Pseudo forces from asymmetric vibrations can provide movement guidance.

MSc Thesis: Nihar Sabnis

TU Delft

Pseudo forces from asymmetric vibrations can provide movement guidance.

by

Nihar Sabnis

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Thesis committee:	Prof. dr. ir. D. Abbink,	TU Delft, chair.
	Dr. M. Wiertlewski,	TU Delft.
	Dr. E. van der Kruk,	TU Delft.
	Dr. L. Crespo,	TU Delft, external.

Preface

I dedicate my thesis to the Reality within all of us.

October 2020: My physiotherapist was demonstrating exercises for a chronic shoulder injury I had, via zoom. We could not understand each other - 'movement-wise'. During that time, I had completed a considerable part of reading literature of haptics in sports and rehabilitation. That is when the idea of developing a tactile interface for remote movement guidance first clicked to me. After sharing it with my supervisors, I decided to work on it as my master thesis. The goal was, and still is, to design a channel for tactile communication for remote movement guidance. Initially, I was too ambitious and wanted to create an end to end system which I would scale and implement. But over the past year, I realized the importance of incremental innovation and having one thing which works is better than a system which may or may not work. Despite Covid and probably due to Covid, the last year has been one of the most happening years for me (at least intellectually!). So many things happened from winning a grant, developing a research mindset, haptic rendering, playing with motion capture systems, learning to communicate scientifically, to getting off-track, being overwhelmed, and having sleepless nights because of that one waveform which was so close, but not yet there! Looking back, all I can say is that I learnt tremendously, enjoyed the journey and would love to do it again sometime.

This journey, wouldn't have been possible without the uncountable people who helped me, including those I never personally met. Out of those, I would like to particularly thank my Parents, my sister - Shalvi, friends and family in India and the Netherlands.

Finally, the most important role for the development of my thesis, and even more so in the development of my attitude as a budding researcher, was played by my supervisors. Michael, Eline and David, I am grateful to be a student under your supervision.

Michael, the discussions with you were always profound with a 'touch' of philosophy. They motivated me to keep learning and put into perspective how much there is to learn and explore in the field of haptics. Your enthusiasm during every stage of the research helped to get over research blocks. The 'Haptics team' on Slack is an amazing platform to collaborate, and your enthusiasm flows in it. Thanks for feeling so many weird vibrations until the perfect one. Your input - 'Less is more' will stay with me.

Eline, the weekly meetings with you were a constant platform for ideation, brainstorming and questioning. Those helped to keep me on track and motivated throughout the past year. The questions you asked during those meetings definitely helped me to go deeper in the topic. Thank you for opening up the world of rehabilitation with your connections. Your feedback on my writing used to be intimidating, but it has definitely made me better and confident at scientific communication.

David, your enthusiasm and vision really helped to put the project into perspective. Right from the introduction 2 years ago, the multiple courses and interactions we had, you have always taught us how to tell our stories and present complex research in a simple way to any audience. Thank you for showing how to think creatively and yet be focused. I will always focus on 'building a strong foundation for the house rather than a roof with holes'. Although we met less frequently, I always had a feeling that you were there if needed. Thank you for that!

Until next time...

Nihar Sabnis
Delft, September 2021

CONTENTS

Pseudo forces from asymmetric vibrations can provide movement guidance.

Nihar Sabnis[1], Eline van der Kruk[1], Michaël Wiertlewski[1], and David Abbink[1]

[1]Department of Mechanical Engineering, Delft University of Technology

***Abstract*—When a trainee is (re)learning a skilled movement, physical guidance from a trainer is crucial. Yet, providing physical cues to guide movements is highly challenging when training is digitally mediated (e.g. remotely). This work demonstrates the utility of pseudo-forces generated by a wearable tactile interface for providing non-intrusive movement guidance. First, we developed hardware to generate pseudo forces using asymmetric vibrations, whose frequency and amplitude can be tuned to vary the acceleration of the pseudo forces. Maximum acceleration of 160 m/s^2 is obtained at a frequency of 40 Hz and amplitude of 1. Second, the utility of the generated pseudo forces to provide movement guidance was explored by involving 19 participants in 4 separate experiments: 1) Symmetric and asymmetric vibration comparison, 2) Duration modulation, 3) Amplitude modulation, 4) Frequency Modulation of asymmetric vibration. For every experiment, the elements of movement guidance: direction and joint angular velocity were evaluated. Participants perceive directional cues with 96% accuracy ($P<0.001$), and translate the perceived pseudo forces into directed arm movements, with a uniform joint angular velocity of $14\pm8^\circ$/s, for the duration of the provided pseudo force. The joint angular velocity of the arm movement can be changed until 12°/s with frequency. With these findings, this research provides a foundation for remote guidance of human body movements using pseudo forces.**

***Index Terms*—Movement guidance, pseudo forces, asymmetric vibrations, directional cues, joint angular velocity of movement.**

I. INTRODUCTION

Physical rehabilitation, sports training and fine motor skill learning are all tasks that initially require a trainer to physically guide movements of the trainee. Guiding a physiotherapy movement at the right pace, a gentle push to adjust the elbow during a tennis serve or the optimal wrist angle when writing is crucial for perfection. With physical movement guidance, the trainer controls two prime components of movement: direction and joint angular velocity. While instructors provide movement guidance to students using audiovisual cues [1], [2], tactile cues that stem from physical interaction are unique as they directly engage the trainee's motor learning system. Hence, there is no need for the student to map the instructor's performance [3], [4]. To provide movement guidance using human-to-human touch, the instructor, and the student need to be in the same location. However, physical contact and co-location is not always possible, post COVID-19 or due to difficulty in accessing a distant location. Therefore, a solution that provides remote movement guidance could help in mitigating the limitation of co-location and further the reach of physical therapy and training. Unfortunately, the current state-of-the-art of remote movement guidance systems are limited to monitoring and assessment of movements [5], and do not provide a haptic cues to the user. This limitation is due to the fact that most of the systems are restricted to audiovisual cues and lack a tactile interface to provide movement guidance [6]. Here, we explore the use of haptic cues to shift from remote assessment to remote treatment of movements.

Haptic feedback can provide movement guidance using force and tactile feedback devices [7]. Force-feedback uses physical forces generated by robots (wearables, exoskeletons) to guide users to the required trajectory [8]. However, these systems are expensive (≈ €10,000), bulky (≈ 25kgs), and intimidating to the users, making them inconvenient to use in remote locations [9]. The other approach is to use light actuators that provide tactile feedback to indicate movement cues to the user. Tactile feedback is provided either by using vibration or by deforming the skin. This form of feedback has been demonstrated to be applicable to movement guidance [10]. The vibration feedback devices are compact, light-weight, and low-cost [11]. However, it takes conscious effort to decode the vibrotactile signals and therefore participants focus on decoding the vibration pattern rather than performing the movement [12]. Moreover, vibrotactile devices cannot convey directional information unless several actuators are coordinated spatially or temporally [13]. These devices typically operate around 250 Hz as it corresponds to the peak sensitivity in humans, but over time the stimulation becomes irritating to the user [14]. Alternatively, other devices cause skin deformation due to the pressure of the skin against the device, combined with a lateral movement of the entire device. Skin deformation uses strong, quick and accurate changes in skin strain to provide movement cues but require cumbersome equipment [15].

This paper presents a vibrotactile interface with asymmetric vibrations which create the illusion of non-intrusive pseudo forces pushing against the skin. The first demonstration of the pseudo-force illusion using asymmetric vibration was showcased in [16], [17]. Considerable research is done on different ways of generating pseudo forces, yet no research is found to use them to provide movement guidance. Therefore, in this research, we explore: ***What properties of pseudo forces can be used to guide movements?***

II. DESIGN AND ANALYSIS OF ASYMMETRIC VIBRATIONS

To generate high fidelity pseudo forces, it is important to understand the characteristics of the asymmetric vibration.

A. Working Principle:

Asymmetric vibrations are generated by accelerating a mass with unequal velocities in two opposite directions. One cycle of an asymmetric vibration, consists of a large acceleration peak for a short duration in one direction followed by a small acceleration peak for a long duration in the opposite direction, such that the net acceleration during the cycle remains zero. Humans only perceive the larger acceleration, such the asymmetric vibrations in succession provide a compelling sensation of being pulled in the direction of the larger acceleration.

B. Asymmetric vibration design:

The asymmetric vibrations are generated using the equation of motion of the moving mass described in [18] with certain modifications. An amplitude factor, A was used as a pre-multiplier. The equation of the asymmetric vibration is as follows:

$$\begin{aligned} x = A \cdot [(r \cos \omega t + \mu(d - r \cos \omega t) \\ + \sqrt{l_2^2 - \{r(\mu - 1) \sin \omega t\}^2})] \end{aligned} \tag{1}$$

where,

$$\mu = \frac{l_1}{\sqrt{r^2 + d^2 - 2rd \cos \omega t}} \tag{2}$$

and,

$$\omega = 2\pi f \tag{3}$$

In equation (1), x is the displacement of the slider. Acceleration values of the slider are obtained by double differentiating the displacement x. In the above equations, r, d, $l1$, $l2$ are the lengths of the swinging slider crank mechanism as described in [18]. The frequency f is calculated as follows:

$$f = \frac{1}{T} \tag{4}$$

where T is the cycle time.

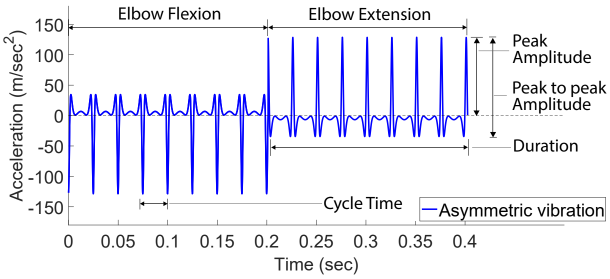


Fig. 1: *Asymmetric vibration parameters, namely: peak amplitude, peak-to-peak amplitude, cycle time and duration of the vibration.*

In Fig. 1, asymmetric vibration for elbow flexion and extension using the asymmetric vibrations are depicted with their peaks in the downward and upward direction respectively. Moreover, the duration of the vibration, the cycle time, the peak amplitude and the peak-to-peak amplitude are shown.

C. Asymmetry Index:

To quantify the asymmetry of the vibration, we define the Asymmetry Index AsI as the ratio of the peak amplitude (A_p) to the peak to peak amplitude (A_{pp}). The AsI is as follows:

$$AsI = \frac{A_p}{A_{pp}} \tag{5}$$

In the preliminary experiments, participants perceived higher pseudo force when the asymmetry index is greater. The peaks in the opposite direction, adjoining the maximum acceleration, decrease the asymmetry index. For experiment 1, the symmetric vibration (control stimuli) is generated based on the asymmetric vibration such that the power during 1 cycle of symmetric and asymmetric vibration is constant for a frequency of 40 Hz. A sine wave was considered as the base function for this symmetric vibration. The symmetric vibration has an AsI of 0.5.

