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ENHANCING HAPTIC EFFECTS DISPLAYED VIA NEUROMUSCULAR ELECTRICAL STIMULATION

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ABSTRACT

This paper presents an experimental setup and results on enhancing sensations of a common haptic effect –a virtual wall– induced via neuromuscular electrical stimulation (NMES). A single degree of freedom (DOF) elbow platform with position sensing was constructed. This platform supports the arm in the horizontal plane while elbow flexion and extension torques are generated by stimulation of triceps brachii or the biceps brachii muscles. The response of the system was experimentally characterized by determining the latency, and the relationship between stimulation pulse width, stimulation current, joint position and generated output torques. After system characterization, stimulation control methods to enhance haptic sensations were designed, implemented and pilot tested under a variety of virtual wall hit scenarios. Our results indicate that the wall hit trajectories and interaction were improved by control laws that initiated low intensity stimulation prior to the wall hit and utilized co-contraction for damping. The "priming" of the muscle with low intensity stimulation prior to the main stimulation improved the responsiveness of muscle contractions.

1 Introduction

Neuromuscular electrical stimulation (NMES) has been used in various medical applications since as early as 1960s [1,2], most notably as part of neuroprostheses that assist spinal cord injury patients in various motor functions such as grasping or avoiding drop foot [3,4]. In these applications, the technology is more commonly referred to as functional electrical stimulation (FES), referring to the functional movements that are generated. Additional applications of NMES/FES include stroke and spinal cord injury rehabilitation, and majority of the knowledge gained about NMES has been through studies on medical applications.

Recently, there has been interest in using NMES for haptic feedback. Electrotactile feedback, which uses stimulations above only the sensory threshold of receptors in the skin, has been previously used to provide feedback information from a hand prosthesis [5, 6] or a remote environment during teleoperation [7]. NMES for haptic feedback, on the other hand, uses stimulations over motor threshold to induce force and movement (proprioceptive) sensations and is significantly less explored.

Kruijff et al. [8] proposed and presented an initial evaluation of NMES-based haptic feedback, and collected qualitative input from users on pain, frequency of reaction loss, intensity/amount of feedback, excitement level and usefulness scales, with positive results on average and in general. As is the case with medical applications, need for frequent calibration was reported as a challenge.

As exemplified by the work by Pfeiffer et al. [9], majority of the work in NMES-based haptics have thus far focused on improving immersion into gaming systems, such as Nintendo Wii and Microsoft Kinect. The same research group also looked into improving virtual pointing and virtual hand selection and providing route guidance (directional cueing) by incorporating NMES-based haptic feedback [10–12]. Lopes et al. have also completed multiple studies on NMES-based haptic feedback, as a method to increase realism and immersion of effects in games for mobile

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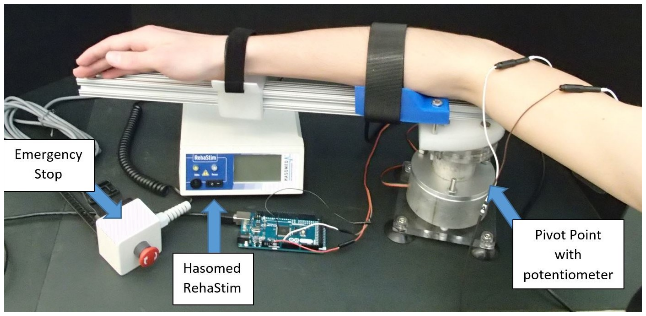

FIGURE 1: Single degree-of-freedom elbow platform developed for characterization experiments and virtual wall hit trials.

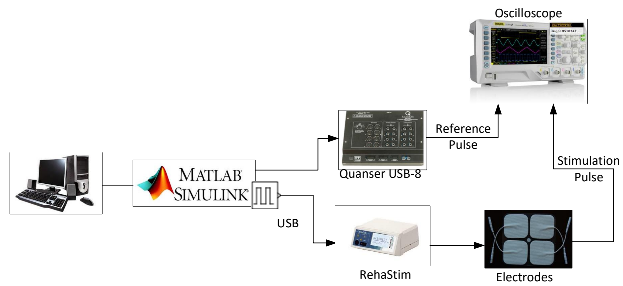

FIGURE 2: Experimental setup configuration for latency characterization.

devices [13] or more recently for virtual reality headsets [14], where NMES was combined with solenoids to render impact sensations. Finally, Lopes et al. have also presented a study using NMES for communicating information on dynamic use of objects (affordances) to users [15]. An example is stimulation of forearm muscles in a pattern to convey a “shaking” sensation, so that a spray paint can, when grasped, can indicate to the user that it should be shaken before use.

