

Proposal of a Framework for Enhancing Teleoperation Experience with Biomechanical Simulation-Based Electrical Muscle Stimulation in Virtual Reality

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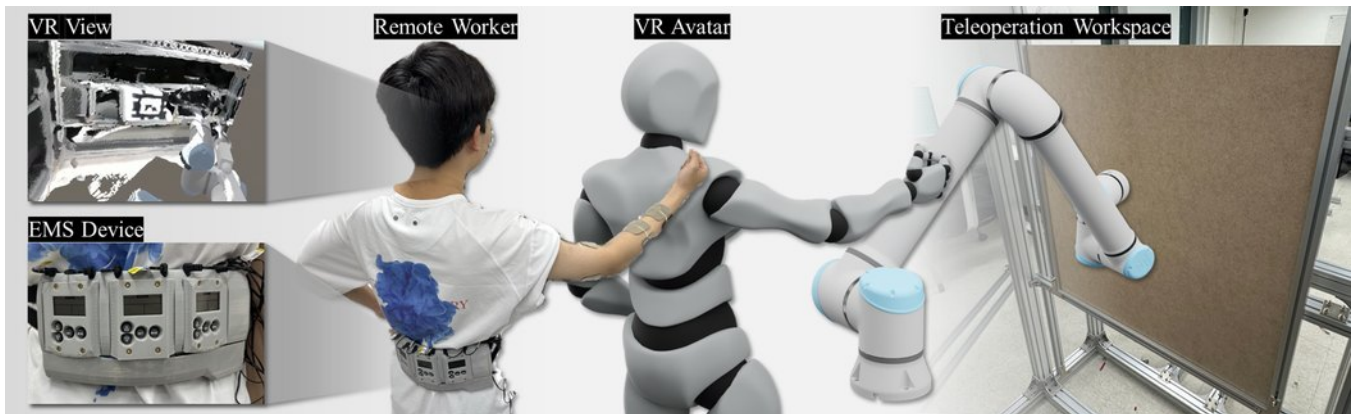


Figure 1: The conceptual graphical representation of the system that provides force feedback measured from the teleoperation workspace to the remote worker. The torque is translated into electrical muscle stimulation parameters, which simulate the virtual joint torque to resemble the state of the remote serial manipulator.

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ABSTRACT

Teleoperation, the remote manual control of robots, is primarily used in high-precision and safety-critical environments such as surgery, space exploration, and deep-sea exploration. Despite being

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a widely utilized technology, teleoperation relies on human cognitive abilities, leading to significant cognitive load for operators. To address this challenge, we propose a concept of a VR teleoperation haptic system that combines biomechanical simulation and electrical muscle stimulation to provide force feedback in a lightweight, wearable form by mimicking natural force generation without the need for external actuators. Our system is divided into two main components: the physical simulation part, which calculates the joint torques to replicate forces from the manipulator, and the electrical stimulation part, which translates torques into muscle stimulations. Through this integration, we expect our system to bridge the gap of execution and evaluation, reducing cognitive load and enhancing teleoperation performance. This paper aims to discuss the detailed framework of our system and potential future research directions.

CCS CONCEPTS

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

KEYWORDS

Teleoperation; Virtual Reality; Haptic; Electrical Muscle Stimulation; Biomechanics; Simulation; Wearable Device

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1 INTRODUCTION

Teleoperation, which involves the remote manual control of robots by users, is a technology that can be widely applied in various environments requiring human intervention within the field of robotics. Despite advancements in autonomous robotic control technology, teleoperation remains a dominant paradigm in atypical environments that demand high levels of precision and safety, such as surgery [34, 35, 44], space exploration [30, 42], disaster response [32, 38], and deep-sea exploration [5, 46]. Teleoperation leverages human cognitive abilities to ensure high reliability in diverse environments, but it requires a high level of concentration and expertise from the operator, potentially leading to significant cognitive load. This cognitive load and the challenges in operation can be interpreted as the “gap of execution and evaluation,” which is the gap between the high-level goals of the robot system (e.g., performing surgery or deep-sea exploration through teleoperation) and the low-level means available to the user (e.g., operating commands via joystick and monitor). Walker et al. summarized the problems that remote operators may encounter due to this gap into three categories: 1) confusion about which commands will achieve the given goal, 2) uncertainty about the impact of their commands on the system, and 3) potential physical dangers around the robot system while it is executing commands [45]. Therefore, we can expect to address these issues by reducing the gap between the user and the remote system.