D. Mechanical Analysis:

We use asymmetric vibrations of a voice coil actuator to generate the pseudo forces. Analysing the pseudo force system provides helps to determine the parameters of the asymmetric vibrations required to create a salient pseudo force for guiding movements. The voice coil actuator consists of a permanent magnet suspended inside an electromagnetic coil. The motion of the magnet in the actuator is controlled by a current signal that is sent through the coil of wire, to generate an electromagnetic field. This field repels or attracts the magnet, depending on the direction of the current. If the commanded signal changes rapidly, the magnet moves inside the actuator, creating vibrations that are transmitted through the actuator body to the user's fingers. For an asymmetric vibration, the magnet is accelerated in one direction faster than the opposite direction.

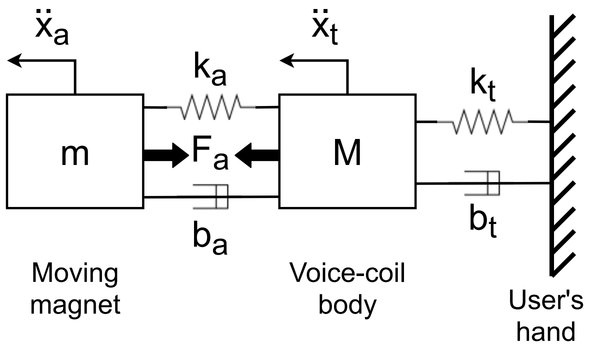


Fig. 2: *Lumped-parameter dynamic model of the linear voice-coil actuator held by a user while the magnet moves relative to the actuator body when the coil is activated.*

The voice coil actuator can be parametrically modelled as a configuration of masses, springs, and dampers as shown in Fig. 2. We assume that the motion of the system is linear. The body of the actuator has mass, M and acceleration, $\ddot{x}_t$ which is held by the user. This interaction is modelled as a spring and damper connected to the user's skin. Similar models have been used to model the human hand holding a tool with spring stiffness k_t and damping factor b_t [19], [20]. The moving mass of the actuator, m has an acceleration of $\ddot{x_a}$, which is suspended from the body of the actuator. This suspension is modelled as a parallel spring-damper pair with spring stiffness k_a and damping factor b_a. By adding the forces on each mass, the corresponding equations of motion for the system are:

$$\begin{aligned} -M\ddot{x_t} = -k_a\left(x_a - x_t\right) - F_a - b_a\left(\dot{x_a} - \dot{x_t}\right) \\ + k_t x_t + b_t \dot{x_t} \end{aligned} \tag{6}$$

$$-m\ddot{x_a} = F_a + k_a\left(x_a - x_t\right) + b_a\left(\dot{x_a} - \dot{x_t}\right) \tag{7}$$

The Laplace transform of the equations of motion yields the transfer function, H, from the force due to the moving magnet, F_a, to the output acceleration on the user's hand, $\ddot{x_t}$.

$$H(s) = \frac{ms^4}{\left(ms^2 + b_a s + k_a\right)\left(Ms^2 + bs + k\right) - \left(b_a s + k_a\right)^2} \tag{8}$$

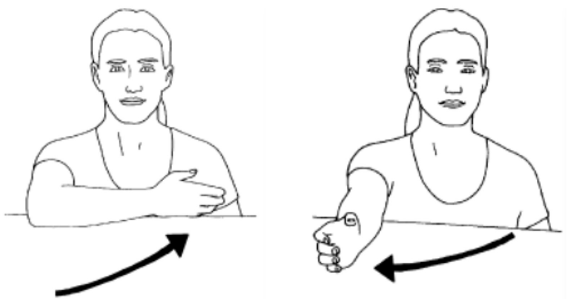
In equation 8, $b = b_a + b_t$ and $k = k_a + k_t$ are used for simplification. The model helps to select system components for desirable performance. The mechanical properties of the skin would affect the k_t and b_t, thus causing a difference in the skin deformation for a constant acceleration of the actuator body. Moreover, the frequency and A of the asymmetric vibrations change the AsI. At a fixed frequency and A, the AsI remains constant for the entire duration. The maximum AsI of 0.62 with a peak acceleration of 160 m/s^2, was obtained for a frequency of 40 Hz and an A of 1. Changing the directionality of the asymmetric vibration reverses the AsI. Based on these observations, we change the directionality of the AsI, keep it constant, and modulate it by varying the A and frequency in 4 separate experiments to evaluate its effect on direction perception and joint angular velocity.

III. Material and Methods

The pseudo forces generated using asymmetric vibrations were evaluated to guide movements, with the following setup:

A. Movement Description

Supported elbow flexion-extension was chosen to evaluate pseudo forces as a mechanism for motion guidance. This movement was selected in collaboration with clinicians due to its importance in activities of daily living (ADL) for stroke patients [21] and because it is a single degree of freedom movement. The participant performing the movement rests their elbow in a fixed position as shown in Fig. 3. The upper arm and forearm are perpendicular to each other, with the forearm parallel to the transverse plane of the body. The palm of the participant is perpendicular to the frontal plane. During the movement, the participant rotates their arm in the same orientation with the elbow as a pivot.



(a) Elbow Flexion (b) Elbow Extension

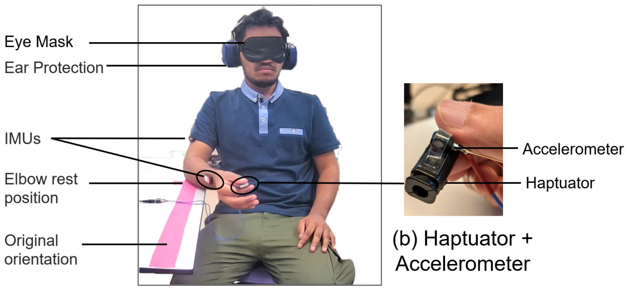
Fig. 3: *Supported elbow flexion-extension movement: (a) Elbow flexion, (b) Elbow Extension. (Physiotools.com)*

B. Apparatus:

A computer with a pre-programmed code written in MATLAB is connected to a data acquisition unit (DAQ Model: NI USB-6215) which generates the vibrations. The output vibration from the DAQ was amplified (Visaton Amplifier 2.2) using an amplifier, with an amplifier gain of 1.6 corresponding to the maximum AsI. One output of the amplifier was provided to Hapcoil One (Actronika) referred to as haptuator. The second output was provided to a techtonic audio exciter attached with an inertial measurement unit (IMU, XSens DOTs) for synchronization. Two DOTs were attached on the wrist and upper-arm of the participants to measure the joint angles and joint angular velocity during the flexion-extension movement. The sampling frequency of the DOTs was 60Hz. The DOTs' readings were recorded with the Xsens DOT application on a mobile phone in real-time. The IMU sensors were calibrated with an infrared motion capture system by Qualisys to quantify the error during measurements. The calibration results showed a root-mean-square error of 2.34 °for elbow flexion-extension movement.

C. Experimental Setup:

The experimental setup consists of a chair and a table on the right side of the participant, Fig. 4. The table was marked with a kinaesthetic tape indicating the elbow rest position and initial orientation of the participants' forearm. Participants wore ear protection (NRR: 37dB), and eye masks to cancel out audiovisual cues.



(a) Setup (b) Haptuator + Accelerometer

Fig. 4: *(a) The experimental setup, (b) Zoomed in view of a participant holding the haptuator with an accelerometer attached.*

The haptuator was placed on the tip of the participant's right-hand thumb, to keep the haptuator tangential to the elbow flexion-extension movement at every point during the movement. Moreover, this region has high density of meissner corpuscles [22], [23], [24], [25]. A medical grade double-sided tape was used to attach the haptuator to the skin, and minimize the relative displacement. An accelerometer (Megitt) measured accelerations of the haptuator.

D. Experiment Overview:

Four experiments were designed to evaluate the effect of the properties of pseudo forces to guide movements. Nineteen (17 males and 2 females) healthy adults, between 22 and 30 years, participated in the experiments. No participants reported any abnormalities to their tactile or kinesthetic sensory systems. None of the participants were involved in this research. The experiments were approved by the local ethics committee. The direction, duration, amplitude, and frequency of the asymmetric vibrations were modulated individually to change the properties of pseudo forces. The default parameters of the asymmetric vibration were: flexion direction, duration of 3s and $A = 1$. A frequency of 40Hz ($f = 40Hz$) was the default based on [26], [27]. The four experiments are as follows:

1) Experiment 1 — Direction Modulation:

To understand if participants perceive directional cues correctly, the direction of the pseudo force was modulated in the elbow-flexion and elbow-extension direction. Each participant was given 4 sets of 24 input vibrations randomly. Each set consisted of 12 asymmetric vibrations (test stimuli) and 12 symmetric vibrations (control stimuli). Both vibrations are shown in Fig. 5.

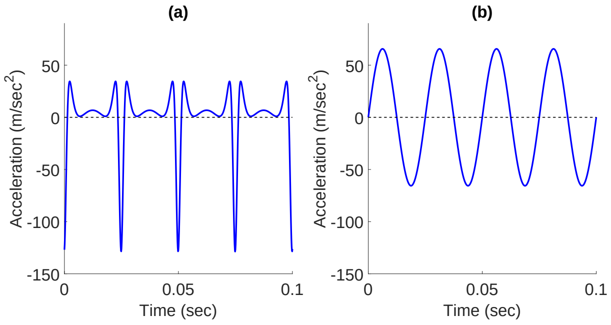


Fig. 5: *Inputs for experiment 1: (a) Asymmetric vibration (test stimuli), (b) Symmetric vibration (control stimuli).*

The verbal responses of the participants were recorded and matched with directional cues generated using the input vibrations. To test the hypothesis of directional cues generated using asymmetric and symmetric vibrations is statistically significant, an independent samples $t-$test was performed. A response is correct if: 'The direction spoken by the participant matches the direction of the provided asymmetric vibration.' Two AFC protocol was used to evaluate the participant responses [28]. The chance and detection threshold were decided to be 50 percent and 75 percent of correct responses respectively using the Spearman–Kärber method [29].

2) Experiment 2 — Duration Modulation:

The goal of this experiment was to understand the effect of changing duration of the vibration on the movement of participants. Three sets of duration—1, 3, 5, 7, 9s of asymmetric vibrations were randomly provided as input and the joint angular velocities of participants were measured. AsI was 0.62.

The time difference between the start of the vibration and the start of the movement was averaged over participants to calculate the 'reaction time to start moving'. The time difference between the end of the vibration and the end of the movement was used to determine the average 'reaction time to stop moving'. The start and end of the vibration was recorded using the audio exciter with IMU and the start of the movement when the joint angular velocity is more than 5 °/s. The end of the movement was recorded when the joint angular acceleration shifts from a positive to a negative value. The joint angles and joint angular velocities during the elbow flexion were calculated with the measured quaternion values. Further analysis included the calculation of the mean and peak joint angular velocities for each participant. The maximum and minimum within participant variation in the joint angular velocities were derived.

