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

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Seokhyun Hwang
anoldhsh@gm.gist.ac.kr
Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

Seongjun Kang
ksjryan0728@gm.gist.ac.kr
Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

Jeongseok Oh
jungseok17@gm.gist.ac.kr
Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

Jeongju Park
jeongjupark@gm.gist.ac.kr
Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

Semoo Shin
sms081700@gm.gist.ac.kr
Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

Yiyue Luo
yiyueluo@mit.edu
University of Washington
Seattle, Washington, USA

Joseph DelPreto
delpreto@csail.mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Wojciech Matusik
wojciech@mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Daniela Rus
rus@csail.mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

SeungJun Kim*
seungjun@gist.ac.kr
Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

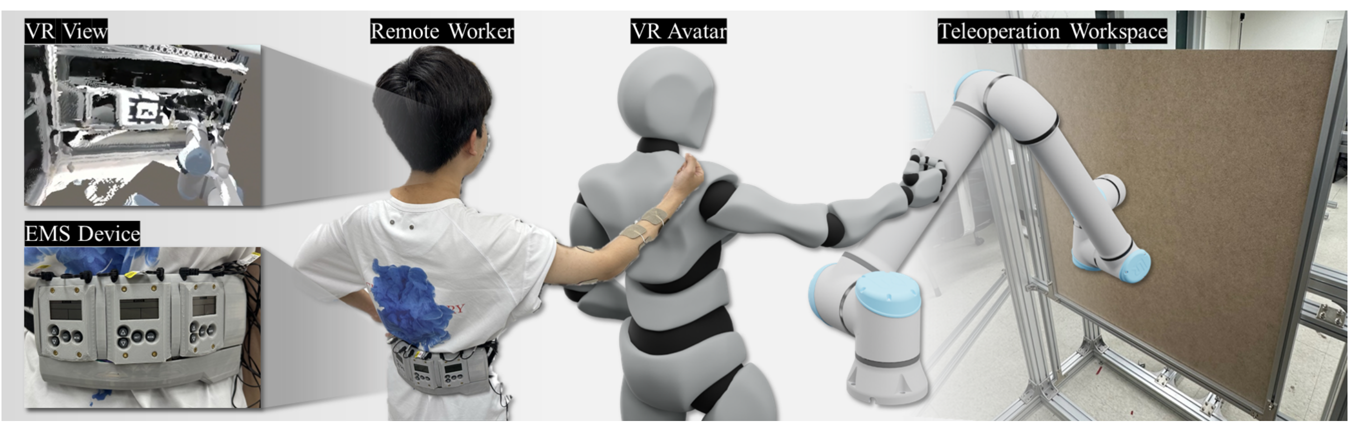

Figure 1: The conceptual graphical representation of the system that provides force feedback measured from the teleoperation workspace to the remote worker. The torque is translated into electrical muscle stimulation parameters, which simulate the virtual joint torque to resemble the state of the remote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

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

*Corresponding author.

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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 gulf 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 "gulf 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 gulf 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 gulf 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:

