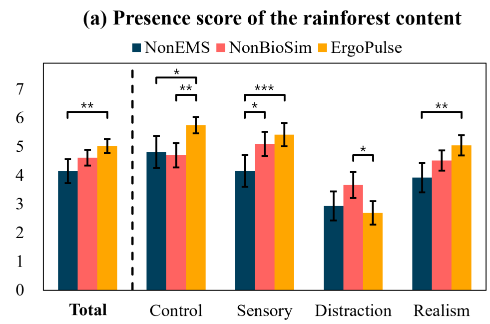
Figure 12: Results of Jaccard similarity in "*Rainforest Treasure Hunt*" and "*Soccer Goal Challenge*". The x-axis displays the type of content and each condition, while the y-axis represents Jaccard similarity with standard error. Significance levels are indicated: $^{**}p$ < .01, $^{***}p$ < .001.

joints of the VR avatar independently obtained through biomechanical simulation (target torque), across three conditions: NonEMS, NonBioSim, and ErgoPulse. To analyze the differences in torque accuracy among these conditions, we conducted a one-way repeated measures ANOVA (one-way RM ANOVA) analysis, and the results are presented in Table. 1. All results satisfied normality as the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively [47], and Mauchly's test confirmed sphericity.

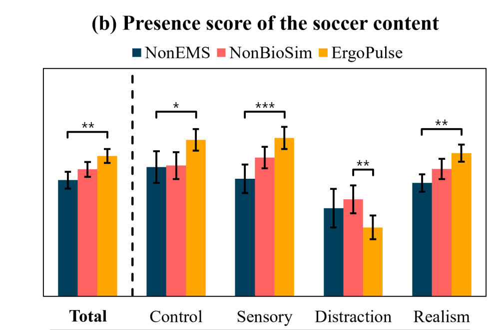
The results of the one-way RM ANOVA indicated that in all conditions, both continuous and impulse force environments, ErgoPulse provided torque significantly more similar to the target torque of the content compared to the NonEMS condition. These results demonstrate that ErgoPulse selects the appropriate EMS to deliver the perceived torque in a virtual environment, regardless of the force characteristics.

Furthermore, we compared ErgoPulse with the NonBioSim condition, which provides medium-intensity EMS stimulation without calculating with biomechanical simulation. In the continuous force environment, the NonBioSim condition showed significant accuracy improvement compared to the NonEMS condition but significant accuracy degradation when compared to the ErgoPulse condition. These results indicate that while EMS stimulation without biomechanical simulation can offer reasonably accurate haptic stimulation in an environment with continuous haptic forces, a significant level of accuracy improvement is possible through biomechanical simulation. Simultaneously, in the impulse force environment, the NonBioSim condition did not significantly improve accuracy compared to the NonEMS condition, but ErgoPulse showed a significant increase in accuracy. Therefore, these results indicate that biomechanical simulation-based calculations helped EMS stimulation provide a significant increase in the accuracy of haptic forces provided to users.

Our analysis of the accuracy of haptic force delivery for each condition using Jaccard similarity showed that ErgoPulse's biomechanical simulation can significantly improve the accuracy of haptic force delivery in VR content. Additionally, we conducted a user survey to assess the impact of ErgoPulse's EMS stimulation on the sense of presence within the content.



		Total	Control	Sensory	Distraction	Realism
NonEMS	*M*	4.140	4.808	4.152	2.931	3.917
	SE	0.835	1.124	1.088	1.011	1.020
NonBioSim	*M*	4.613	4.699	5.091	3.667	4.512
	SE	0.548	0.845	0.843	0.913	0.709
ErgoPulse	*M*	5.018	5.744	5.417	2.694	5.036
	SE	0.487	0.577	0.812	0.813	0.703



		Total	Control	Sensory	Distraction	Realism
NonEMS	*M*	4.027	4.487	4.076	3.056	3.929
	SE	0.575	1.096	0.985	1.343	0.614
NonBioSim	*M*	4.403	4.532	4.811	3.361	4.417
	SE	0.513	0.929	0.741	0.964	0.704
ErgoPulse	*M*	4.867	5.429	5.492	2.389	4.964
	SE	0.480	0.750	0.763	0.821	0.594

Figure 13: Results from Witmer-Singer presence questionnaire for (a) "*Rainforest Treasure Hunt*" and (b) "*Soccer Goal Challenge*". The x-axis displays the five presence factors, comparing scores based on the NonEMS, NonBioSim, and ErgoPulse conditions. The y-axis represents participants' responses, which have been normalized on a 7-point Likert scale. Significance levels are indicated: $^{*}p$ < .05, $^{**}p$ < .01, $^{***}p$ < .001.

