Proposing a framework for evaluating haptic feedback as a modality for velocity guidance

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Abstract— **Current approaches to motion guidance with haptic feedback largely focus on correcting errors in position. Yet, for applications such as rehabilitation, there are advantages to adding velocity guidance. In this paper, we present an experimental platform designed to evaluate haptic feedback as a feasible modality for velocity guidance. This wearable platform consists of two vibration motors actuated via a microcontroller in response to changes in angular velocity of a user's upper limb. The system produces vibrotactile stimuli with intensities dependent on the difference between the participant's velocity and a prescribed velocity profile. The observations made through this analysis will enable future studies into the role of haptic feedback in velocity modulation. Coupled with existing work in trajectory guidance, this system holds the potential to enable more robust motion guidance.**

I. INTRODUCTION

Rehabilitation for individuals with impaired motor control remains a challenging issue with inadequate solutions [1]. The benefit to patients of a high-intensity, task-specific rehabilitation approach suggests the need for robotic assistance [2]. In particular, wearable haptic interfaces have shown significant promise within this area as they provide an intuitive and instantaneous feedback modality for motion guidance without need for extraneous equipment or the constant presence of a physical therapist [3]. The ability to perform physical therapy exercises with a wearable system providing real-time feedback could increase patient adherence to treatments and improve motor learning by increasing the accessibility to and frequency of treatments. This leads to better patient outcomes, shorter recovery periods, and a lowered chance of re-injury [2].

Existing motion guidance systems providing haptic feedback primarily track and provide feedback for position guidance. However, for stroke patients, increased velocity of motion has been found to have positive impact on recovery times and return of motor control [4], highlighting the importance of velocity guidance for rehabilitation. Current velocity guidance solutions rely heavily on other forms of feedback such as visual and auditory cues [5], [6]. In current research, it is unclear if haptic feedback is a more suitable alternative to these other modalities for velocity guidance. Here, we propose a wearable haptic display designed to evaluate the effectiveness of haptic guidance as a feedback mechanism for velocity guidance. The intent is to investigate the utility of tactile feedback for velocity guidance. In what follows, we describe the mechanical design of our device and the proposed haptic guidance algorithm, along with a brief evaluation of the system.

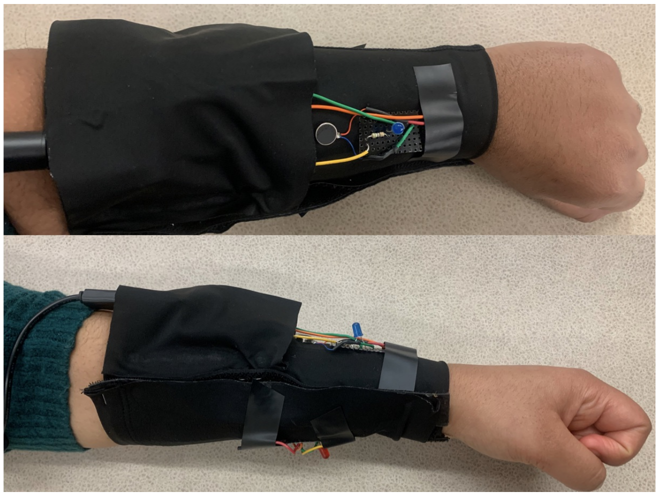

Fig. 1. Adjustable haptic guidance wearable consisting of a Raspberry Pi and IMU in a sleeve, vibration motors, and LED's

II. METHODS

A. Mechanical Design

We have designed a 1-DOF wearable haptic guidance device about the shoulder that consists of two vibrotactile actuators controlled by a Raspberry Pi Zero W (RPi) microcontroller. An Adafruit BNO055 inertial measurement unit (IMU) tracks changes in angular velocity and rotational position. The vibrotactile actuators, RPi, and IMU are sewn into an adjustable compression sleeve that can be fit to the lower arm for user comfort. The increased portability and adaptability of wearable devices to the user have proven to be successful in supporting improved function in rehabilitation and prosthetic applications [7]. We selected vibrotactile feedback as the initial modality for evaluating the efficacy of haptic feedback for velocity guidance as it has been proven to be successful in providing motion guidance within wearable devices [8], [5], [9]. The vibrotactile actuators are placed such that they lie on opposite sides of the forearm to most closely replicate human touch based guidance [5] (Fig. 1).