There is significant potential for using NMES as a haptic feedback interface in applications beyond gaming and affordances. NMES-based haptic feedback can be employed to provide grasp force information from a hand prosthesis to its user. NMES can actually provide this information in a more intuitive way due to matching the modality (force) of the original signal, and without requiring invasive neural interfaces [16]. In a different application scenario, NMES can provide haptic feedback during teleoperation of an unmanned vehicle or a robot, and in the form of a completely wearable, lightweight and energy-efficient haptic interface, in contrast to bulky and power hungry exoskeletons. Finally, NMES can enable augmentation or enhancement of the human sensorimotor capability or motor skill. For example, NEMS can be used to implement resistive forces to reduce movement variability [17] or virtual fixtures/walls that can reduce movement errors or restrict motion in specific directions in delicate tasks [18–20]. However, much work remains to be completed before such applications can be realized.

In this paper, our goal has been to implement and enhance sensations of a common haptic effect –a virtual wall– induced via neuromuscular electrical stimulation on the elbow joint. A virtual wall effect was pursued since it can be used as a building block for various NMES-based haptic feedback or sensorimotor augmentation applications. Particularly, we developed an experimental setup to conduct virtual wall hit trials and to design and test controllers to improve the response of virtual wall hit trajectories and sensations. We have looked into effects of stimulation current (mA) and pulse width (μs) parameters on elbow torque. While similar parameters were studied within the context of haptic effects by Lopes et al. [13], our work aimed to provide a characterization within the context of our specific hardware, stimulator, and electrode properties. Using these characterization results, our main focus has been on development and pilot testing of stimulation control methods to enhance haptic virtual wall effects.

2 Problem Description

Implementing virtual walls or fixtures using NMES poses multiple challenges. First, a highly responsive computer controlled stimulation system with minimal time delay (preferably on the order of 1ms) is necessary to enable smooth force feedback. Second, a characterization and calibration of human-in-the-loop system needs to be completed to identify the torques generated by the system under varying stimulation control parameter values. Finally, stimulation control laws for creating a virtual wall haptic effect need to be defined, tested and refined to improve the wall hit sensations. We have conducted experiments to study and pursue all three problems.

The remainder of this paper is organized as follows: Section 3 presents the experimental setup, and methods used in (1) characterization of stimulator latency, (2) effect of stimulation parameters on torque output and (3) virtual wall control laws and wall hit experiments. Section 4 presents and discusses the results obtained. Section 5 concludes the paper.

3 Methods

3.1 Experimental Setup

To characterize effects of stimulation parameters and elbow joint position on generated torques, and to conduct virtual wall hit trials, we have built a single degree-of-freedom elbow platform, shown in Fig. 1. The platform is made up of a thrust and a sleeve bearing supported pivot that incorporates a potentiometer (Midori Green Pot), to measure angular position of the elbow. The potentiometer is read into a PC using a Quanser Q8-USB data acquisition board. Quanser QuaRC, together with Math-

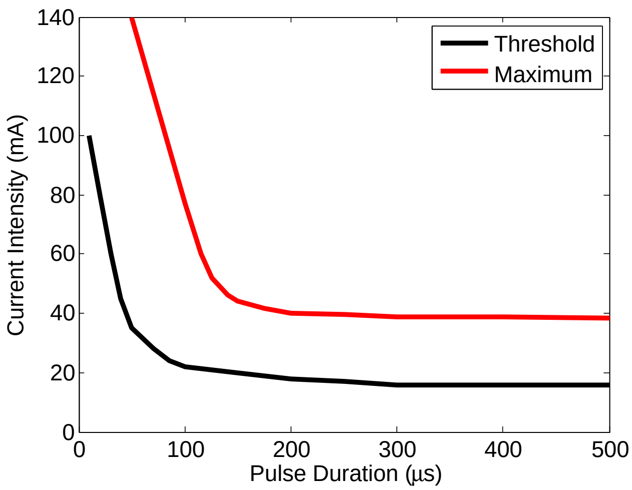

FIGURE 3: Plot showing current and pulse width combinations for minimum (contraction threshold) and recommended maximum (to avoid pain) stimulation levels. These plots are recreated from [21].

works Matlab Simulink is used for data acquisition and control software implementation. We developed custom Simulink code for interfacing the Hasomed RehaStim neuromuscular electrical stimulator, using USART communication protocols over USB. Adhesive, hydrogel stimulation electrodes were placed on the triceps brachii muscle during the experiments.