3) Experiment 3 — Amplitude factor Modulation:

The goal of the third experiment was to understand the effect of changing A of the asymmetric vibration on the joint angular velocity of participants. Three sets of A: from 0.1 to 3.4 with an interval of 0.3, were randomly provided as input to every participant and the corresponding joint angular velocities were measured. AsI was between 0.4 and 0.6 which shows that A does not influence the AsI significantly, Fig. 6.

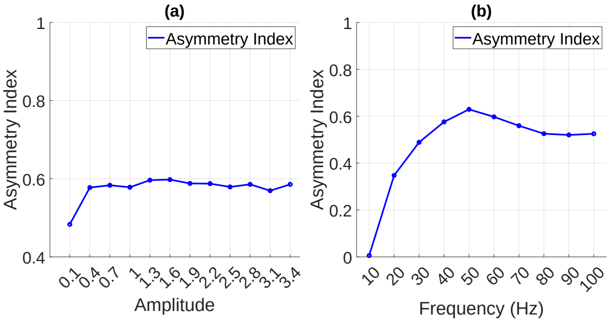


Fig. 6: *AsI values for a) Experiment 3: Amplitude Modulation, b) Experiment 4: Frequency Modulation*

4) Experiment 4 — Frequency Modulation:

The goal of the fourth experiment was to understand the effect of changing the frequency of the asymmetric vibration on the joint angular velocity of participants. Three sets of frequencies: from 10Hz to 100Hz with an interval of 10Hz, were randomly provided as input to every participant and the corresponding joint angular velocities were measured. The frequency influences the AsI as it varies from almost 0 to 0.65. Changing the frequency (f) of the asymmetric vibration using the equation 1, changes the amplitude (A_p) of the asymmetric vibration.

The compensation for this effect was not done using hardware but by conducting experiments 3 and 4 where the difference in results would give the individual effect of frequency modulation.

For experiment 3 and 4, the joint angular velocities during the elbow flexion were calculated for each participant. Non-parametric tests were used for comparing the joint angular velocities corresponding to each A or frequency. The maximum and minimum within participant variation in the joint angular velocities were derived.

E. *Instructions to Participants:*

For experiment 1, the participants were instructed to hold the haptuator and indicate 'Left' (elbow flexion direction) or 'Right' (elbow extension direction) verbally, depending on the perceived direction of pseudo force. If a participant could not feel a direction, they were instructed to randomly select a direction.

For experiment 2, 3 and 4, the participants were instructed to perform two elbow flexion-extension movements to orient the DOTs with the global coordinate system. Moreover, the participants were instructed to strictly "follow the force". If at any point, they stop feeling the force, they were instructed to stop moving. No instruction was given regarding the velocity at which they should follow the perceived force. If the participant would reach the end of the range of motion, and would still feel a force, they were instructed to stay in that position until they stop feeling the force. After every vibration, they were instructed to return to the initial position.

IV. RESULTS

This section describes the results of the 4 experiments conducted with 19 participants:

A. *Experiment 1 — Direction Modulation:*

The mean percentage of correct responses for the test stimuli (48 vibrations per participant), of all participants was 96% with a standard deviation of 4.66%, Fig 7. Hence, as per 2-AFC protocol, the mean of percentage of the correct stimuli for the asymmetric vibrations are above the detection threshold of 75% [29].

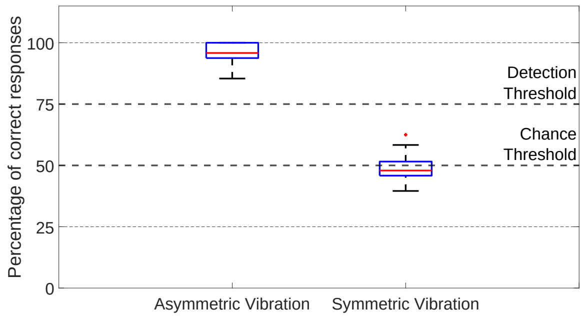


Fig. 7: *Experiment 1: Box plot of correct response rate of 19 participants for asymmetric and symmetric vibrations.*

Whereas for the control stimuli, the percentage of correct responses has a mean of 49% with a standard deviation of 5.61%, which is around the chance threshold. The independent samples t−test was demonstrated significantly better perception of directional cues with asymmetric vibrations compared to symmetric vibrations (t_{36} = 27.9, P < .001).

B. *Experiment 2 — Duration Modulation:*

In Fig. 8, we observe that as the participant starts moving, there is a sudden rise in the joint angular velocity of the participant. The joint angular velocity then reaches a maximum value, after which it continuously decreases until zero, when the participant stops moving. Moreover, the average reaction time of 19 participants to initiate movement is 340ms, with a standard deviation of 130ms. Average reaction time to stop movement for the participants is 300ms, with a standard deviation of 150ms.

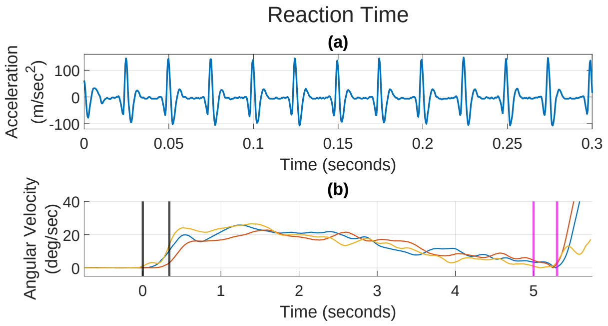


Fig. 8: *Experiment 2: a) Input: acceleration of the haptuator, b) Output: joint angular velocities. The time difference in black lines is the reaction time to start moving, whereas the time difference in magenta lines is the reaction time to stop moving.*

Each histogram in Fig. (9) contains 285 data points (19 participants*3 sets*5 durations). The mean and the peak joint angular velocity is normally distributed (D_{36} = 0.13, P < .001) and (D_{36} = 0.116, P < .001). The average of the mean joint angular velocity during the elbow flexion-extension movement is 14.3°/s with a standard deviation of 8°/s, whereas, the average of peak joint angular velocity is 26°/s with a standard deviation of 14°/s.

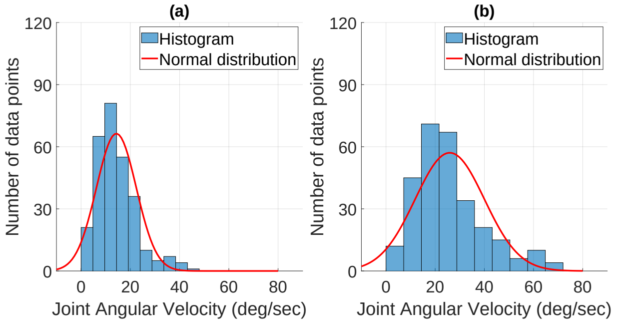


Fig. 9: *Experiment 2: Histogram of — (a) Mean joint angular velocity, (b) Peak joint angular velocity. The red curve is the fitted normal distribution on histograms.*

Fig. 10 depicts the box plots based on 3 sets of data of 19 participants for each duration. The median of the mean and peak joint angular velocities is lower for 1 second and then remains constant for longer duration of pseudo force. The median of mean joint angular velocity is found to increase from 8.5°/s for 1 s to 14°/s, whereas, the median of the peak joint angular velocity increases from 16.3°/s for 1 second to 24.6°/s for longer duration. The variation of the joint angular velocities is uniform over duration. The minimum and the maximum difference in the mean joint angular velocities within participants is 0.76°/s and 7°/s, respectively. Whereas, the minimum and the maximum difference in the peak joint angular velocities within participants is 1.2°/s and 20.25°/s, respectively.

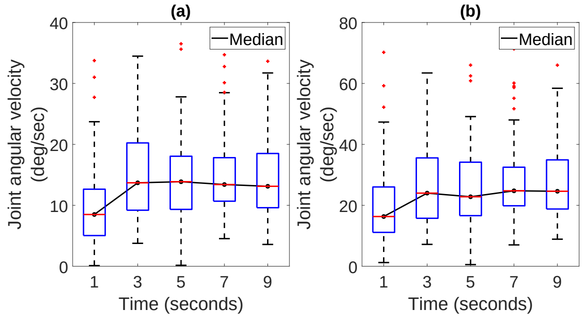


Fig. 10: *Experiment 2: Box Plots of — (a) Mean, (b) Peak, joint angular velocities over different durations. The black line depicts the median for each duration.*

C. *Experiment 3 — Amplitude factor Modulation:*

The joint angular velocity data points for every amplitude factor, are shown in Fig. 11. No particular trend in the change of median of joint angular velocities can be observed. It can be observed that the median of the joint angular velocity has very little variation as the amplitude factor is modulated. The minimum and the maximum difference in the mean joint angular velocities within participants is 0.73°/s and 20.65°/s, respectively.

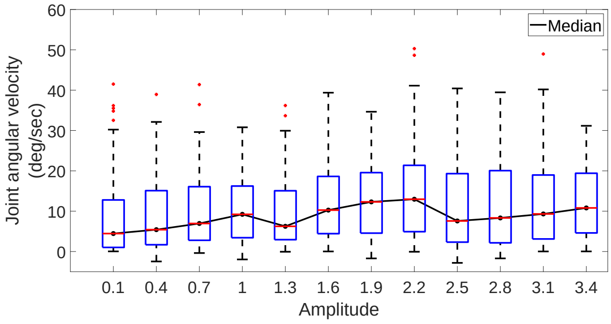


Fig. 11: *Experiment 3: Box Plots of mean joint angular velocities over amplitude. The black line depicts the median for each amplitude.*

D. *Experiment 4 — Frequency Modulation:*

The joint angular velocities at every frequency are shown in Fig. 12. The median of the joint angular velocities start increasing from almost 0°/s value at 10 Hz until it reaches a maximum value of 12°/s at 40Hz and then decreases to a constant value of around 10°/s for values greater than 80Hz. The variation of the joint angular velocities for the group remains analogous over frequencies higher than 30Hz. The minimum and the maximum difference in the mean joint angular velocities within participants is 0.78°/s and 12.71°/s, respectively. This variation of joint angular velocity is found to be less up to a frequency of 70Hz, after which it increases.

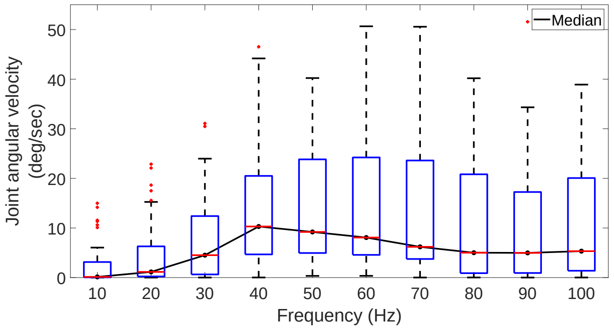


Fig. 12: *Experiment 4: Box Plots of mean joint angular velocities over frequency. The black line depicts the median for each frequency.*

V. DISCUSSION

We evaluated the effect of varying the properties of pseudo-forces as a mechanism to guide movements. The results of the experiments show that participants unambiguously perceive the directional cues generated using pseudo forces. The joint angular velocity of the participants remains constant for longer duration of the provided pseudo force, and the joint angular velocity changes along with the frequency of provided pseudo forces.