To reduce cognitive load and achieve high-level goals with greater clarity in the execution and evaluation phases of the human action cycle, researchers are investigating teleoperation utilizing virtual reality (VR) and haptic technology. The integration of VR and haptic technology allows for a more realistic and immersive experience through tactile and force feedback in virtual environments, providing operators with various situational information and enabling more precise and complex tasks. Conventional teleoperation systems with haptics were initially researched in the form of grounded mechanical devices. These devices used robot manipulators fixed to the ground or a desk to provide force feedback between the remote robot and its surrounding environment, either synchronizing identical or differently scaled robots. While this approach could deliver relatively large forces to the user, it had drawbacks such as complex installation, high cost, and limited mobility, restricting its use to specific locations. Consequently, recent research on teleoperation haptics has focused on wearable devices, which allow users greater mobility and can be implemented at a lower cost. Although wearable devices can provide haptic sensations using vibration motors [4, 21], small actuators [1, 8] and electrotactiles [36, 37], their small size limits them to tactile stimulation on the skin surface and cannot provide actual force feedback. To address this, some studies have explored exoskeleton forms of wearable devices [3, 15] that can offer real force as haptic feedback, but these face a technical trade-off due to the increased weight of batteries and actuators required to deliver substantial force.

Therefore, in this paper, we propose a haptic system framework that combines biomechanical simulation and electrical muscle stimulation (EMS) to provide actual force feedback to users in a lightweight, wearable form in teleoperation scenarios. EMS is a technology that induces muscle contractions through electrical stimulation, mimicking the natural process by which humans generate force. Unlike other haptic devices, EMS does not use external actuators, allowing it to simulate large forces with relatively low power consumption and a compact size. However, EMS operates on individual muscles, requiring the stimulation of multiple muscles with varying intensities to provide the forces resulting from interactions between the robot and the environment. To determine which muscles to stimulate, when, and at what intensity, we perform biomechanical simulations based on user-specific biomechanical characteristics. This includes calculating real-time joint torques considering the user’s posture, body length, joint movements, and weight.

Our proposed framework is divided into two main parts: 1) the physical simulation part (**PhySim** part) and 2) the electrical stimulation part (**EleStim** part). Firstly, the **PhySim** part calculates the magnitude and direction of the force to be provided to the user based on the kinematic data and force-torque sensor (F-T sensor) data from the remote manipulator. It then performs biomechanical simulations that reflect the user’s characteristics to compute the target torque for each joint in real time. Secondly, the **EleStim** part receives the target torque calculated by the **PhySim** part and converts it into EMS intensities calibrated for the individual user, providing the remote manipulator’s force as haptic feedback in real time. This paper aims to discuss the detailed framework of the system and potential future researches.

2 SYSTEM OVERVIEW

The schematic representation of the proposed system is illustrated in Fig. 2. The envisioned teleoperation environment between the user and the environment could be implemented through a controller and a VR head-mount display (HMD), as shown on the left side of Fig. 2. In this conceptual design, the user would determine the tool center point of the manipulator using the controller. The joint coordinates required for the remote manipulator to reach this position could be determined through inverse kinematics and transmitted to the robot system. Simultaneously, the workspace, including the manipulator, could be converted into a point cloud using a depth cam and presented to the user in VR.