5.2.2 The Influence of ErgoPulse on Presence in a Gaming Environment. The results from the Witmer-Singer presence questionnaire

Table 2: Results of one-way RM ANOVA from Witmer-Singer presence questionnaire for "*Rainforest Treasure Hunt*" and "*Soccer Goal Challenge*". Significance levels are indicated: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

RM ANOVA	Bonferroni post-hoc	
Rainforest content		
Total		
F(1.255, 13.803) = 8.142	N.EMS - N.BioSim	$p = .123$
$p = .010^{*}$	N.EMS - ErgoP	$p = .002^{**}$
	N.BioSim - ErgoP	$p = .229$
Control Factor		
F(2, 22) = 7.312	N.EMS - N.BioSim	$p = 1.000$
$p = .004^{**}$	N.EMS - ErgoP	$p = .015^{*}$
	N.BioSim - ErgoP	$p = .006^{**}$
Sensory Factor		
F(1.171, 12.880) = 10.452	N.EMS - N.BioSim	$p = .011^{*}$
$p = .005^{**}$	N.EMS - ErgoP	$p < .001^{***}$
	N.BioSim - ErgoP	$p = .807$
Distraction Factor		
F(2, 22) = 4.909	N.EMS - N.BioSim	$p = .099$
$p = .017^{*}$	N.EMS - ErgoP	$p = 1.000$
	N.BioSim - ErgoP	$p = .020^{*}$
Realism Factor		
F(2, 22) = 8.842	N.EMS - N.BioSim	$p = .108$
$p = .002^{**}$	N.EMS - ErgoP	$p = .001^{**}$
	N.BioSim - ErgoP	$p = .186$
Soccer content		
Total		
F(2, 22) = 7.551	N.EMS - N.BioSim	$p = .289$
$p = .003^{**}$	N.EMS - ErgoP	$p = .002^{**}$
	N.BioSim - ErgoP	$p = .130$
Control Factor		
F(2, 22) = 4.568	N.EMS - N.BioSim	$p = 1.000$
$p = .022^{*}$	N.EMS - ErgoP	$p = .041^{*}$
	N.BioSim - ErgoP	$p = .055$
Sensory Factor		
F(2, 22) = 10.803	N.EMS - N.BioSim	$p = .074$
$p < .001^{***}$	N.EMS - ErgoP	$p < .001^{***}$
	N.BioSim - ErgoP	$p = .107$
Distraction Factor		
F(2, 22) = 6.860	N.EMS - N.BioSim	$p = .802$
$p = .005^{**}$	N.EMS - ErgoP	$p = .063$
	N.BioSim - ErgoP	$p = .005^{**}$
Realism Factor		
F(2, 22) = 7.759	N.EMS - N.BioSim	$p = .231$
$p = .003^{**}$	N.EMS - ErgoP	$p = .002^{**}$
	N.BioSim - ErgoP	$p = .148$

for two demo contents are shown in Fig. 13 and Table. 2. The x-axis represents the overall presence score and the four subscales of presence, while the y-axis denotes the presence score normalized on a 7-point Likert scale with a standard deviation. For all conditions, the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively, satisfying normality [47]. We conducted a one-way RM ANOVA to analyze the impact of ErgoPulse on each element of presence in two different contents. Detailed results are available in Table. 2. For all presence subscales, the assumption of sphericity was tested using Mauchly's test. If sphericity was not satisfied, we used the Greenhouse-Geisser correction for degrees of freedom.

For the *rainforest content*, there was a significant difference in all presence subscales among the three conditions. For pairwise comparisons, we conducted a post-hoc test using the Bonferroni correction. The results of the one-way RM ANOVA indicated that the ErgoPulse condition provided the highest overall total presence level in a continuous force environment, offering a high level of immersion. Compared to the NonEMS condition, ErgoPulse demonstrated higher levels of immediate responsiveness (Control factor), allowed for deeper immersion through quality sensory stimuli (Sensory factor), did not introduce additional distractions (Distraction factor), and enabled a more realistic VR experience (Realism factor).