3.2 Characterization of Stimulator Latency

The setup for latency characterization included the standard experimental setup and an analog output channel of Quanser Q8-USB for reference pulse generation, as depicted in Fig. 2. A Rigol oscilloscope was used to measure the latency between the reference pulse, triggered simultaneously in software with a stimulation pulse train, and the first pulse generated by the stimulator. For this characterization, a wide range of stimulation patterns can be used. As a practical choice, a stimulation pulse width and current combination that was below functional muscle contraction levels was selected, following the minimum threshold and recommended maximum stimulation level plots provided by Baker et al. [21], recreated here in Fig. 3. Particularly, the pulse width of the stimulator was set to 40 μs and the current took values between 0 mA to 20 mA alternating at 0.5 Hz.

3.3 Characterization of Effects of Current, Pulse Width, and Elbow Joint Angle on Torque Output

The setup for this characterization consisted of the standard setup, and a Futek single degree-of-freedom load cell to measure the response of the triceps muscle to different stimulation parameters (see Fig. 4). One side of load cell was attached perpendicular to the elbow platform and the other side was constrained to a fixed surface using a wire. In these characterizations, we stimulated the triceps muscle, allowing elbow extension, which placed the load cell in tension.

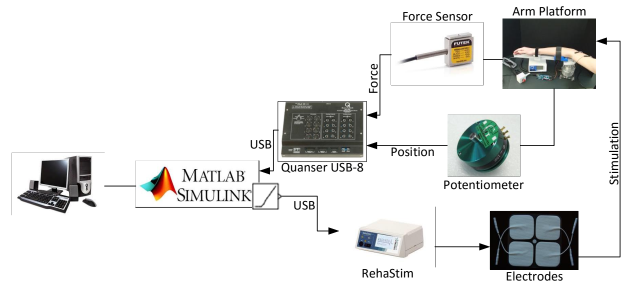

FIGURE 4: Experimental setup configuration for characterization of effects of stimulation parameters on elbow extension torque.

For the first set of trials, the current was set to ramp linearly from 0 to 80 mA. These trials were performed at pulse widths of 25, 35, and 45 μs. The second set of trials ramped the pulse width from 0 to 300 μs, while keeping current at 25 mA, 30 mA, and 35 mA for each trial. For all tests, the force being generated by the stimulation was recorded and converted to torque at the elbow. We defined the elbow angle as the angle between the forearm and the upper arm. The two aforementioned trials were then repeated at elbow angles of 75°, 90°, and 105°. Each test was ran at an angle within $\pm$ 5° of the desired angle and was held fixed during each test. A five minute rest period between tests was included to prevent muscle fatigue from affecting the force output [22]. These current and pulse width values were chosen within the light of the suggested values by Baker et al. [21] (see Fig. 3) and with the purpose of obtaining a linear torque response as much as possible, and not based on chronaxie values.

At the beginning of characterization tests, the parameter being ramped began at zero. As this parameter crossed the stimulation threshold, the muscle began to create force. The parameter continued to ramp until it reached the preset maximum values and the test ended before the stimulation parameters reached values that fall beyond the maximum (pain) levels in Fig.3.

3.4 Virtual Wall Hit Experiments

The setup for the experiments consisted of the standard setup, and made use of the potentiometer for elbow position measurement. For every test, one set of stimulation electrodes were placed on the triceps in the same manner as previous experiments. A second set of stimulation electrodes was placed on the biceps for a portion of the trials that involved stimulation-induced co-contractions. For all trials, a virtual wall was simulated via NMES at 90 degrees elbow flexion angle. A single participant completed all wall hit trials. The participant was instructed to approach and hit the walls with an approximately uniform velocity, and once in contact with the wall, keep pushing towards the wall at a low force level, held as constant as possible. All scenarios were ran at a stimulation pulse width of 35 μs, which provided closer to linear torque responses than 25 μs and 45 μs.