B. Processing Algorithm

A key component of this design is the real-time velocity monitoring and tactile feedback algorithm. Here we outline the proposed process in further detail.

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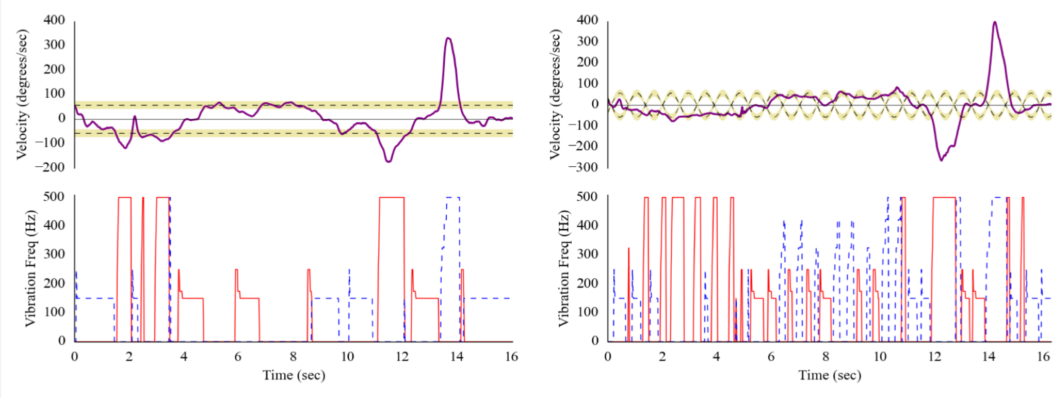

Fig. 2. System performance under constant target velocity (left) and a sinusoidal velocity profile (right). The dashed black lines represent the target velocity profile, red line represents posterior motor activation, blue dashed line represents anterior motor activation, the purple solid lines depict the participant's measured velocity. The yellow bands represent the "target velocity" ranges. If the participants velocity is within this range, the motors will be off.

1) Initialization: During the initialization phase, participants will be asked to hold their arm parallel to the floor at shoulder height maintaining a rigid elbow to enable calibration of the IMU. Holding the elbow rigid ensures that the angular velocity data collected is from the extension and flexion from the shoulder of the arm. They will then be asked to move their arm in a single degree of freedom about the shoulder joint to establish each participant's minimum and maximum range of motion. No stimuli will be actuated during this phase.

2) Range of Motion: The system will allow participants to move between the minimum and maximum range of angles specified during initialization. Outside of this range, both vibrotactile actuators will be activated to indicate to the participant that they are outside of the experimental range of motion. This range can be modified to each user. For this paper, a full range (-90 to +90 degrees) of 1-DOF shoulder extension and flexion is demonstrated.

3) Velocity Measurement: The system measures angular velocity and Euler angle position data from the IMU at a frequency of 100 Hz. A 3-sample moving average filter is applied to the IMU readings to smooth the velocity signal and remove signal noise. The selected IMU performs on-board data fusion enabling velocity readings to be directly obtained from the sensor output.

4) Vibrotactile Stimuli: As repulsive cues have been found to minimize reaction time [9], our algorithm actuates repulsive vibrotactile cues in response to the deviation of the participant's velocity from the desired velocity using pulse-width modulation commands. The intensity of the stimulus is dependent on a $k = 0.3$ Weber fraction as observed for just noticeable difference (JND) for vibration perception [10]. The relationship is dependent on defined as

$$f_n = \begin{cases} 1 + f_{n-1}, & \dot{\theta}_n - \dot{\theta}_{n-1} > 0 \\ 1 - f_{n-1}, & \dot{\theta}_n - \dot{\theta}_{n-1} < 0 \\ f_{n-1}, & \dot{\theta}_n - \dot{\theta}_{n-1} = 0 \end{cases} \qquad (1)$$

where f is the frequency command sent to the vibrotactile actuator, $\dot{\theta}$ is the difference between actual and desired velocities. Though the exact ranges of perceptibly of vibrotactile cues are still being explored, the minimum frequency threshold was set at 150 Hz while the maximum was set to 500Hz due to prior work [10], [11].