Our EMS haptic system framework is composed of two parts: 1) the **PhySim** part and 2) the **EleStim** part. Firstly, the **PhySim** part is designed to receive upper body motion capture data from an HMD with motion tracking capabilities. The position data of each joint, obtained through motion capture, could be converted into joint coordinates through inverse kinematics. Using these joint coordinates, the system is conceptualized to perform two different inverse dynamics. The first model (**Model 1** in Fig. 2) would calculate the joint torques without considering external forces measured by the F-T sensor, while the second model (**Model 2** in Fig. 2) would calculate the joint torques considering the external forces. The difference in joint torques calculated by the two models will determine the torque magnitude provided through EMS.

Secondly, the **EleStim** part of the system is designed to determine the EMS intensity required to provide the calculated torque. The intensity and characteristics of the EMS stimulus would depend on the user's muscle properties and electrode placement [10, 14, 39]. To personalize the EMS intensity, the torque-intensity relationship for each muscle of each user could be calculated, as detailed in section 3. The stimulus calculated from the torque-intensity relationship would then be transmitted to the user's arm muscles via remotely operated EMS equipment, ultimately allowing the user to feel the forces resulting from the interaction between the remote manipulator and the environment.

3 PERSONALIZATION PROCESS OF EMS

As previously introduced, biomechanical simulation and EMS require a personalization process based on individual characteristics (such as height, weight, bone length, and musculoskeletal properties) to ensure accurate simulation results and stimulation. The personalization process consists of two stages: 1) measuring the user's body information for the geometrical calibration of the biomechanical simulation, and 2) performing EMS calibration to determine the torque-intensity relationship.

Firstly, for the geometrical calibration of the biomechanical simulation, we measured the distances between each joint for each user, as shown in Fig. 3 (a). These measured joint distances are computed through the body retargeting process of motion capture system. The user's total body mass was measured using a scale, and the weights of the body segments (upper arm, lower arm, and hand in the primary use direction) calculated by Dempster model were applied to the biomechanical simulation.

Secondly, because the relationship between EMS intensity and the joint torque varies according to each participant's musculoskeletal characteristics, we established a torque-intensity graph for each participant. The EMS used for haptic stimulation applies stimuli within the range between the motor threshold (I_{MT}), which is the minimum stimulus intensity needed to induce muscle contraction, and the pain threshold (I_{PT}), which is the maximum stimulus intensity that does not cause discomfort to the participant. The usable EMS stimulation range falls within the acceleration region of the sigmoid-shaped overall torque-intensity graph [2, 6, 22, 28]. The relationship between torque (T) and stimulus intensity (I) can be simplified as an exponential function with fitting parameters a and b (Eqn. 1) [2, 6, 14, 22, 27, 28] as follows:

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

To determine the maximum stimulus intensity that does not cause discomfort, we gradually increased the stimulus intensity until I_{PT} was identified for each participant. Next, to establish the torque-intensity relationship in this range, we divided the interval between I_{MT} and I_{PT} into seven segments and measured the torque three times generated at each stimulus intensity using a load cell. To reduce personalization errors, we repeated the torque measurements three times for each stimulus intensity and calculated the average torque generated. This data was then fitted to Eqn. 1 to personalize the torque-intensity relationship for each muscle, which results in graphs such as Fig. 3 (b) for each user. The targeted muscles were biceps brachii (Biceps), triceps brachii (Triceps), extensor carpi radialis longus (ECRL), extensor carpi ulnaris (ECU), flexor carpi radialis (FCR), and flexor carpi ulnaris (FCU) muscles, to simplify the attachment of EMS electrodes and facilitate rapid calculations. Through these process, we were able to create an optimized biomechanical simulation model for each user and calculate the torque requirements for each joint. Consequently, we established a total of six torque-intensity graphs for each user. Our system utilizes these relationships to determine the appropriate EMS intensity required to produce joint torque.

4 IMPLEMENTATION

4.1 Biomechanical Simulation Implementation

Through geometrical calibration, the body model adjusted to each user includes information on the length, weight, and relative position of each body segment. For biomechanical simulation, we also incorporated joint characteristics, such as degrees of freedom and motion properties, into the body model. Therefore, we parsed the *MoBL-ARMS Dynamic Upper Limb* model [29, 41] used in the open-source biomechanical simulation software *OpenSim* [9] to obtain the joint characteristics and segment connection information.