Limitations of a strict on-off control law for implementing virtual walls were significant, and therefore it was excluded from the test scenarios. On-off controllers led to strong but often too late contractions, leading to significant "bounce-back". Tested scenarios considered alternative controllers to avoid bounce-back and improve the wall hit sensation.

The first set of experiments considered four different scenarios based on pilot testing with the stimulator and results of torque characterization.

The first scenario introduced the concept of a "pre-wall". The idea is to start the stimulation prior to actual wall penetration to prevent sudden and somewhat late stimulations. This "pre-wall" was used to reduce the delay in the system response allowing for a more responsive system via stimulation. Through experimentation, a good value for the pre-wall angle was determined as 9° prior to the wall. The current for the pre-wall was chosen at a level that would be noticeable by the user but low enough such that force produced was minimal or zero. This current would then be ramped up at a rate reaching the maximum stimulation current of 80 mA at the wall. This method can be considered as "priming" of the muscle shortly before the actual stimulation demanding a fast force response, improving system responsiveness and rise time.

The second scenario involved starting the stimulation at the wall angle with a steep ramp of current (proportional only control) to the maximum stimulation current. This scenario constitutes a nominal scenario that is similar to virtual wall implementations found in traditional haptic interfaces, where the proportional control gain corresponds to wall stiffness [23]. The control law for the triceps stimulation current I_{stim} corresponded to

$$I_{stim,triceps} = \begin{cases} K(\theta(t) - \theta_{wall}), & \text{if } \theta(t) > \theta_{wall} \\ 0, & \text{if } \theta(t) \leq \theta_{wall} \end{cases} \tag{1}$$

where K is the proportional control gain corresponding to the virtual wall stiffness, θ_{wall} is the location of the virtual wall and $\theta(t)$ is the position of the elbow joint at any time instant t.

The third and fourth scenarios repeated the same procedure and setup as the first two, with the addition of biceps stimulation. The motivation of this addition was to help reduce the oscillations in wall interactions through increased damping via muscle co-contraction [24, 25]. The stimulation parameters for the biceps were set much lower than that of the triceps. This placed the arm under a 25% to 50% asymmetrical co-contraction, creating a damping effect similar to those reported in the literature [24]. The current and pulse width for biceps stimulation were fixed at 40 mA and 25 μs respectively. Incorporation of damping during wall hit is motivated by the wall damping (derivative control) commonly used to improve stability and damping characteristics of wall hits with traditional haptic interfaces [23]. The control law for the triceps stimulation current stayed the same (Equation 1), while a new control law for biceps stimulation current $I_{stim,biceps}$ was added as follows.

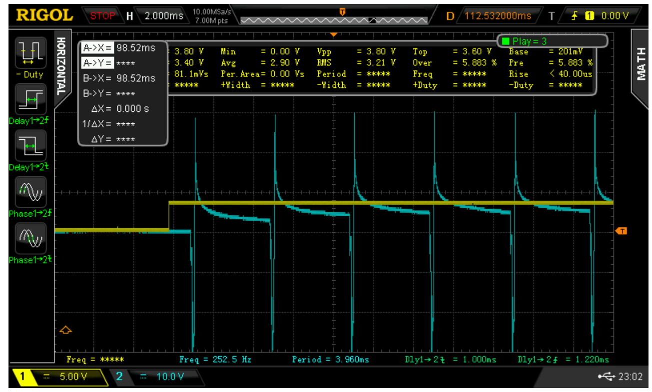

FIGURE 5: Result of the latency characterization. The latency of the stimulator was measured to vary between 1.22 ms to 1.3 ms. This oscilloscope screenshot shows a value of 1.22 ms.

$$I_{stim,biceps} = \begin{cases} 40mA, & \text{if } \theta(t) > \theta_{wall} \\ 0, & \text{if } \theta(t) \leq \theta_{wall} \end{cases} \tag{2}$$

Each of the four scenarios was tested with two approach speeds for the wall hit: approximately 15 deg/sec (slow condition) and 55 deg/sec (fast condition).

The second set of experiments more closely focused on the two scenarios with best outcomes for virtual wall implementation from the first set of experiments. Based on experimental data and user feedback, the first (pre-wall without co-contraction) and third (pre-wall with co-contraction) scenarios were selected as the scenarios that showed the best performance. In the second set of experiments, these tests were repeated, with the addition of simple visual feedback on a monitor for the user. The visual feedback consisted of a plot displaying a horizontal line for the wall, and a running trace for the current arm position.