A. *Directional guidance:*

Experiment 1 confirms that participants perceive directional cues generated using the test stimuli (asymmetric vibrations) with 96% accuracy, whereas no directional cues can be provided using the control stimuli (symmetric vibrations). This is inline with previous studies in which the correct response rate of the participants was more than 90 %, when asymmetric vibrations were provided [30], [31], [18], [32]. Hence, pseudo forces can guide humans in the desired direction to perform elbow flexion-extension.

B. *Joint angular velocity guidance:*

The results of duration, amplitude and frequency modulation, show that participants translate the provided pseudo forces to movements. Perceiving a pseudo force to dynamically following it involves a combination of the process of skin deformation, perception, cognition, decision-making, and movement. The decision to follow the perceived direction also depends on the understanding of the instructions given to the participants and individual preferences of joint angular velocities to follow the movement. We speculate that the initial acceleration along the perceived direction is a reflex action, and following the pseudo force is a conscious decision taken by the participant.

1) *Maintaining a constant joint angular velocity:*

The median of the joint angular velocity for the group of participants remains constant when the duration of the provided pseudo force longer than 1 second. Since the AsI is constant throughout, the results suggests that participants associate AsI to a particular joint angular velocity. The high variation in this association between participants, although the AsI remains constant, can be explained due to variation in the amount of deformation depending on the mechanical properties of skin (section II-D), the sensitivity of participants to perceive pseudo forces, and how participants translate the perceived forces to joint angular velocities. Whereas for a single participant, the variation in joint angular velocity is low due to a uniform value of skin deformation, sensitivity, and translation of pseudo forces to movement. Moreover, the box plots in Fig 10, show that participants are able to perceive the pseudo force and move even for short duration of the asymmetric vibration. For the group of participants, a normal distribution of the joint angular velocity emerged, since the analysis included a high number of data points. This distribution indicates the joint angular velocity characteristics of the group. Based on these findings, an AsI of 0.62 can be maintained for the desired duration to generate pseudo forces which direct a group of participants with a mean and peak joint angular velocity of $14.3 \pm 8°$/s and $26 \pm 14°$/s, respectively.

2) Changing the joint angular velocity:

The variation in joint angular velocity follows a similar pattern as the variation in the AsI in the modulated range of frequency (10Hz to 100Hz) indicating that participants translate the changes in pseudo forces with different frequencies to joint angular velocities. Participants have high variation and don't associate the frequency of the pseudo forces to homogenous joint angular velocities, as seen in the whiskers of the box plot 12. More data and longer duration of the vibration is needed to model this variation between participants. The high variation at frequencies (>=70Hz) is because at those frequencies, Pacinian corpuscles which lack directional sensing ability [33] dominate, instead of Meissner corpuscles, Moreover, the asymmetric vibration starts becoming symmetric [26]. Hence, the frequency of pseudo forces can be modulated between 0 and 60Hz to control the joint angular velocity between a median of 0°/s to 12°/s, although more data is required to characterize the group behaviour.

C. Joint angular velocity variation due to design factors:

At lower values of A (<=0.4), the asymmetric vibrations have very less peak acceleration. Similarly, at low frequencies (<=30Hz), the asymmetric vibrations are attenuated, which explains the low variation in the joint angular velocities between participants at frequencies (<=30Hz). The attenuation is due to less power generated to oscillate the magnet in the haptuator. Hence, for low A and low frequency, the joint angular velocities being zero is not a perceptual effect but due to the fact that the haptuator is not generating the intended vibration. On the other hand, for higher values of A (>=2.0), the moving magnet in the haptuator reaches the end of its stroke length and hits the ends of the haptuator body, thus vibrating the haptuator in multiple directions. These vibrations interfere with the directional cues generated by the asymmetric vibration, and hence no particular direction is perceived by the participant. Moreover, there can be partial or full slippage of the haptuator on the skin at larger A, which explains the high variation within and between participants' joint angular velocity.

D. Joint angular velocity variation in participants:

The variation of joint angular velocity within participants is due to the changing location and orientation of the haptuator during the trials. Moreover, there is an inherent variation in the dynamics of human movement [34]. It would be interesting to analyse if this variation is within the affordance limit of movement tasks in humans [35], [36].

The differences in the joint angular velocities between participants might be due to multiple reasons. Firstly, the skin deformation depends on the mechanical properties of the skin and the strength of the normal forces against the haptuator [37], [38]. Secondly, the skin displacement is different for participants with some participants being not at all sensitive to skin deformation [37] thus leading to inter-participant variation in the perception of pseudo forces. Further research should investigate the relation between amount of skin deformation to joint angular velocity associated by the participants. Thirdly, following the perceived pseudo force is a cognitive task and hence there can be a difference in how participants process the asymmetric vibration, decide to move, associate the force to a joint angular velocity and actually move. Finally, the finger size and shape varied across participants, and hence a consistent actuator placement is not possible, leading to a possible difference in the skin displacement.

E. Reaction time and joint angular velocity curves:

The reaction times found in our experiment align with literature, wherein, reaction time to vibrotactile stimuli for different tasks was below 500ms [39], [40]. We speculate that the difference between start and end reaction times is due to the difference in complexity of the decision-making processes. The decision to move in the direction of pseudo force with a particular joint angular velocity requires longer time and higher cognitive effort compared to the decision to stop moving. The effect of reaction time to start moving can be observed in Fig. 8 where the median of joint angular velocity for 1 second is less than higher duration of provided pseudo forces. The reaction time needs to be verified with dedicated experiments and should be taken into account while designing a system to guide movements.

Some research describes the pseudo force to be a tactile illusion [27], [41] whereas other research describes that asymmetric vibrations create a physical pulling force [26]. In Fig. 8, a higher rate of change of angular velocity during movement initiation might be due to a higher force requirement from the participant to overcome the static stiffness and damping of the joints. But once the movement is initiated, a lower value of force is required to keep moving. Moreover, the participants decrease their joint angular velocity as they move closer to the fully flexed orientation of the elbow. The sudden movement of the participant after they react indicates that the initial acceleration along the perceived direction is in fact a reflex action, whereas the association to a constant joint angular velocity is a cognitive task. Our experiments strengthen the research that asymmetric vibrations act as a physical pulling force on the participants, at least when the movement is initiated as a reflex action.

F. Implication for movement guidance:

We established the open loop characteristics of the vibrotactile interface using pseudo forces as the input, and the direction and joint angular velocity of the movement as the output. A closed loop system can be achieved by using the same vibrotactile interface as a feedback element in combination with IMU sensors and a PID controller. The coefficients of proportional and derivative terms can be tuned using the results obtained in the duration and frequency modulation experiments. The closed loop system can be used to provide accurate movement guidance.

VI. CONCLUSION

We developed a vibrotactile interface to generate pseudo forces which provide movement guidance and evaluated the system on a group of participants. We found that pseudo forces provide directional cues and control the joint angular velocity of movement. Using pseudo forces, the trainers can guide the movement of trainees in the right direction with an accuracy of 96%. Furthermore, the trainer can move the trainee at a constant joint angular velocity of 14.3 ± 8°/s, by providing pseudo forces for the desired duration. Finally, the trainer can modulate the frequency of the pseudo forces to change the joint angular velocity up to 12°/s. The trainers can thus tune the properties of pseudo forces to provide the desired movement guidance to trainees, even remotely.

VII. FUTURE RESEARCH

Future research should inspect different asymmetric vibrations with higher AsI to generate the pseudo forces. Post experiments, we designed vibrations using the powers of sines which yielded better results for movement guidance, but elaborate experiments are necessary. In Fig. 13, the AsI has a value of 0.83 and there is no immediate damping of the peak as in the asymmetric vibration used in the above experiments. The equation is:

$$V = \left[\cos(0.75\omega t)^{100} - 0.2\cos\left(0.75\omega t - \frac{\pi}{2}\right)^{4}\right] \tag{9}$$

ω is the angular velocity and t is the instantaneous time.

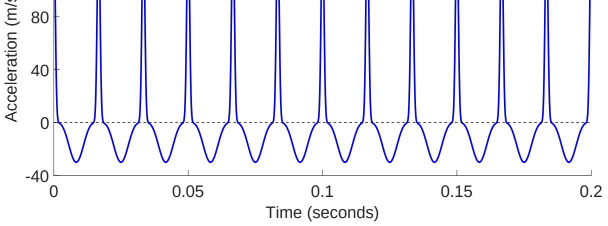


Fig. 13: *Asymmetric vibration using powers of sinusoid.*

The analysis of using multiple haptuators for movement guidance will help to understand how participants perceive multiple pseudo forces simultaneously. Other kinds of actuators should be considered for generating the vibrations since the cost of haptuators (€100 each) is not economically feasible. The vibrotactile interface needs to be evaluated on patients undergoing physical rehabilitation and athletes. Further research should strategically combine the properties of pseudo forces and evaluate participants' responses. Moreover, future research should validate the conclusions of this paper for multiple degrees of freedom movements. Pseudo force as a feedback mechanism to guide users' movement can be the potential next step in remote movement guidance.

VIII. ACKNOWLEDGEMENT

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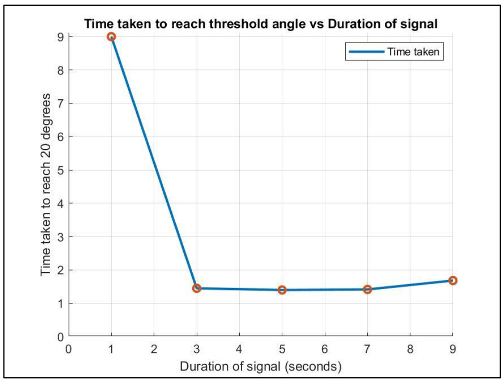
APPENDIX

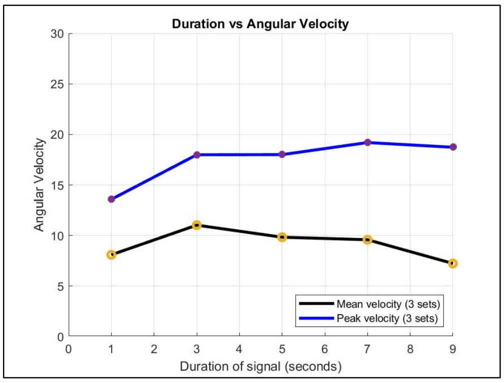
Contents of the appendix:

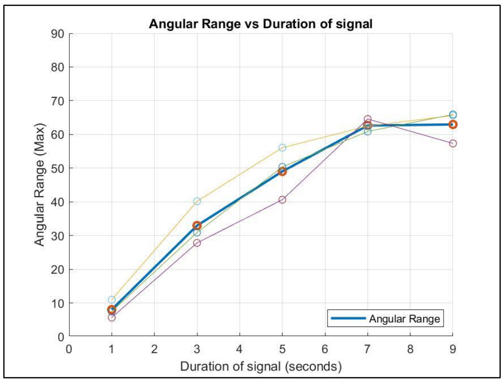
1. Participant data for conditions 2 to 4 for 1 participant each.
2. Extended mathematical model.
3. IMU calibration with infrared motion capture system.
4. Haptic rendering.
5. Final Sleeve pictures.
6. Information Letter for participants.
7. Letter of informed consent.
8. Ethics Approval.