Furthermore, the data showed that the NonBioSim condition, which has been commonly utilized in previous research, notably enhanced users' perceived sensory experience in a continuous force environment when compared to the NonEMS condition. This observation confirmed that even without biomechanical simulation, the NonBioSim condition provided a degree of sensory stimulation that enabled an immersive VR experience. However, the data showed that the NonBioSim condition did not show a statistically significant improvement in control and realism factors compared to the NonEMS condition. This finding suggests that it is difficult to achieve immediate responsiveness and realistic sensory experiences under the NonBioSim condition. Furthermore, the data showed that the control factor was significantly lower and the distraction factor was significantly higher when comparing the NonBioSim condition to the ErgoPulse condition. This finding highlights that the application of biomechanical simulation in a continuous force environment improves perceived responsiveness and minimizes perceived distractions.

For the *soccer content*, one-way RM ANOVA showed significant differences in all presence subscales across each condition. Subsequently, to identify which conditions and subscales significantly influenced user presence, we conducted a post-hoc test using the Bonferroni correction. The analysis revealed results similar to those for the rainforest content, with the ErgoPulse condition showing the highest overall total presence level. Compared to the NonEMS condition, ErgoPulse provided higher responsiveness and immersive sensory stimulation, along with a heightened sense of realism, while not causing distractions to the user.

However, when comparing the NonBioSim and ErgoPulse conditions, we observed differences in user experience in both continuous and impulse force environments, which can be attributed to the presence or absence of biomechanical simulation. In the impulse force environment of the *soccer content*, there was no significant difference in the control factor between NonBioSim and ErgoPulse, but in the continuous force environment of the *rainforest content*, there was a statistically significant difference. However, ErgoPulse demonstrated a more significant reduction in the distraction factor in the *soccer content* than in the *rainforest content*. Therefore, our findings indicate that biomechanical simulation helps reduce distractions in an impulse force environment, but its impact on responsiveness is not as pronounced as in scenarios involving continuous forces.

Through the presence questionnaire conducted regarding two content environments where two different types of forces were applied, we discerned that the ErgoPulse condition had the most significant influence on user presence. Furthermore, our findings indicate that when comparing the ErgoPulse condition to the NonBioSim condition, users perceive improved responsiveness, enhanced sensory stimulation, increased realism, and reduced distraction. Subsequently, we conducted interviews to analyze the user experience of ErgoPulse and gather feedback on both the positive and negative aspects of the haptic feedback.

5.2.3 Discussion: Analysis of the Interview. We investigated participants' experiences of the haptic stimuli provided by ErgoPulse through interviews and summarized them based on the content environment and the positive/negative opinions (Table. 3). All participants who experienced the *rainforest* environment responded that they felt distinctly different directions of force when moving upstream and downstream. The direction of the perceived force was consistent with the audiovisual elements of the content *(P1-5, P7, P10-11)* and the stimuli contributed to a surprisingly enjoyable experience *(P1-5, P10-11)*. Furthermore, it was confirmed that ErgoPulse's EMS stimuli provided tactile sensations, with participants responding that they felt tickling of their legs when crossing the river or the wind blew *(P1, P4-5, P10-11)* and that these stimuli had a positive impact on the content.

The interviews further confirmed that in the *rainforest* environment where continuous force is provided, participants were more deeply engaged in the content through ErgoPulse. However, participants' negative responses revealed that certain aspects of ErgoPulse stimuli felt different from the real world. Some participants expressed this difference in terms of the absence of temperature and skin stretch stimuli. This suggested that additional temperature and skin stretch stimuli, similar to Wang et al.'s *Gaiters* [91], could be used in conjunction with ErgoPulse to provide more realistic stimuli. Additionally, some participants reported feeling startled when the stimuli were first applied *(P12)*, experiencing an unpleasant tingling sensation *(P2, P12)* or sensing differences in force between their left and right legs *(P2, P12)*. We believe that these issues can be resolved by gradually increasing the intensity of the stimuli or further refining the EMS personalization process.

Next, we interviewed participants to gather information on the impulse stimuli provided by the *soccer* environment. A majority of participants, when provided with impulse force, responded with positive comments, stating they felt a definite shock and power when kicking the ball *(P1-12)*, and that such sensations were very similar to reality (P1-11). Particularly, the responses of participants who noted that the weight of different balls was clearly distinguished through the intensity of the stimuli *(P1, P5-11)* confirmed that the content design methodology of E1 and the discrimination threshold were appropriately applied. Moreover, some participants felt vibrations in their legs when hitting the ball, which enhanced the realism of the environment *(P1, P5-7)*.