4 Results and Discussion

4.1 Characterization of Stimulator Latency

In Fig. 5, a screen shot of the oscilloscope showing the stimulation pulse train can be seen as well as the reference pulse. Through multiple tests, the latency between the reference pulse and the stimulation was measured to vary between 1.22 ms to 1.3 ms. This latency is minimal and would be unnoticeable by

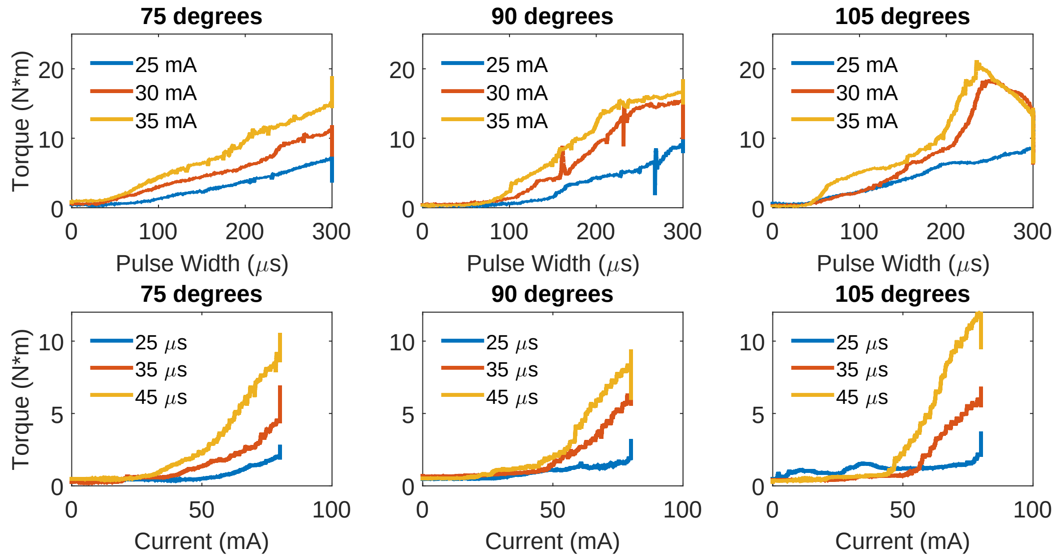

FIGURE 6: Elbow torque generated using NMES on triceps muscle. Top row: pulse width ramps administered at three constant current levels (traces), for three different joint angles (left to right). Bottom row: current ramps administered at three constant pulse width levels (traces), for three different joint angles (left to right). These results are for Participant 1.

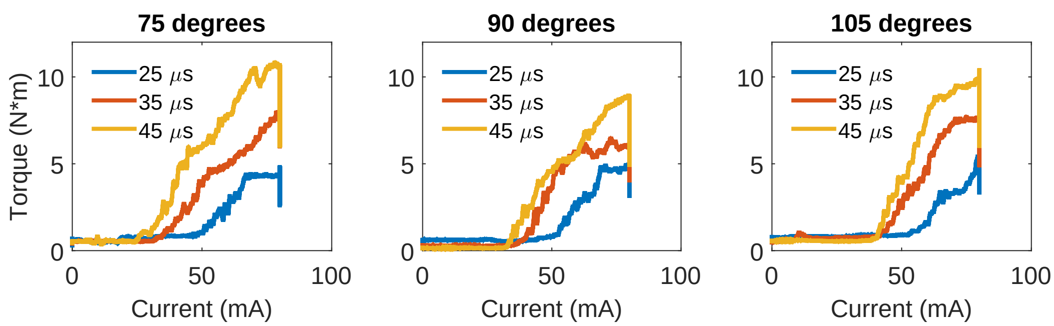

FIGURE 7: Elbow torque generated by administering current ramps on the triceps muscle, at three constant pulse width levels (traces), for three different joint angles (left to right), for Participant 2.

the users. It is important to note that this characterization considers only the delay in command signals to the stimulator and does not take into account the reaction time of the muscle.