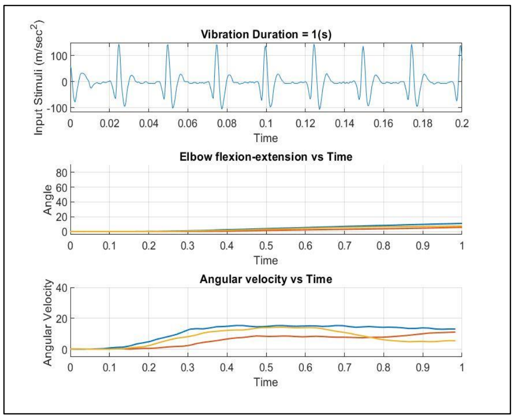
Experiment 2: Duration Modulation

Raw data: Participant 8.





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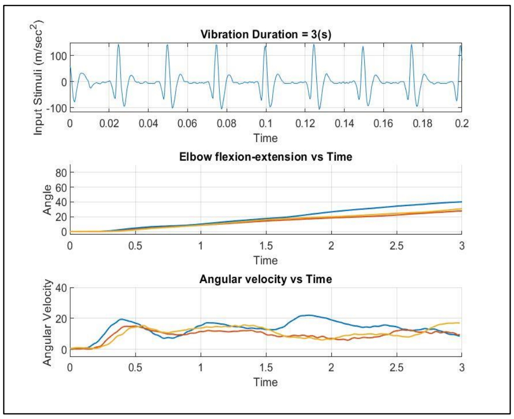
Input Stimuli (m/sec^2)
100
0
-100
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Time
Elbow flexion-extension vs Time
Angle
80 60 40 20 0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Time
Angular velocity vs Time
Angular Velocity
40 20 0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Time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Input Stimuli (m/sec^2)
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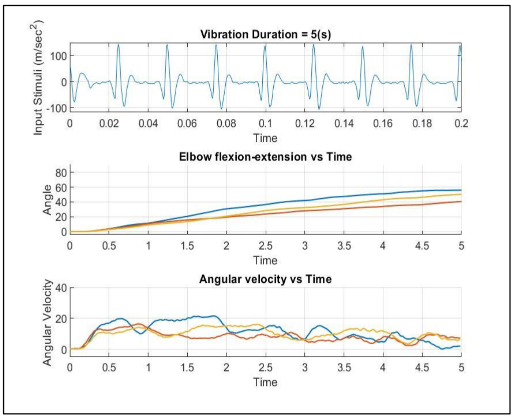
0
-100
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Time
Elbow flexion-extension vs Time
Angle
80 60 40 20 0
0 0.5 1 1.5 2 2.5 3
Time
Angular velocity vs Time
Angular Velocity
40 20 0
0 0.5 1 1.5 2 2.5 3
Time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Input Stimuli (m/sec^2)
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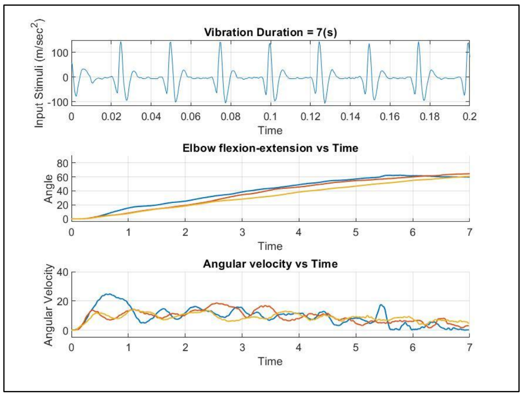
0
-100
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Time
Elbow flexion-extension vs Time
Angle
80 60 40 20 0
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Time
Angular velocity vs Time
Angular Velocity
40 20 0
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Time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Input Stimuli (m/sec^2)
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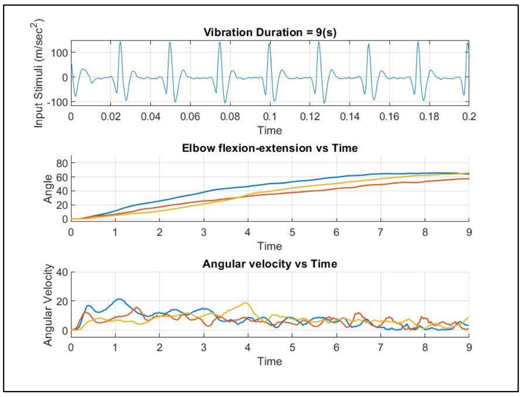
0
-100
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Time
Elbow flexion-extension vs Time
Angle
80 60 40 20 0
0 1 2 3 4 5 6 7
Time
Angular velocity vs Time
Angular Velocity
40 20 0
0 1 2 3 4 5 6 7
Time


Vibration Duration = 9(s)
Input Stimuli (m/sec^2)
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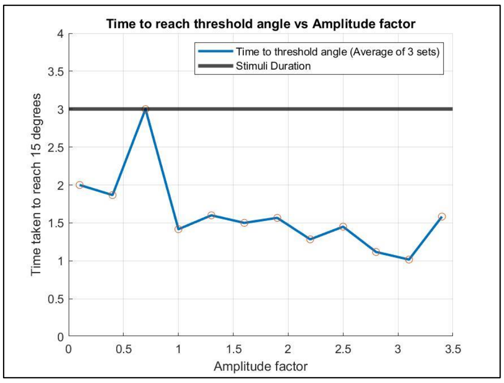
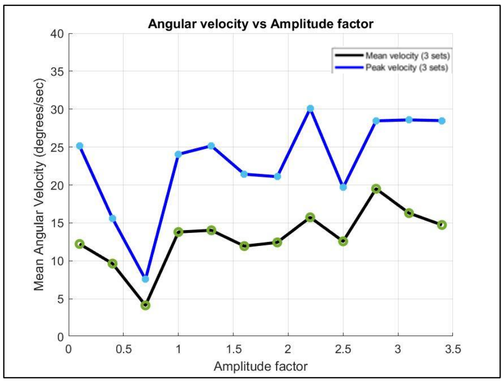
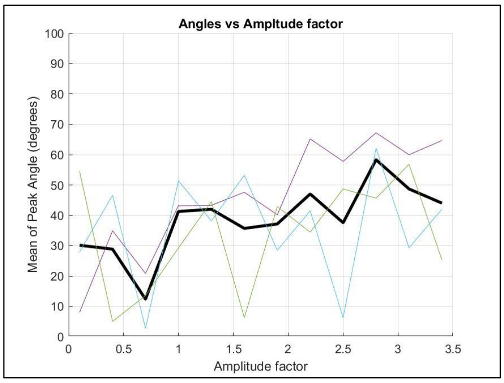
0
-100
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Time
Elbow flexion-extension vs Time
Angle
80 60 40 20 0
0 1 2 3 4 5 6 7 8 9
Time
Angular velocity vs Time
Angular Velocity
40 20 0
0 1 2 3 4 5 6 7 8 9
Time

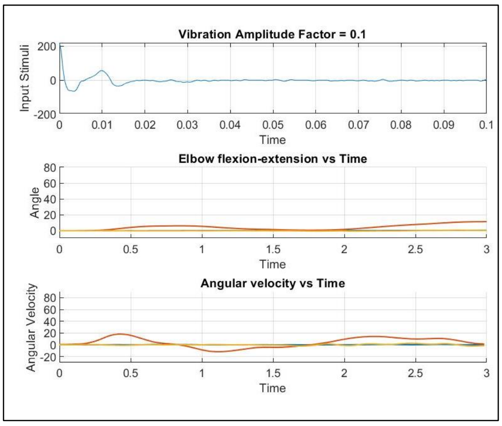
Experiment 3: Amplitude Modulation

Raw data: Participant 15.





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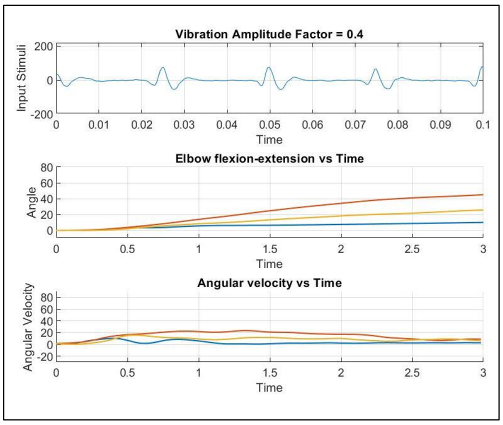
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time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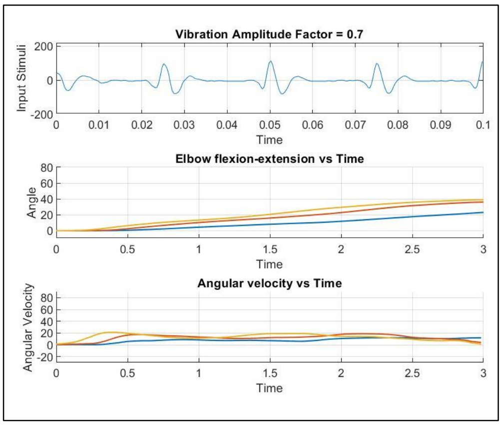
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time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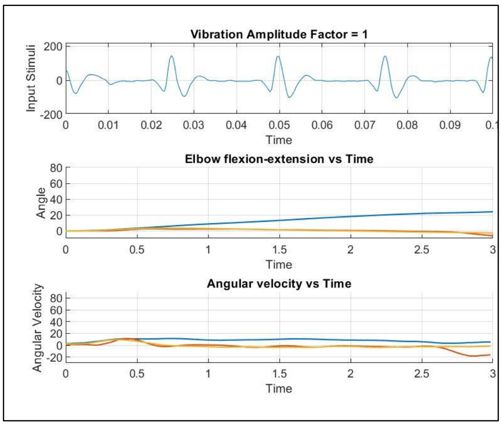
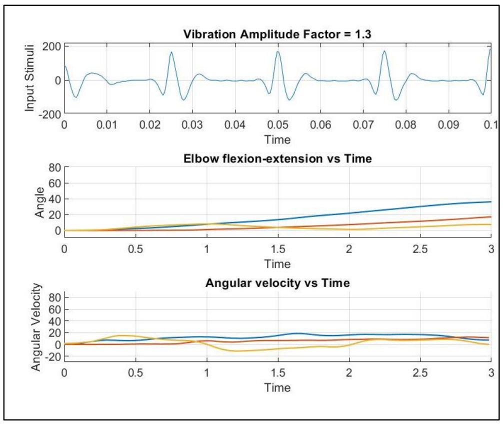
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time