We investigated the negative responses regarding the *soccer* content to explore the limitations of ErgoPulse system on impulse stimuli. Some responses revealed a possible perceivable delay in the provision of impulse force *(P2-4, P12)*. The commonality between the devices and communication environments utilized in the *rainforest* and *soccer content* suggests that there is a delay in the biomechanical simulation calculation and communication process of ErgoPulse, and users might perceive this delay in situations where short-duration stimuli are provided. We anticipate that this issue can be addressed by optimizing the calculation process, improving the communication environment, and refining the EMS hardware. Additionally, several participants *(P2-4, P12)* reported the unnatural experience of feeling tactile impulse stimuli throughout their legs but not on their feet. We identified that the EMS-induced tactile stimuli were consistently perceived in both environments (*rainforest, soccer*) and, depending on the situation, might feel unnatural. Therefore, if devices such as the *Impacto* [58], proposed by Lopes et al., are added to enhance the pressure and impact felt on the feet, we can expect that it will further enhance user immersion. Finally, some participants mentioned sensations of being pulled from behind rather than kicking a ball *(P2)*, which is consistent with the limitations of EMS stimuli in certain situations as reported by Lopes et al [59]. However, a majority of participants in our study did not experience this sensation (91.7% of participants). We believe that further research is necessary to analyze the conditions under which such discrepancies are perceived to ensure robust and realistic haptic stimulation.

Through E2, it was observed that ErgoPulse enhances user presence in environments that provide two distinct types of force — continuous and impulse— by providing highly synchronized force feedback in conjunction with audiovisual elements. ErgoPulse provides immediate perceived environmental responses based on user actions in environments with continuous force and can create experiences that feel similar to reality in environments with impulse force. Furthermore, we acknowledge areas for improvement for more realistic haptic systems that incorporate temperature stimuli, skin stretch, and additional impact devices such as solenoids.

6 DISCUSSION

In this study, we confirmed the discrimination threshold of the ErgoPulse system through E1 and discovered that perception of the system's resolution depends on the direction of gravity and lower body anisotropies. Furthermore, through E2 we developed game content based on the results of E1 and found that, in this new setting, ErgoPulse's biomechanical simulation-based EMS offers more accurate torque through haptic stimulation than conventional EMS. We also found that, under the ErgoPulse condition, users perceive increased responsiveness and levels of immersive sensory stimulation and realism with significantly reduced user distraction. Analysis of interviews allowed us to assess the causes, advantages, and limitations of ErgoPulse. In terms of ErgoPulse accuracy, we formulated three research questions and associated answers:

RQ1. What level of precision can users achieve in distinguishing the intensity and direction of haptic force applied to their lower body through the combination of biomechanical simulation and EMS? – We experimentally discerned that users could perceive a difference in force when there was a difference in intensity between Forward: ±5.91%, Backward: ±8.92%, Upward: ±23.2%, and Downward: ±23.4% of the maximum force. They could also sense differences in force direction when there was an angular

Table 3: Interview responses from participants who experienced E2 game environment. Responses for each content were categorized as positive or negative.

	Positive Feedback	Negative Feedback
Rainforest	The direction and intensity of the force are clearly perceived. *(P1-12)*	Water temperature is not perceptible. *(P2, P5-6, 12)*
	Resistance is felt appropriately when moving the lower body. *(P1-12)*	There's a lack of resistance felt on the skin. *(P1-4, P9, P11-12)*
	The visual direction of flowing water matches the perceived direction of the force. *(P1-5, P7, P10-11)*	I felt startled when the first stimulus was given. *(P12)*
	There's a high consistency between sound and stimuli. *(P1-5, P7, P10-11)*	There's a tingling sensation, similar to electricity. *(P2, P12)*
	The haptic force felt is surprisingly enjoyable. *(P1-5, P10-11)*	The sensation in the right and left leg feels different. *(P2, P12)*
	The sensation of water and wind brushing against the skin is noticeable. *(P1, P4-5, P10-P11)*	
Soccer	The impact when hitting the ball is distinctly felt. *(P1-12)*	A short delay is felt between the moment the ball is hit and when the stimulus is perceived. *(P2-4, P12)*
	The intensity of the force exerted by the ball is well perceived. *(P1-11)*	Sensations are felt not just in the foot but throughout the entire leg. *(P2-4, P12)*
	Felt an impact of similar intensity and direction as in reality. *(P1-11)*	Pressure and tactile sensations in the foot are not felt. *(P2-3, P12)*
	The weight difference between each ball is starkly noticeable. *(P1, P5-11)*	It feels as if someone is pulling from behind rather than kicking the ball. *(P2)*
	A vibration was felt in the leg that matched the impact of hitting the ball. *(P1, P5-7)*	