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

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

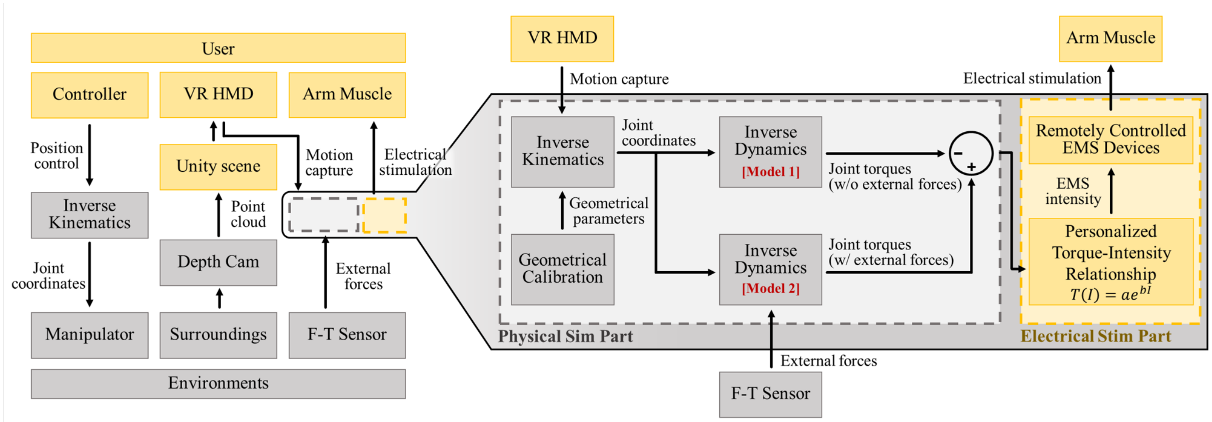

Figure 2: Schematic representation of proposed system

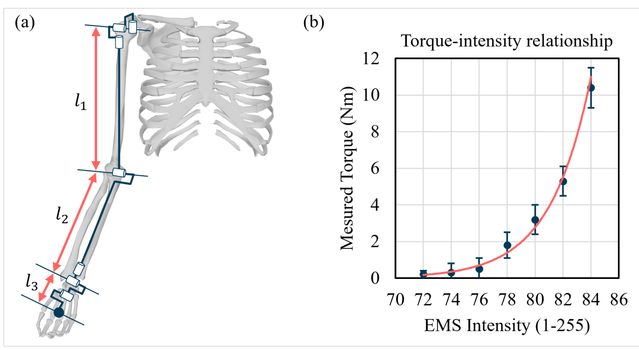

Figure 3: (a) Inter-joint distances of the participant for geometrical calibration, (b) EMS intensity to joint torque fitting.

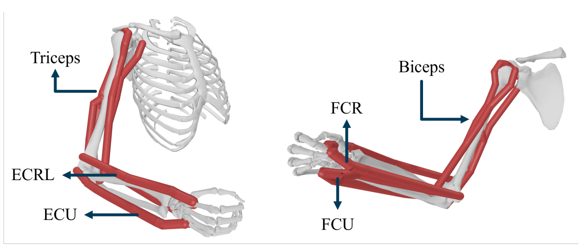

Figure 4: Enumerated muscles utilized in *MoBL-ARMS Dynamic Upper Limb* biomechanical simulation model. Six muscles are labeled: Biceps, Triceps, ECRL, ECU, FCR, and FCU muscles.

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

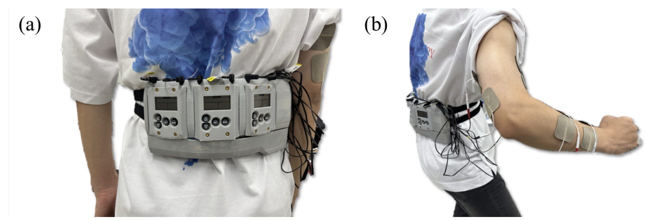

Figure 5: (a) The EMS device implemented this study, (b) the image of EMS device attached to the muscles of the participant.

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 electrotactile 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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REFERENCES

[1] Marco Aggravi, Florent Pausé, Paolo Robuffo Giordano, and Claudio Pacchierotti. 2018. Design and evaluation of a wearable haptic device for skin stretch, pressure, and vibrotactile stimuli. *IEEE Robotics and Automation Letters* 3, 3 (2018), 2166–2173.

[2] Tadej Bajd and Marko Munih. 2010. Basic functional electrical stimulation (FES) of extremities: an engineer's view. *Technology and Health Care* 18, 4-5 (2010), 361–369.

[3] Massimo Bergamasco, Benedetto Allotta, L Bosio, Luca Ferretti, G Parrini, GM Prisco, Fabio Salsedo, and G Sartini. 1994. An arm exoskeleton system for teleoperation and virtual environments applications. In *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*. IEEE, 1449–1454.

[4] Joao Bimbo, Claudio Pacchierotti, Marco Aggravi, Nikos Tsagarakis, and Domenico Prattichizzo. 2017. Teleoperation in cluttered environments using wearable haptic feedback. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 3401–3408.

[5] BG Boyle, RS McMaster, and J Mixon. 1995. Teleoperation of an underwater robotic repair system using graphical simulation. (1995).

[6] Alie J Buckmire, Danielle R Lockwood, Cynthia J Doane, and Andrew J Fuglevand. 2018. Distributed stimulation increases force elicited with functional electrical stimulation. *Journal of neural engineering* 15, 2 (2018), 026001.

[7] Ernest J Cheng, Ian E Brown, and Gerald E Loeb. 2000. Virtual muscle: a computational approach to understanding the effects of muscle properties on motor control. *Journal of neuroscience methods* 101, 2 (2000), 117–130.

[8] Nicoletta Colella, Matteo Bianchi, Giorgio Grioli, Antonio Bicchi, and Manuel G Catalano. 2019. A novel skin-stretch haptic device for intuitive control of robotic prostheses and avatars. *IEEE Robotics and Automation Letters* 4, 2 (2019), 1572–1579.

[9] Scott L Delp, Frank C Anderson, Allison S Arnold, Peter Loan, Ayman Habib, Chand T John, Eran Guendelman, and Darryl G Thelen. 2007. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE transactions on biomedical engineering* 54, 11 (2007), 1940–1950.