Vibration Amplitude Factor = 1
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time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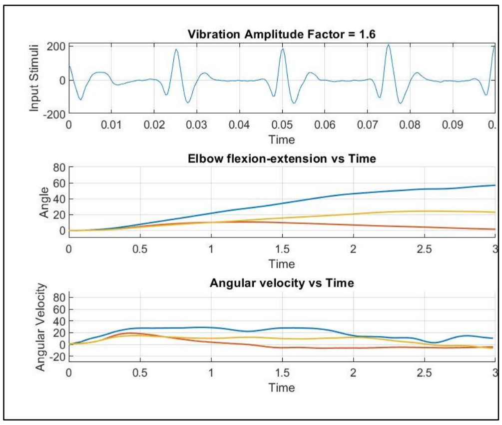
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time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Input Stimuli
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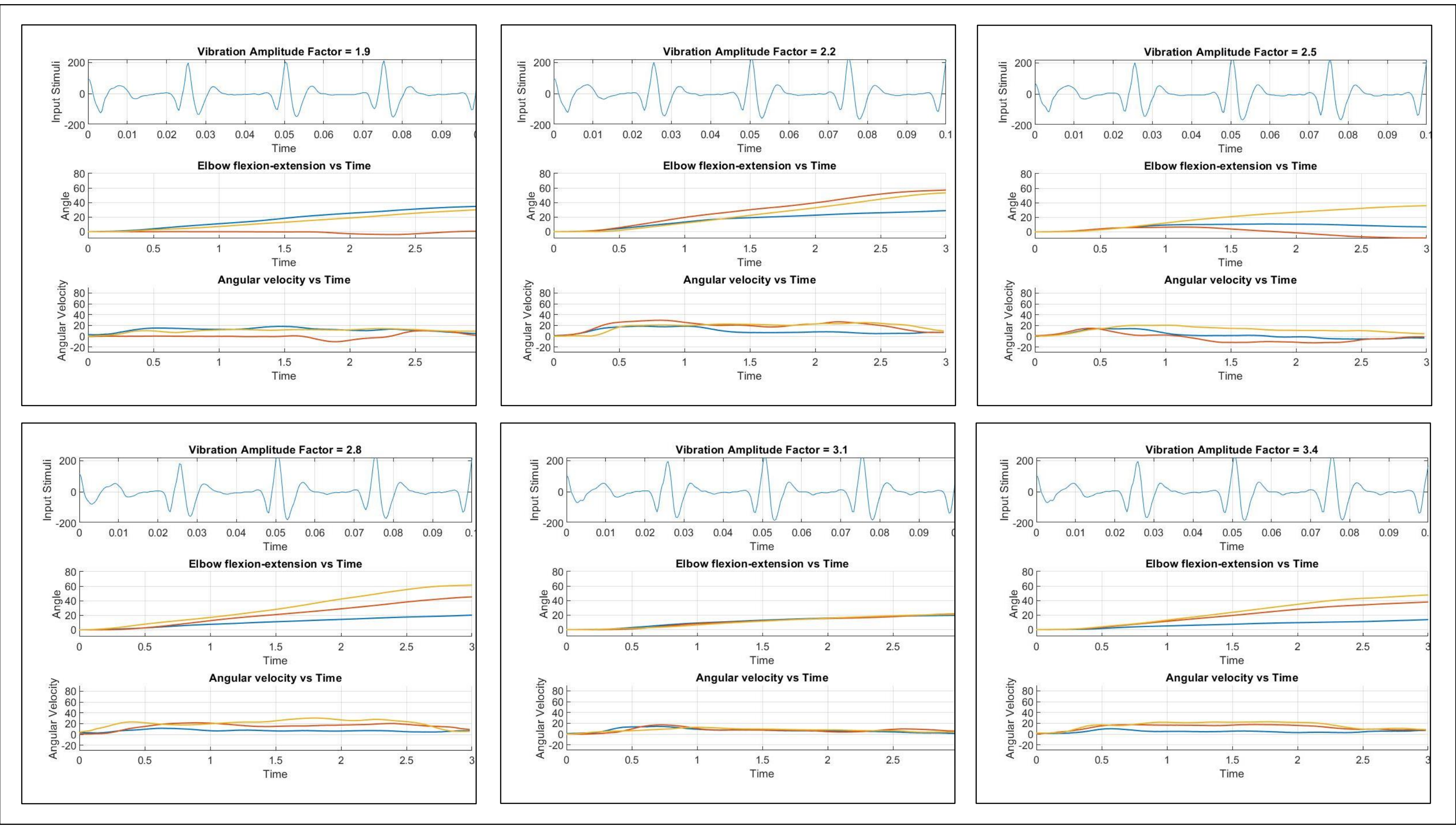
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time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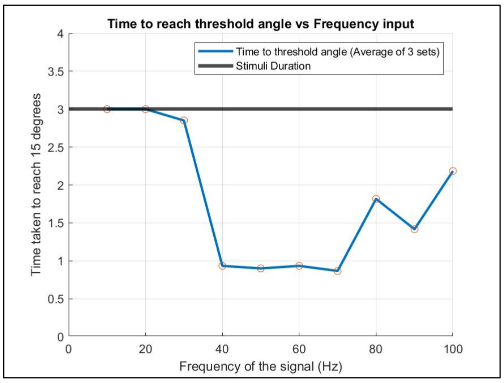
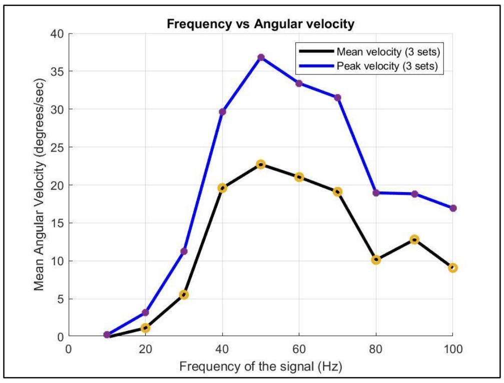
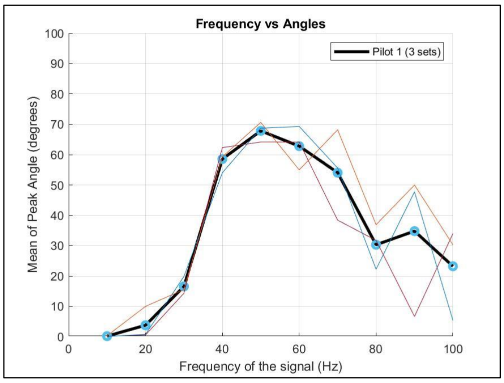
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time
Vibration Amplitude Factor = 2.2
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time
Vibration Amplitude Factor = 2.5
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time
Vibration Amplitude Factor = 2.8
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time
Vibration Amplitude Factor = 3.1
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time
Vibration Amplitude Factor = 3.4
Input Stimuli
Time
Elbow flexion-extension vs Time
Angle
Time
Angular velocity vs Time
Angular Velocity
Time

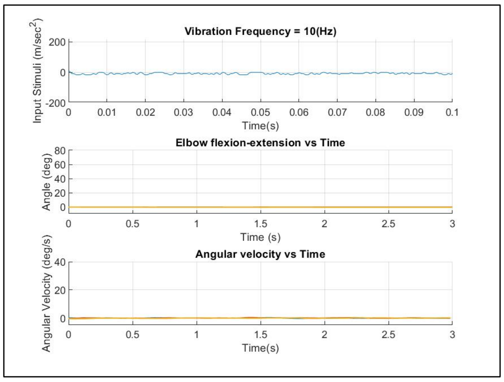
Experiment 4: Frequency Modulation

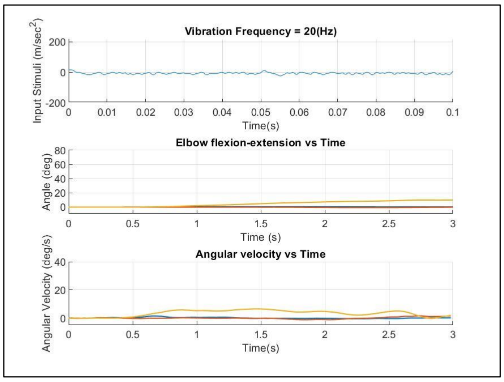
Raw data: Participant 19.








Vibration Frequency = 10(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
0
0.5
1
1.5
2
2.5
3
Time(s)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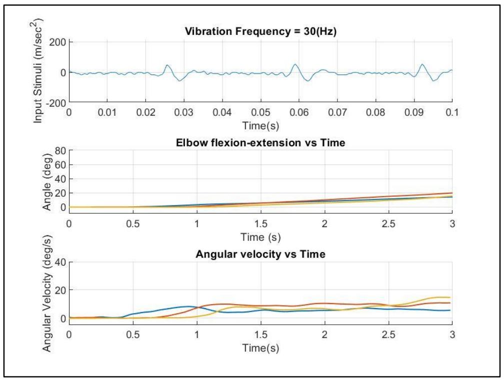
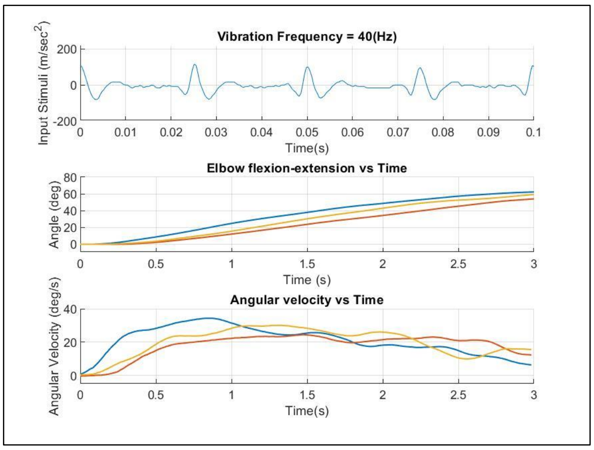
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
0
0.5
1
1.5
2
2.5
3
Time(s)