difference of Forward: ±35.4°, Backward: ±27.1°, Upward ±15.2°, and Downward ±15.3°. Our discrimination threshold experiment revealed that ErgoPulse has varying user perception resolutions depending on the direction of the force. Further analysis indicated that these anisotropies arise from gravity and the biomechanical anisotropies of the human body. Based on previous research, we concluded that external forces [83] and structural anisotropy in human anatomy [87, 88] can affect the perception of force intensity and direction, suggesting that, to deliver forces at different intensities and angles, the ErgoPulse content environment should apply varying levels of stimuli based on the direction of the force.

RQ2. Can the use of a lower-body haptic device based on biomechanical simulation and EMS enhance the immersion of users experiencing VR content? - We developed two game environments based on the discrimination threshold and differences in resolution of ErgoPulse that applied, respectively, a continuous haptic force on the lower body and a short-duration impulse haptic force. We examined the variation in haptic force accuracy in the presence/absence of biomechanical simulation using Jaccard similarity analysis and found that the presence of biomechanical simulation significantly improved Jaccard similarity in both cases, indicating that incorporating biomechanical simulation in EMS calculations enhanced torque accuracy. We then investigated the impact of this accuracy difference on user through a survey-based study of perceptions of user presence and found a significant increase in all aspects of user presence. We observed that the application of biomechanical simulation in EMS stimulation effectively reduced user distraction in environments with both continuous and impulse forces.

RQ3. What are the limitations of systems that deliver EMS haptic force to the lower body through biomechanical simulation and how can these limitations be overcome? - User interviews to evaluate game environments experience revealed a desire for temperature and tactile stimuli with continuous force and that, under impulse force, tactile stimuli are felt at points other than the impact point. To make the experience more immersive and align sensations with actual impact points, we proposed the integration of temperature elements, skin-stretching devices such as *Gaiters* [91], and impact devices such as *Impacto* [58]. Despite these concerns, most users had a positive experience with ErgoPulse's stimuli, finding them enjoyable and well-matched with the content's audiovisual experience, which increased the content's presence. During interviews, it they also noted the occurrence of a tingling sensation, a known characteristic of conventional EMS systems [41, 49, 58, 68, 71, 85] that occurs when the electrical pulse initially moves through the electrode and passes over skin receptors before activating the muscle fibers [40, 85]. This kind of stimulation typically leads to an involuntary, unpleasant tactile sensation, commonly referred to as "tingling" or "buzzing" [33, 34, 41, 49, 68, 71, 85]. Note that this issue is not unique to ErgoPulse but is rather a common challenge faced by most electrical-based stimulation techniques [85]. To address this, alternative stimulation methods such as magnetic muscle stimulation (MMS) have been explored [85]. In future research, we expect to apply alternative stimulation methods with minimal tingling, such as MMS, to ErgoPulse.

Additional Discussion: Does the user's muscle mass affect the additional sense of presence provided by ErgoPulse in VR content? - Because ErgoPulse provides haptic force by directly stimulating muscles, its usability might be affected by individual differences in muscle mass. Using personalization, we examined the relationship between joint torque and EMS intensity, allowing us to customize the EMS system according to participants' individual muscle characteristics and to apply the appropriate EMS intensity to achieve the desired torque. However, although the personalization process guarantees optimized system performance, differences in user experience can occur owing to variations in applied EMS intensity resulting from the personalization process. If the user's muscle mass influences ErgoPulse's impact on perceived user presence, ErgoPulse's application might be limited to specific users, as factors such as gender, age, height, or weight can cause individual variations in muscle mass. Thus, the impact of muscle mass should be more thoroughly investigated before expanding the use of ErgoPulse.

Table 4: The results of the Pearson correlation analysis between muscle mass and the increase in presence when using ErgoPulse.