[10] Ahmed Ibrahim Ahmed Mohamed Elsharkawy, Aya Abdulnasser Saed Ataya, Dohyeon Yeo, Eunsol An, Seokhyun Hwang, and SeungJun Kim. 2024. SYNC-VR: Synchronizing Your Senses to Conquer Motion Sickness for Enriching In-Vehicle Virtual Reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–17.

[11] Seokhyun Hwang, YoungIn Kim, Youngseok Seo, and SeungJun Kim. 2023. Enhancing Seamless Walking in Virtual Reality: Application of Bone-Conduction Vibration in Redirected Walking. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 1181–1190.

[12] Seokhyun Hwang, Jieun Lee, YoungIn Kim, and SeungJun Kim. 2022. REVES: Redirection Enhancement Using Four-Pole Vestibular Electrode Stimulation. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 1–7.

[13] Seokhyun Hwang, Jieun Lee, Youngin Kim, Youngseok Seo, and Seungjun Kim. 2023. Electrical, Vibrational, and Cooling Stimuli-Based Redirected Walking: Comparison of Various Vestibular Stimulation-Based Redirected Walking Systems. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–18.

[14] Seokhyun Hwang, Jeongseok Oh, Seongjun Kang, Minwoo Seong, Ahmed Ibrahim Ahmed Mohamed 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*. 1–21.

[15] Inseong Jo, Younkyu Park, and Joonbum Bae. 2013. A teleoperation system with an exoskeleton interface. In *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 1649–1654.

[16] Taewoo Jo, Dohyeon Yeo, Gwangbin Kim, Seokhyun Hwang, and SeungJun Kim. 2024. WatchCap: Improving Scanning Efficiency in People with Low Vision through Compensatory Head Movement Stimulation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 8, 2 (2024), 1–32.

[17] Seongjun Kang, Gwangbin Kim, Seokhyun Hwang, Jeongju Park, Ahmed Elsharkawy, and SeungJun Kim. 2024. Dual-sided Peltier Elements for Rapid Thermal Feedback in Wearables. *arXiv preprint arXiv:2405.11807* (2024).

[18] Seongjun Kang, Gwangbin Kim, and SeungJun Kim. 2023. Giant Finger: A Novel Visuo-Somatosensory Approach to Simulating Lower Body Movements in Virtual Reality. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 233–242.

[19] Seongjun Kang, Gwangbin Kim, Kyung-Taek Lee, and SeungJun Kim. 2023. Giant Finger: Visuo-proprioceptive congruent virtual legs for flying actions in virtual reality. In *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 933–934.

[20] YoungIn Kim, Seokhyun Hwang, Jeongseok Oh, and Seungjun Kim. 2024. GaitWay: Gait Data-Based VR Locomotion Prediction System Robust to Visual Distraction. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. 1–8.

[21] Yosuke Kurihara, Taku Hachisu, Katherine J Kuchenbecker, and Hiroyuki Kajimoto. 2013. Jointonation: robotization of the human body by vibrotactile feedback. In *SIGGRAPH Asia 2013 Emerging Technologies*. 1–3.

[22] Yuichi Kurita, Takaaki Ishikawa, and Toshio Tsuji. 2016. Stiffness display by muscle contraction via electric muscle stimulation. *IEEE Robotics and Automation Letters* 1, 2 (2016), 1014–1019.

[23] Melissa J Lambeth and Martin J Kushmerick. 2002. A computational model for glycogenolysis in skeletal muscle. *Annals of biomedical engineering* 30 (2002), 808–827.

[24] Jieun Lee, Seokhyun Hwang, Aya Ataya, and SeungJun Kim. 2024. Effect of optical flow and user VR familiarity on curvature gain thresholds for redirected walking. *Virtual Reality* 28, 1 (2024), 35.

[25] Jieun Lee, Seokhyun Hwang, Kyunghwan Kim, and SeungJun Kim. 2022. Auditory and olfactory stimuli-based attractors to induce reorientation in virtual reality forward redirected walking. In *CHI conference on human factors in computing systems extended abstracts*. 1–7.

[26] Jieun Lee, Seokhyun Hwang, Kyunghwan Kim, and SeungJun Kim. 2024. Evaluation of visual, auditory, and olfactory stimulus-based attractors for intermittent reorientation in virtual reality locomotion. *Virtual Reality* 28, 2 (2024), 104.

[27] Jungeun Lee, Yeongjin Kim, and Hoeryong Jung. 2020. Electrically Elicited Force Response Characteristics of Forearm Extensor Muscles for Electrical Muscle Stimulation-Based Haptic Rendering. *Sensors* 20, 19 (2020), 5669.