Vibration Frequency = 30(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
0
0.5
1
1.5
2
2.5
3
Time(s)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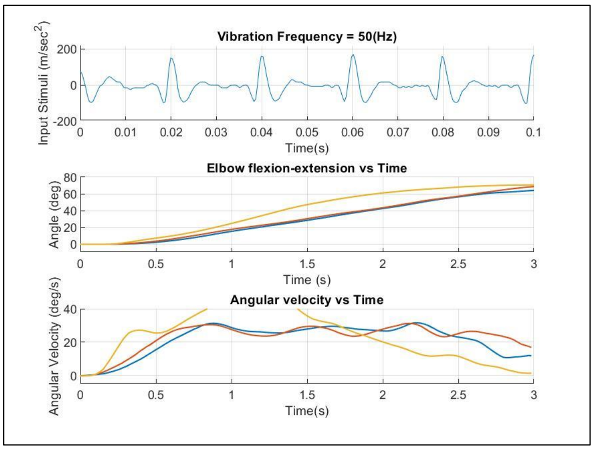
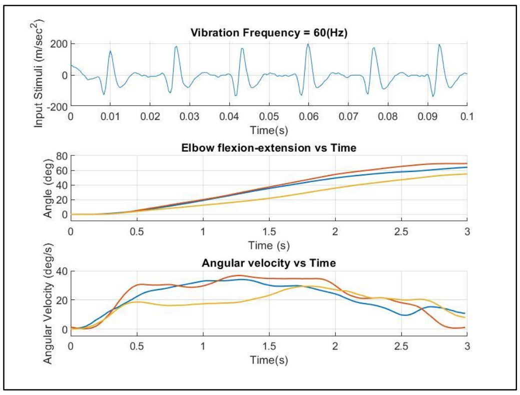
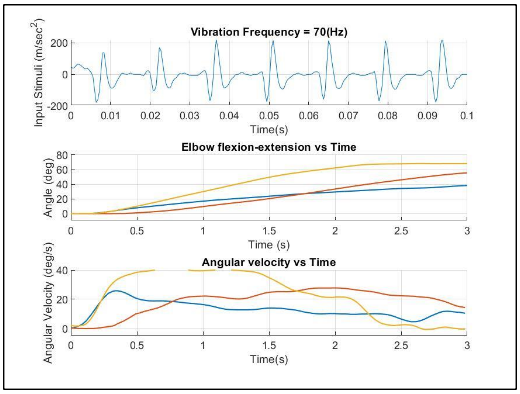
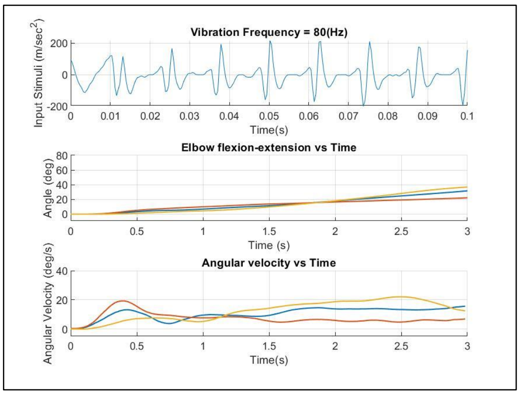
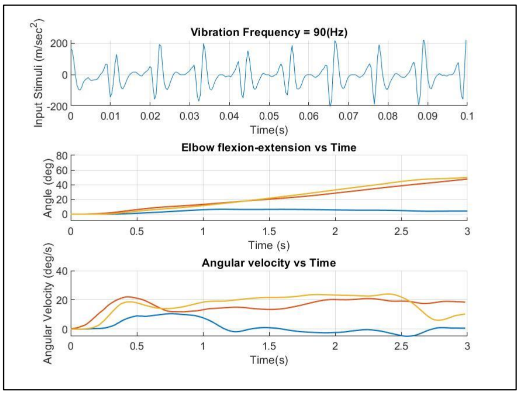
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
0
0.5
1
1.5
2
2.5
3
Time(s)


Vibration Frequency = 50(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
0
0.5
1
1.5
2
2.5
3
Time(s)


Vibration Frequency = 60(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
Time(s)


Vibration Frequency = 70(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
Time(s)


Vibration Frequency = 80(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
Time(s)


Vibration Frequency = 90(Hz)
Input Stimuli (m/sec^2)
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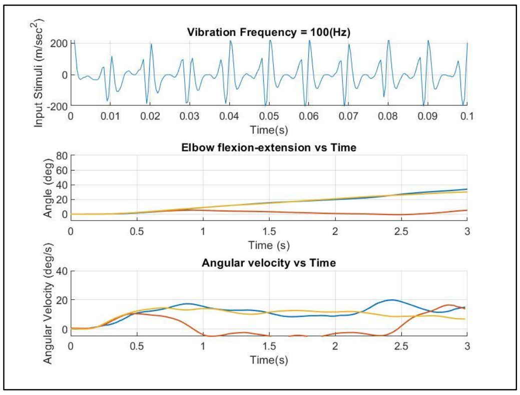
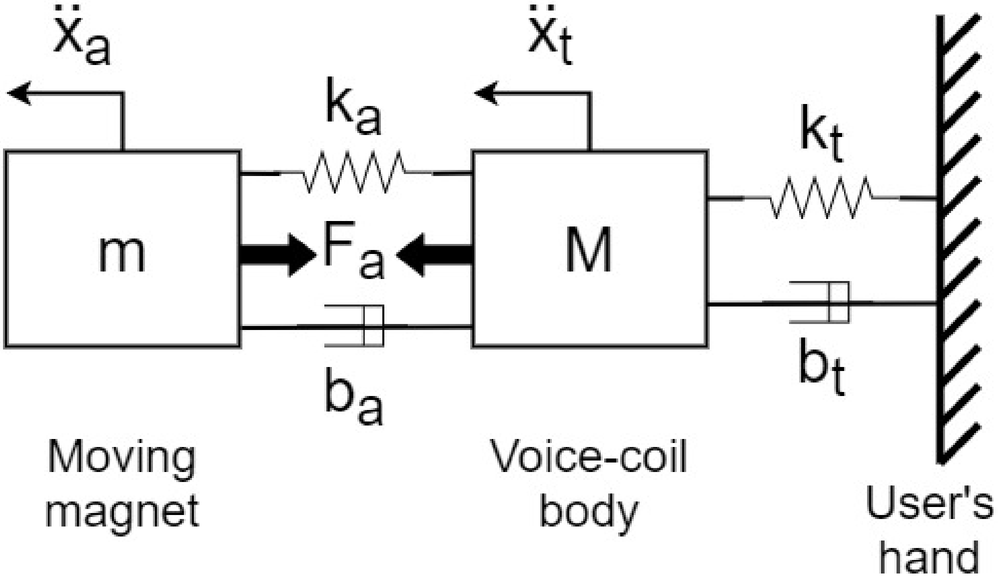
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
Time(s)


Vibration Frequency = 100(Hz)
Input Stimuli (m/sec^2)
200
0
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time(s)
Elbow flexion-extension vs Time
Angle (deg)
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Time (s)
Angular velocity vs Time
Angular Velocity (deg/s)
40
20
0
Time(s)

Mathematical Model

For a two degree of freedom system there are two equations of motion, each one describing the motion of one of the degrees of freedom. In general, the two equations are in the form of coupled differential equations. Assuming a harmonic solution for each coordinate, the equations of motion can be used to determine two natural frequencies, or modes, for the system.



The voice coil actuator can be parametrically modelled as a configuration of masses, springs, and dampers as shown in Fig. 2. We assume that the motion of the system is linear. The body of the actuator has mass, M and acceleration x'' which is held by the user. This interaction is modelled as a spring and damper connected to the user's skin. Similar models have been used to model the human

hand holding a tool with spring stiffness kt and damping factor bt. The moving mass of the actuator, m has an acceleration of xa, which is suspended from the body of the actuator. This suspension is modelled as a parallel spring-damper pair with spring stiffness ka and damping factor ba. By adding the forces on each mass, the corresponding equations of motion for the system are:

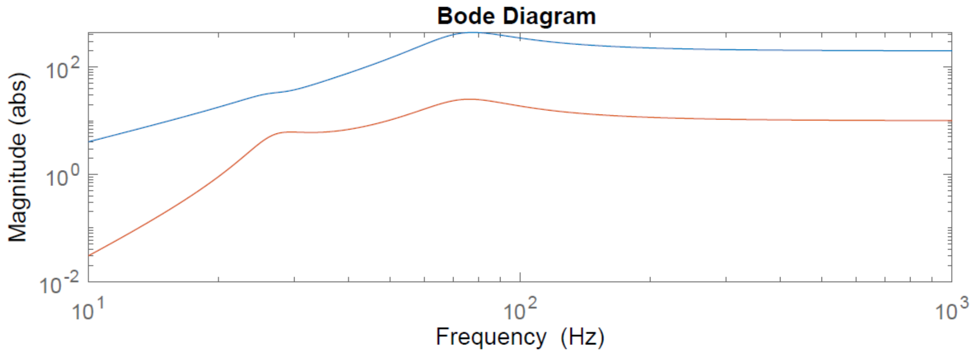
$$\begin{aligned} -M\ddot{x}_t = -k_a\left(x_a - x_t\right) - F_a - b_a\left(\dot{x_a} - \dot{x_t}\right) \\ +k_t x_t + b_t \dot{x}_t \end{aligned}$$

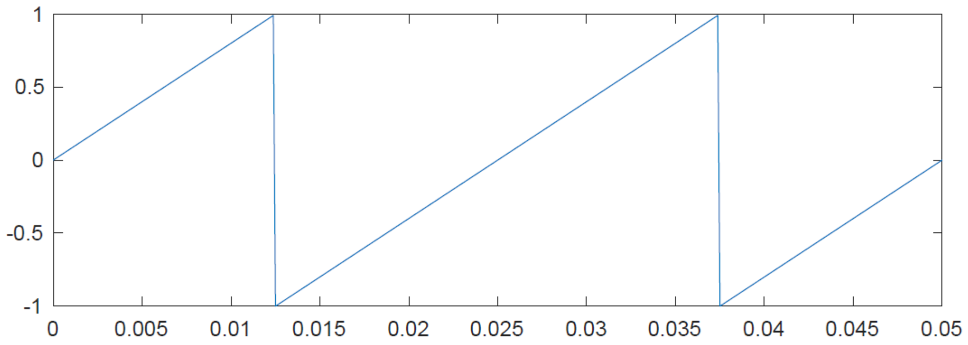
$$-m\ddot{x}_a = F_a + k_a\left(x_a - x_t\right) + b_a\left(\dot{x_a} - \dot{x_t}\right)$$

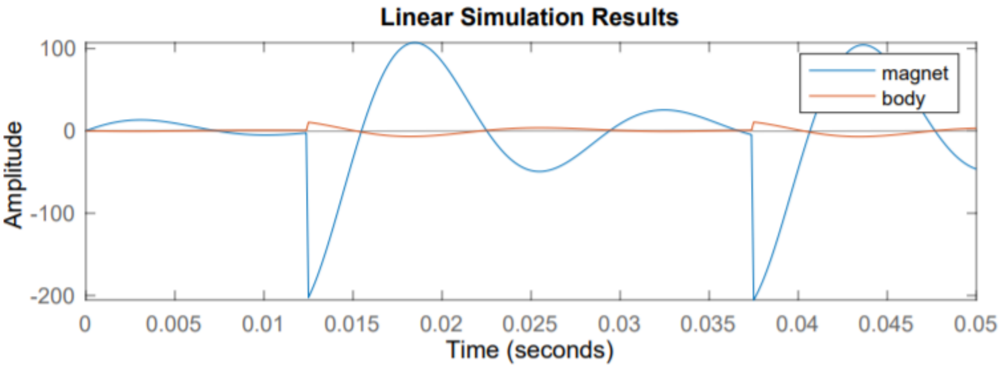
The following transfer function is obtained based on the system of equations:

$$H(s) = \frac{ms^4}{(ms^2 + b_a s + k_a)(Ms^2 + bs + k) - (b_a s + k_a)^2}$$

The bode plot and the Linear simulation model of the 2 DOF haptuator body and the haptuator mass system are:







Calibration of the Xsens DOT IMU sensors

Purpose:

For the experiment, the elbow flexion-extension was measured using an Xsens DOT sensors. The DOTs are IMU sensor combined with a patented Xsens sensor fusion algorithm. Since substantial accuracy of the measured angles and angular velocities of the movement was essential, it was necessary to calibrate the sensors with a clinically accepted motion capture system. Moreover, no literature was found regarding the accuracy of the Xsens DOTs for elbow flexion-extension movement and hence we decided to calibrate the sensors. For the same, the Xsens DOT (https://www.xsens.com/xsens-dot) sensors and clinically accepted Qualisys (https://www.qualisys.com/) infrared motion capture system were compared.