Content Type	Presence Factor	*r*	*p*
Rainforest	Control	-0.533	0.074
	Sensory	-0.416	0.179
	Distraction	0.403	0.195
	Realism	-0.507	0.093
Soccer	Control	-0.105	0.744
	Sensory	-0.519	0.084
	Distraction	0.354	0.259
	Realism	-0.478	0.116

To address this, we measured the muscle mass of 12 participants who took part in the E2 using body composition analyzers, namely, the *InBody Dial H20N* device, which measures muscle mass using eight electrodes via multi-frequency bioelectrical impedance analysis. The muscle masses of the participants were normal, with an average of 26.925 and a standard deviation of 6.527, *skewness* of -0.101, and *kurtosis* of -1.388. We conducted a Pearson correlation analysis to examine the relationship between muscle mass and the increase in presence when using ErgoPulse. The results are shown in Table. 4. None of these correlations were statistically significant, suggesting that muscle mass did not have a significant linear relationship with increase in presence, regardless of content or factor. Based on the statistical results, it can be concluded that ErgoPulse can improve the presence on average regardless of muscle mass in the range of participants recruited in this study. This also suggests that the personalization process used in this study was an effective method for ensuring consistent usability among a wide range of users.

7 CONCLUSION & FUTURE WORKS

In this paper, we proposed ErgoPulse, an EMS haptic system that uses biomechanical simulation to provide large-scale kinesthetic force feedback to the lower body. The proposed ErgoPulse system consists of two parts: the biomechanical simulation part and the EMS part. The biomechanical part uses IMU and foot pressure sensors to calculate real-time biomechanical simulations. It translates the force on the user's lower body in the virtual environment into torque for each joint. The EMS part then converts the calculated torque into EMS intensity and stimulation location using a personalized torque-intensity relationship. Our research confirmed the threshold for distinguishing the intensity and direction of haptic force using ErgoPulse and discovered the anisotropy of the system. We used the measured discrimination threshold to guide our content design and confirmed an enhancement in the presence of the content we designed. Our findings showed that, regardless of the type of force used in the content – continuous or impulse – in both environments, ErgoPulse's biomechanical simulation-based EMS calculations provided more accurate torque and enabled ErgoPulse to facilitate a more immersive user experience. Lastly, we conducted interviews to discuss the contributions and limitations of ErgoPulse and explore possible ways to improve it. Moreover, further analysis revealed that the positive experience of enhancing presence by ErgoPulse stimulation is guaranteed regardless of the user's muscle mass in the range of participants recruited in this study.

Based on our findings, we recommend conducting the following research in the future: In this paper, our biomechanical simulation focused on calculating torque for four joints and delivering it to the user through eight electrodes. To enhance ErgoPulse's degree of freedom, future work could include calculations for additional joints and muscles by using other biomechanical models, such as the *Lower-extremity model* [21], which simulates forty-three muscle-tendon actuators, or the *Gait2392* and *Gait2354* models [3], which support 23 degrees of freedom along with additional electrodes.

Furthermore, we recommend further verifying the accuracy of our system's ability to deliver forces in each direction through a motor task. In E2, we conducted a study to validate the accuracy of the torque induced by EMS stimulation in a simple game content environment. Verifying torque accuracy in a content environment is valid as it demonstrates how closely ErgoPulse matches the target torque experienced by each joint of the avatar in the virtual environment, in content that users are likely to actually experience. However, to achieve more rigorous validation, we could assess accuracy during specific motor tasks in predefined postures. For instance, conducting lower-extremity motor coordination tests (LEMOCOT) [24] and foot tapping tests (FTT) [67] could enable rigorous future research on the movement accuracy of users with ErgoPulse.

Moreover, integrating computational muscle models [16, 51, 64] could improve the personalization process of ErgoPulse in terms of both realism and personalization time. Human muscle properties can vary based on factors such as muscle fiber length, tendon properties, contraction speeds, and fatigue levels [11, 56, 93, 96]. Therefore, incorporating a computational muscle model would enable ErgoPulse to better reflect these real-world muscle characteristics. Additionally, computational muscle models can improve torque transmission accuracy by considering voluntary muscle activation in humans. The current version of ErgoPulse does not include considerations for voluntary muscle activation, which may lead to inaccuracies in predicted muscle activation levels in environments requiring strong voluntary forces (such as running or squatting). Therefore, integrating models that account for voluntary muscle activation, such as the *Flexing Computational Muscle* model [64], will aid in improving usability by enhancing accuracy in environments that demand strong forces. Furthermore, these models could simplify the EMS personalization process, which currently takes about one hour per person, by directly calculating the muscle activation within the given force. We anticipate that reducing the personalization time could make ErgoPulse more practical by decreasing the preparation required before each use of our system.