4.2 Characterization of Effects of Current, Pulse Width, and Elbow Joint Angle on Torque Output

Plots from a single participant for the resultant torque under the various experimental conditions are provided in Fig. 6. The top row of plots in Fig. 6 shows results of pulse width ramps at three constant current levels and the bottom row shows results of current ramps at three constant pulse width levels. The impact of elbow joint angle on torques can be observed from left to right in each row.

Three additional plots in Fig. 7 present results from a second participant in order to properly adjust the stimulation parameters in preparation for the experiment on using NMES to simulate a virtual wall. When compared with Fig. 6, they provide an illustration of the variability in response to NMES by different users.

The results of this characterization were comparable to similar tests performed by other groups, with the torque increasing as the stimulation pulse width or current was increased. The ramp for the pulse width was able to generate higher stimulation forces; however, the contraction responses were far from linear and not sufficiently isolated. As the pulse width reached higher levels, especially at higher currents, stimulation of other, untargeted muscle groups were observed. On the other hand,

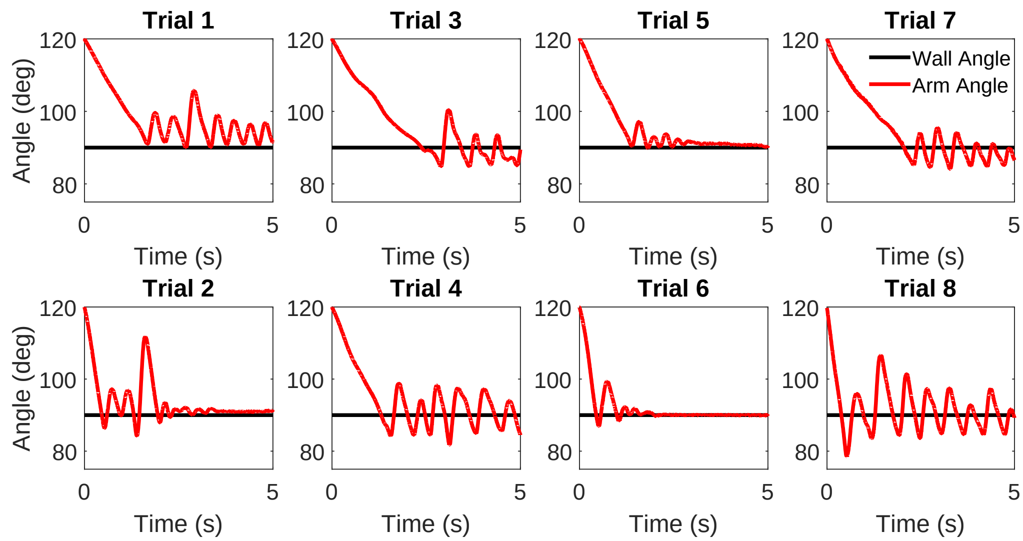

FIGURE 8: The first set of trials showing wall hit trajectories of all wall implementation scenarios, without visual feedback, and approaching slow (top row) and fast (bottom row). See text for details of conditions/controllers for each trial.

stimulation with a current ramp at constant pulse width levels generated more linear contractions, isolated within the targeted muscles. Both test participants reported that the stimulations felt uncomfortable during the tests with a pulse width of 45 μs and a current ramp of 0-80 mA. A change of $\pm$15 degrees in joint angle did not alter the torque output significantly.

It should be noted that electrode placement constituted an additional source of variability. When the electrodes were placed sufficiently close to the motor point, the relationships between the variables were similar and consistent, but the maximum torque generated by each participant was different. This inter-participant difference in torque can be observed by comparing Fig.s 6 and 7.

4.3 Virtual Wall Hit Experiments

The plots in Fig. 8 present wall hit responses under the four different scenarios in the first set of experiments. Trials 1 and 2 correspond to the first scenario with a pre-wall at 9° before the wall and no biceps stimulation (co-contraction). Trials 3 and 4 correspond to the second scenario with no pre-wall and no biceps stimulation (nominal proportional only control). Scenario three shown in trials 5 and 6 is the same as the first scenario, except the biceps were also stimulated. Trials 7 and 8 show the fourth scenario which involved biceps stimulation as well, but the pre-wall was removed. Trials 1, 3, 5, and 7 show a slow approach while the other trials show a fast approach speed to the wall. These experiments were completed by Participant 2.