The actuation of either motor of the device is governed by the direction of rotation. If the participant is performing shoulder flexion and moving from the minimum ($\theta = -90$ deg) to maximum ($\theta = 90$ deg) position, the anterior actuator is activated to motivate a decrease in velocity and the posterior actuator is activated to motivate an increase in velocity. Likewise, if the participant is performing shoulder extension and moving from the maximum to minimum position, the posterior actuator is activated to motivate an decrease in velocity and the anterior actuator is activated to motivate a increase. If the user is within the desired velocity range $\dot{\theta}_{desired} \pm 14.3\ deg$, no stimuli will be actuated.

C. System Evaluation

In this preliminary analysis, we evaluated the ability of our system to provide cutaneous stimuli in real-time to a prescribed velocity profile. All analysis was performed with the authors. The algorithm enables the establishment of a fixed desired velocity or a variable velocity profile to be tailored to the participant's needs. To enable system evaluation we have defined a fixed desired velocity of 57.3 degrees/second and a variable velocity profile defined by.

$$\dot{\theta}_{desired} = \sin 5t \qquad (2)$$

where t is time in seconds. As shown in Fig. 2, we assessed the system's ability to apply the appropriate feedback. In future studies, we will test participant's abilities to respond to this instruction as they attempt to follow the prescribed velocity profile.

III. RESULTS AND DISCUSSION

As seen in Fig. 2, the device is able to accurately track the participant's angular velocity in 1-DOF about the shoulder joint and output vibrotactile cues in response to the difference between the participant's velocity and the desired velocity. The left image displays the system's performance with respect to a constant desired velocity while the right displays the performance with respect to a variable velocity profile. The top half of the figure displays the participant's measured velocity over time as compared to the desired velocity while the bottom half displays the activation frequencies of the vibrotactile motors. As shown, when the participant moves at velocities outside of the desired range, the system produces a stimulus in real-time, that increases and decreases in accordance with Weber's Law of Just Noticeable Difference.

There is an average latency of approximately 4 milliseconds between the reading of the sensor data and actuation of the vibrotactile stimulus. However, as Stanley and Kuchenbecker observed, human response time for directional cues is around 0.4 seconds [8]. Therefore, we consider the observed latency inconsequential with respect to a participant's ability to receive and process the feedback in real-time.

The results observed confirm the ability of the device to effectively track velocity and actuate haptic guidance in real-time, enabling the use of this platform as a tool to evaluate the utility of haptic feedback as a means for velocity guidance.

IV. CONCLUSION

In this paper we proposed a wearable haptic display that aims to guide velocity in 1-DOF motion. The results show the feasibility of accurate tracking and guiding of velocity using vibrotactile cues. This preliminary assessment establishes a method to initiate further study into comprehensive motion guidance that includes both position and velocity. By leveraging this platform, it will be possible to explore and compare the effect of multiple haptic feedback modalities on velocity guidance.

Following validation of this platform, realizing the goal of a fully wearable velocity and trajectory guidance mechanism would likely require inclusion of motion prediction algorithms. Such algorithms would reduce the ambiguity caused by delayed reaction times to the vibrotactile stimuli. The implementation of additional degrees of freedom could also expand the application for such a device.

The application of haptic feedback in motion guidance has had significant impact in a variety of applications ranging from rehabilitation [3], to robot-assisted surgery [12]. As it stands, there is a gap in understanding the value of velocity guided haptic displays, specifically in the rehabilitation space. Expanding current motion guidance capabilities to include velocity alongside position opens up the potential for novel and innovative uses in multiple application domains.

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