Finally, to achieve even more realistic haptic stimuli, future developments could consider integrating temperature stimuli, skin stretch, and additional impact devices based on our interview results. Moreover, leveraging EMS's tactile capabilities to deliver skin tactile stimuli through additional electrodes could extend ErgoPulse's capabilities, enabling it to provide not only force feedback but also tactile sensations on the lower limbs.

ACKNOWLEDGMENTS

This work was supported by the GIST-MIT Research Collaboration grant funded by the GIST in 2024, 'Project for science and technology opens the future of the region' program through the Innopolis Foundation funded by Ministry of Science and ICT (Project Number: 2022-DD-UP-0312).

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APPENDIX A. WITMER-SINGER PRESENCE QUESTIONNAIRE [95]

(1) How much were you able to control events?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(2) How responsive was the environment to actions that you initiated (or performed)?
NOT RESPONSIVE | MODERATELY RESPONSIVE | COMPLETELY RESPONSIVE
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(3) How natural did your interactions with the environment seem?
EXTREMELY ARTIFICIAL | BORDERLINE | COMPLETELY NATURAL
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(4) How completely were all of your senses engaged?
NOT ENGAGED | MODERATELY ENGAGED | COMPLETELY ENGAGED
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(5) How much did the visual aspects of the environment involve you?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(6) How much did the auditory aspects of the environment involve you?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(7) How natural was the mechanism which controlled movement through the environment?
EXTREMELY ARTIFICIAL | BORDERLINE | COMPLETELY NATURAL
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(8) How aware were you of events occurring in the real world around you?
NOT AWARE AT ALL | MILDLY AWARE | VERY AWARE
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(9) How aware were you of your display and control devices?
NOT AWARE AT ALL | MILDLY AWARE | VERY AWARE
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(10) How compelling was your sense of objects moving through space?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(11) How inconsistent or disconnected was the information coming from your various senses?
NOT AT ALL INCONSISTENT | SOMEWHAT INCONSISTENT | VERY INCONSISTENT
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(12) How much did your experiences in the virtual environment seem consistent with your real-world experiences?
NOT CONSISTENT | MODERATELY CONSISTENT | VERY CONSISTENT
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(13) Were you able to anticipate what would happen next in response to the actions that you performed?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(14) How completely were you able to actively survey or search the environment using vision?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(15) How well could you identify sounds?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(16) How well could you localize sounds?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(17) How well could you actively survey or search the virtual environment using touch?
NOT AT ALL | SOMEWHAT | COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(18) How compelling was your sense of moving around inside the virtual environment?
NOT COMPELLING | MODERATELY COMPELLING | VERY COMPELLING
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(19) How closely were you able to examine objects?
NOT AT ALL PRETTY CLOSELY VERY CLOSELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(20) How well could you examine objects from multiple viewpoints?
NOT AT ALL SOMEWHAT EXTENSIVELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(21) How well could you move or manipulate objects in the virtual environment?
NOT AT ALL SOMEWHAT EXTENSIVELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(22) To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?
NOT AT ALL MILDLY DISORIENTED VERY DISORIENTED
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(23) How involved were you in the virtual environment experience?
NOT INVOLVED MILDLY INVOLVED COMPLETELY ENGROSSED
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(24) How distracting was the control mechanism?
NOT AT ALL MILDLY DISTRACTING VERY DISTRACTING
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(25) How much delay did you experience between your actions and expected outcomes?
NO DELAYS MODERATE DELAYS LONG DELAYS
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(26) How quickly did you adjust to the virtual environment experience?
NOT AT ALL SLOWLY LESS THAN ONE MINUTE
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(27) How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
NOT PROFICIENT REASONABLY PROFICIENT VERY PROFICIENT
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(28) How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
NOT AT ALL INTERFERED SOMEWHAT PREVENTED PERFORMANCE
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(29) How much did the control devices interfere with the performance of assigned tasks or with other activities?
NOT AT ALL INTERFERED SOMEWHAT INTERFERED GREATLY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(30) How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
NOT AT ALL SOMEWHAT COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(31) Did you learn new techniques that enabled you to improve your performance?
NO TECHNIQUES LEARNED LEARNED SOME TECHNIQUES LEARNED MANY TECHNIQUES
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

(32) Were you involved in the experimental task to the extent that you lost track of time?
NOT AT ALL SOMEWHAT COMPLETELY
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7