The plots in Fig. 9 present the results of the second set of experiments. These results mirror the conditions in scenarios 1 (pre-wall, no co-contraction) and 3 (pre-wall, with co-contraction) from Fig. 8, however, they were ran allowing the participant to have visual feedback of their current position and the wall position on a computer screen.

Of the four scenarios, the two with the pre-wall performed the best at rendering a virtual wall hit with minimal penetration and oscillations using NMES. Trials 3-4 and 7-8 for stimulation without the pre-wall clearly show that the user experienced a significant amount of penetration into the wall. Additionally, the oscillations due to the wall hit lasted much longer in scenarios without the pre-wall. Without the pre-wall, the stimulation's sudden start at a relatively high current level led to the significant number of oscillations. The pre-wall allowed for a more gradual current ramp so that the muscle was not immediately subject to the maximum stimulation. Such "priming" stimulations of the muscle to improve responsiveness of contractions has the potential to find applications beyond inducing haptic effects, such as in FES, where fast responses to stimulation can play an important role in controllability and tracking considerations [26,27]. It can also be used in conjunction with delay-compensating controllers for improving FES tracking performance [28].

Anecdotally, biceps stimulation was also preferred by the test participant as more closely simulating a virtual wall. It can be seen in trials 5-6 that significantly less oscillations occurred due to the damping of the motion through biceps stimulation. However, it was also noted that the co-contraction-based damping did not have much effect in the fourth scenario. This led to the conclusion that the effect of the pre-wall was more important in implementing virtual walls than the added damping effect

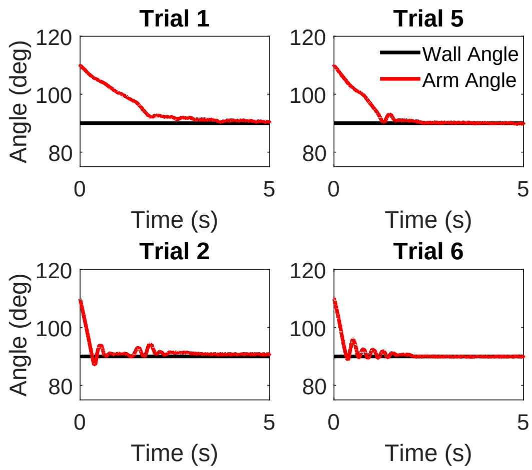

FIGURE 9: Second set of wall hit trials using the best scenarios for wall hits, with addition of visual feedback. Slow approach (top row) and fast approach (bottom row). Trials 1 and 2 include the pre-wall. Trials 5 and 6 include both the pre-wall and damping based on co-contraction.

of co-contractions. The biceps stimulation improved the virtual wall hit effects, but only when the pre-wall method was used. This might be due a relative ineffectiveness of damping when the oscillations grow beyond a particular level.

The results of the second set experiments indicated that addition of visual feedback further improved the virtual wall hit trajectories. The interactions in this condition show minimal wall penetration and further reduction in oscillations. Anecdotally, the test participants also reported enhanced experience and realism of the haptic interface when visual feedback was included.

It was observed that the lack of physical touch/contact sensation limited the realism of the interactions. Nevertheless, our results present novel control methods that improved the performance of NMES in implementing a virtual wall haptic effect. The particular mechanisms behind pre-wall's (or priming's) ability to enhance responsiveness of muscle contractions via stimulation warrants further study. A more comprehensive evaluation and comparison of NMES-based haptic effects can be conducted by experiments involving a commercial haptic device in comparable conditions and scenarios. Additional exploration can also look into other haptics effects, beyond a virtual wall, such as viscous friction, virtual springs, or various resistive or assistive fields. Indeed, Kurita et al. have recently provided results from successful haptic display of varying virtual stiffness values using NMES [29]. Also, NMES can be utilized to complement or enhance the haptic effects of traditional force feedback interfaces, as part of a hybrid system.

5 Conclusion

Control methods to enhance NMES-based virtual wall hit effects was proposed and tested. Current modulation for control of muscle forces was preferred over pulse width modulation, due to more linear and consistent response behavior obtained by experimental characterization. Implementation of a "pre-wall", a region with low intensity stimulation as one approaches the wall was proposed, implemented, and shown to improve virtual wall hit trajectories and interaction. Addition of damping via NMES induced co-contractions was also found to improve the sensation, however only when used in combination with the pre-wall. Addition of visual feedback further enhanced the realism and dynamics of the wall hits.

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