The body model obtained through this process is applied to the our system, where it undergoes real-time inverse dynamics calculations using the *Nvidia PhysX* engine, a physics simulation solution, within the Unity framework. The body model, along with joint coordinate information derived from inverse kinematics using real-time motion capture data, takes into account gravitational effects. When necessary (as in model 2 of Fig. 2), it can also incorporate forces measured by the F-T sensor from the robotic system, which would be added in our future study to calculate the torque for each

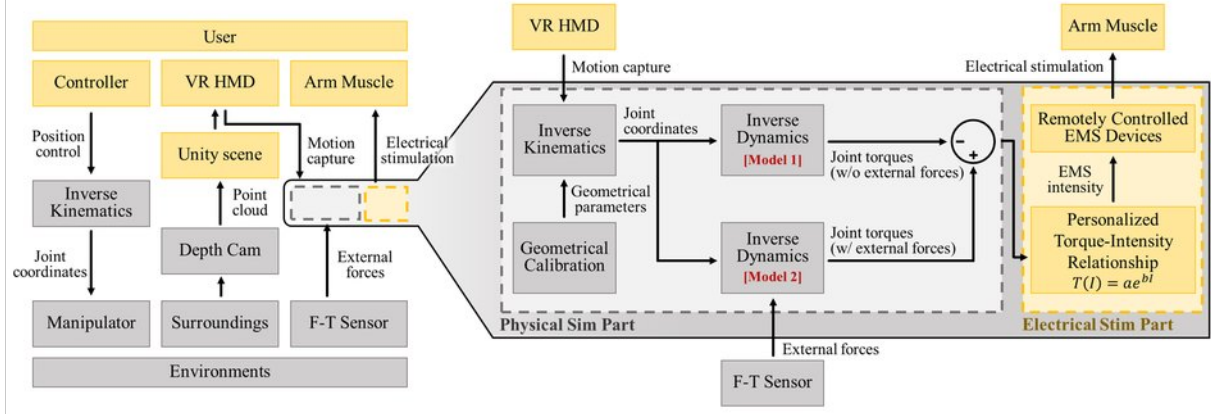


Figure 2: Schematic representation of proposed system

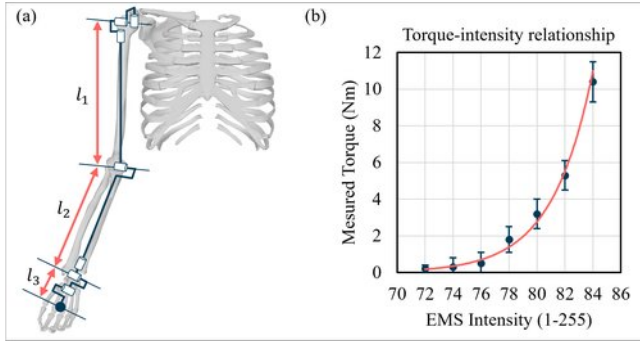


Figure 3: (a) Inter-joint distances of the participant for geometrical calibration, (b) EMS intensity to joint torque fitting.

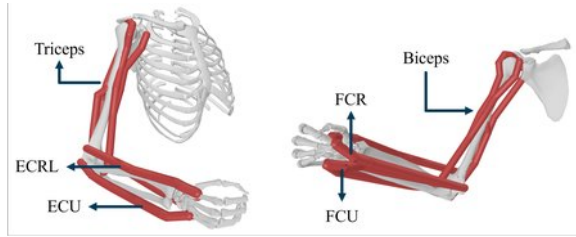


Figure 4: Enumerated muscles utilized in *MoBL-ARMS Dynamic Upper Limb* biomechanical simulation model. Six muscles are labeled: Biceps, Triceps, ECRL, ECU, FCR, and FCU muscles.

joint. Therefore, the biomechanical simulation in this system can calculate the torque exerted on the user's joints in real-time based on the given conditions, determining the torque that needs to be provided by EMS for each joint.