[28] M Levy, J Mizrahi, and Z Susak. 1990. Recruitment, force and fatigue characteristics of quadriceps muscles of paraplegics isometrically activated by surface functional electrical stimulation. *Journal of biomedical engineering* 12, 2 (1990), 150–156.

[29] Daniel C McFarland, Emily M McCain, Michael N Poppo, and Katherine R Saul. 2019. Spatial dependency of glenohumeral joint stability during dynamic unimanual and bimanual pushing and pulling. *Journal of biomechanical engineering* 141, 5 (2019), 051006.

[30] M Alejandra Menchaca-Brandan, Andrew M Liu, Charles M Oman, and Alan Natapoff. 2007. Influence of perspective-taking and mental rotation abilities in space teleoperation. In *Proceedings of the ACM/IEEE International Conference on Human-robot interaction*. 271–278.

[31] Matthew Millard, Thomas Uchida, Ajay Seth, and Scott L Delp. 2013. Flexing computational muscle: modeling and simulation of musculotendon dynamics. *Journal of biomechanical engineering* 135, 2 (2013), 021005.

[32] Robin R Murphy, Karen L Dreger, Sean Newsome, Jesse Rodocker, Eric Steimle, Tetsuya Kimura, Kenichi Makabe, Fumitoshi Matsuno, Satoshi Tadokoro, and Kazuyuki Kon. 2011. Use of remotely operated marine vehicles at Minamisanriku and Rikuzentakata Japan for disaster recovery. In *2011 IEEE International symposium on safety, security, and rescue robotics*. IEEE, 19–25.

[33] Niels Christian Nilsson, Stefania Serafin, and Rolf Nordahl. 2016. Walking in place through virtual worlds. In *International Conference on Human-Computer Interaction*. Springer, 37–48.

[34] Shahin S Nudehi, Ranjan Mukherjee, and Moji Ghodoussi. 2003. A haptic interface design for minimally invasive telesurgical training and collaboration in the presence of time delay. In *42nd IEEE International Conference on Decision and Control (IEEE Cat. No. 03CH37475)*, Vol. 5. IEEE, 4563–4568.

[35] Allison M Okamura. 2004. Methods for haptic feedback in teleoperated robot-assisted surgery. *Industrial Robot: An International Journal* 31, 6 (2004), 499–508.

[36] Daniel Pamungkas and Koren Ward. 2015. Immersive teleoperation of a robot arm using electro-tactile feedback. In *2015 6th International Conference on Automation, Robotics and Applications (ICARA)*. IEEE, 300–305.

[37] Daniel S Pamungkas and Koren Ward. 2013. Tele-operation of a robot arm with electro tactile feedback. In *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 704–709.

[38] FJ Perez-Grau, R Ragel, F Caballero, A Viguria, and A Ollero. 2017. Semi-autonomous teleoperation of UAVs in search and rescue scenarios. In *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 1066–1074.

[39] Max Pfeiffer, Tim Duente, and Michael Rohs. 2016. Let your body move: a prototyping toolkit for wearable force feedback with electrical muscle stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 418–427.

[40] Sharif Razzaque, Zachariah Kohn, and Mary C. Whitton. 2001. Redirected Walking. In *Eurographics 2001 - Short Presentations*. Eurographics Association. https://doi.org/10.2312/egs.20011036

[41] Katherine R Saul, Xiao Hu, Craig M Goehler, Meghan E Vidt, Melissa Daly, Anca Velisar, and Wendy M Murray. 2015. Benchmarking of dynamic simulation predictions in two software platforms using an upper limb musculoskeletal model. *Computer methods in biomechanics and biomedical engineering* 18, 13 (2015), 1445–1458.

[42] Thomas B Sheridan. 1993. Space teleoperation through time delay: Review and prognosis. *IEEE Transactions on robotics and Automation* 9, 5 (1993), 592–606.

[43] Mel Slater, Martin Usoh, and Anthony Steed. 1995. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)* 2, 3 (1995), 201–219.

[44] Russell H Taylor, Arianna Menciassi, Gabor Fichtinger, Paolo Fiorini, and Paolo Dario. 2016. Medical robotics and computer-integrated surgery. *Springer handbook of robotics* (2016), 1657–1684.

[45] Michael E Walker, Hooman Hedayati, and Daniel Szafir. 2019. Robot teleoperation with augmented reality virtual surrogates. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 202–210.

[46] Pengxiang Xia, Fang Xu, Zhuoyuan Song, Shuai Li, and Jing Du. 2023. Sensory augmentation for subsea robot teleoperation. *Computers in Industry* 145 (2023), 103836.