4.2 Hardware Implementation

In this paper, we developed a hardware system to remotely deliver the calculated EMS intensity to the remote operator. The module

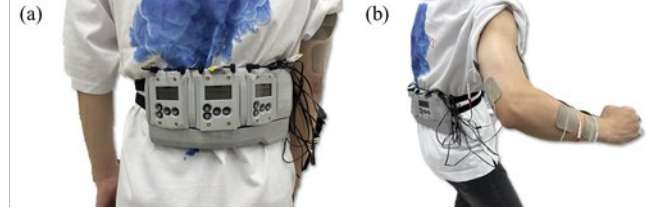


Figure 5: (a) The EMS device implemented this study, (b) the image of EMS device attached to the muscles of the participant.

that generates the medical-grade EMS signal uses the TENS 7000 device. We attached electrodes to six muscles illustrated in Fig. 4. The TENS 7000 device can provide up to 100mA of EMS, and to ensure user safety, we used the original signal generation unit of the TENS 7000 device without any modifications. To control the intensity of the stimulation, we employed a digital potentiometer, allowing fine adjustments in 0-255 steps, as shown in Fig. 5, and controlled remotely via Wi-Fi WebSocket communication with a computer. For safety, the stimulation unit and control unit are electrically isolated, and a switch that can shut down all devices simultaneously is placed within easy reach of the user. We utilized the Unity Profiler to gauge the end-to-end delay and determined that it is approximately 45 ms at its maximum. This total delay encompasses motion capture (≈ 15 ms), physical simulation (≈ 10 ms), Wi-Fi communication with the EMS device (≈ 5 ms), and muscle contraction delays (≈ 15 ms). In our study, we applied forces computed within the degrees of freedom defined by the biomechanical simulation model. Consequently, we attached electrodes to six muscles illustrated in Fig. 4.

5 CONCLUSION AND FUTURE WORKS

In this paper, we propose a concept of a haptic system for VR teleoperation to reduce cognitive load and enhance operational efficiency for remote operators. Future research implementing this system is expected to overcome the limitations of previous wearable teleoperation haptic systems that offer only tactile stimulation on the

skin surface. Additionally, this framework can be applied not only to the serial manipulator used as an example in this paper but also to robotic dogs, submersibles, surgical robots, and mobile robots. Moreover, we expect that the strengths of our system—maintaining lightweight and mobility while providing force feedback—which differentiate it from other wearable haptic systems, will be particularly beneficial when combined with VR locomotion technologies such as redirected walking [20, 24, 40], walking-in-place [18, 19, 33], and omnidirectional treadmills [43]. This combination is expected to be especially advantageous for mobile robots freely navigating and performing missions in unstructured environments.

In subsequent studies, we will implement the concept proposed in this paper and compare it with various wearable haptic devices, such as vibration motors [4, 16, 21], skin stretch [1, 8], and electro-tactile devices [36, 37], to investigate the remote operator's experience and task efficiency in real-world environments. Moreover, by integrating feedback types that have been rarely utilized in teleoperation, such as thermal sensation [17], vestibular sensation [11–13], and olfaction [25, 26], we anticipate developing a new form of haptic feedback system.

Our current system targets only six muscles for rapid computation and ease of electrode attachment. Future research will also aim to stimulate a broader variety of muscles in different locations to enable higher degrees of freedom in movement and force feedback. By including shoulder and hand muscles in the simulation system, we anticipate providing more realistic and accurate haptic feedback. Furthermore, we plan to expand the use of biomechanical simulation beyond torque calculation. By employing computational muscle models [7, 23, 31], we can calculate the activation levels of individual muscles, allowing for simulations that account for voluntary muscle activation. Through these enhancements in additional electrode attachment and the sophistication of biomechanical simulation, we aim to develop a teleoperation haptic system that delivers more accurate and varied force feedback in different magnitudes and directions.

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