Experimental Setup:

The experimental setup consisted of a chair and a table on which the participant compared multiple repetitions of the elbow flexion-extension movement. The participant's right arm was attached with 4 Xsens DOT IMU sensors. 2 of them were placed on the upper arm and the other 2 were placed on the forearm near the wrist. 1 of the Xsens DOT on the upper arm and forearm was redundant in case one of the sensors fails to record. Moreover, the participant was attached with reflective markers on the anatomical landmarks of their right hand. The participant also had 1 hapcoil one and 1 hapcoil plus attached to replicate the real experiment condition (although later it was decided to not use hapcoil plus). 3 sets of 10 repetitions of elbow flexion-extension were performed by the participant. The quaternion measurements with respect to the local frame of reference were recorded for the DOTs and the coordinates in space with respect to the local frame were recorded by the Qualisys system. Figure 1 shows the front view and side view of the participant performing the experiment.

Results:

Figure 2 shows the measured values of elbow flexion-extension using based on the motion capture system and the Xsens DOTs. The error is also plotted for every data point of measurement. It can be observed that the error is maximum at the end position of elbow flexion and extension. The error during the flexion has an average of 8 degrees whereas the error for flexion has an average of 11 degrees over 3 sets for 10 repetitions each. The root means squared error for all sets over all repetitions is close to 2.3 degrees.

Calibration of the Xsens DOT IMU sensors

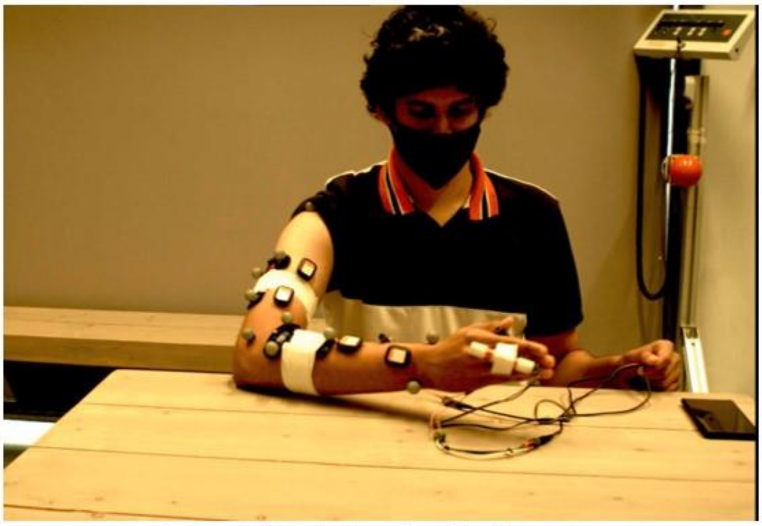


Image 1: Front view of calibration setup

Image 2: Side view of calibration setup

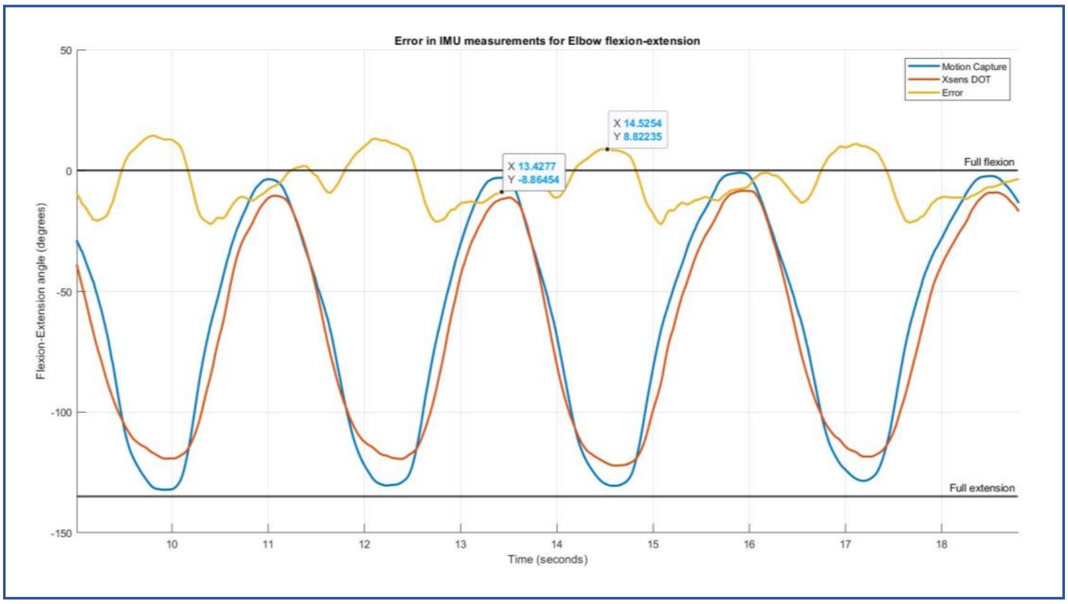


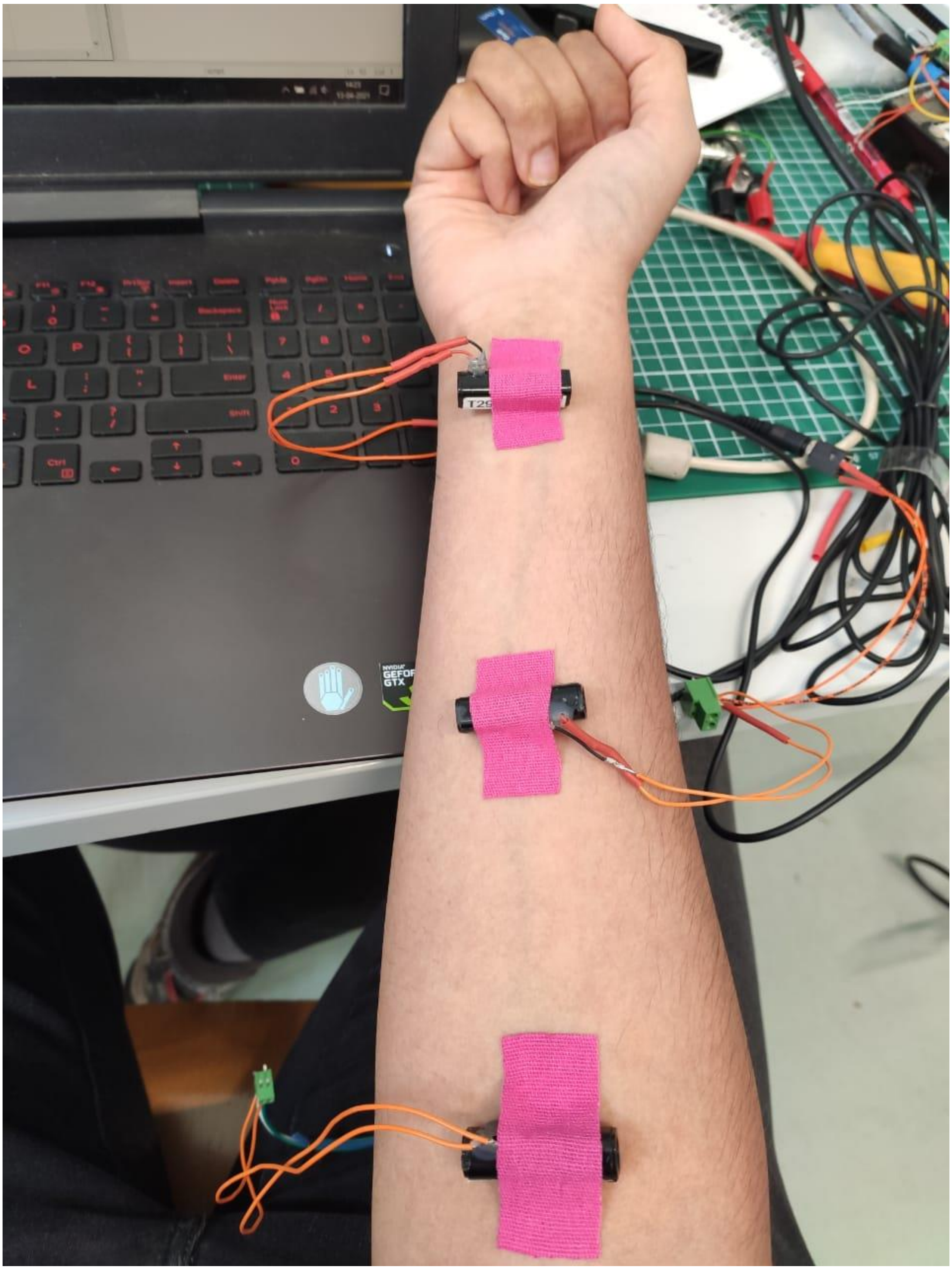
Image 3: Results.

Haptic Rendering

In this section, we describe the various iterations rendered before coming to the final setup and deciding the location of the haptuator. A trial-and-error method was also used to inspect the various locations to place the haptuator. The locations which were tried include: forearm, wrist, palm, fingers and forehead. Placing multiple haptuators simultaneously on multiple locations on the forearm was prevented to reduce the complexity of perceptual cues and cognitive load on the participant. Moreover, having multiple haptuators simultaneously would not help in the understanding whether the movement guidance is due to single element generating pseudo force of multiples of the elements. Moreover, which haptuator location is responsible for what part of the total angular velocity of the movement will not be clear. Hence, changing the location of the haptuator and assessing its effect on the movement should be inspected in the future research.

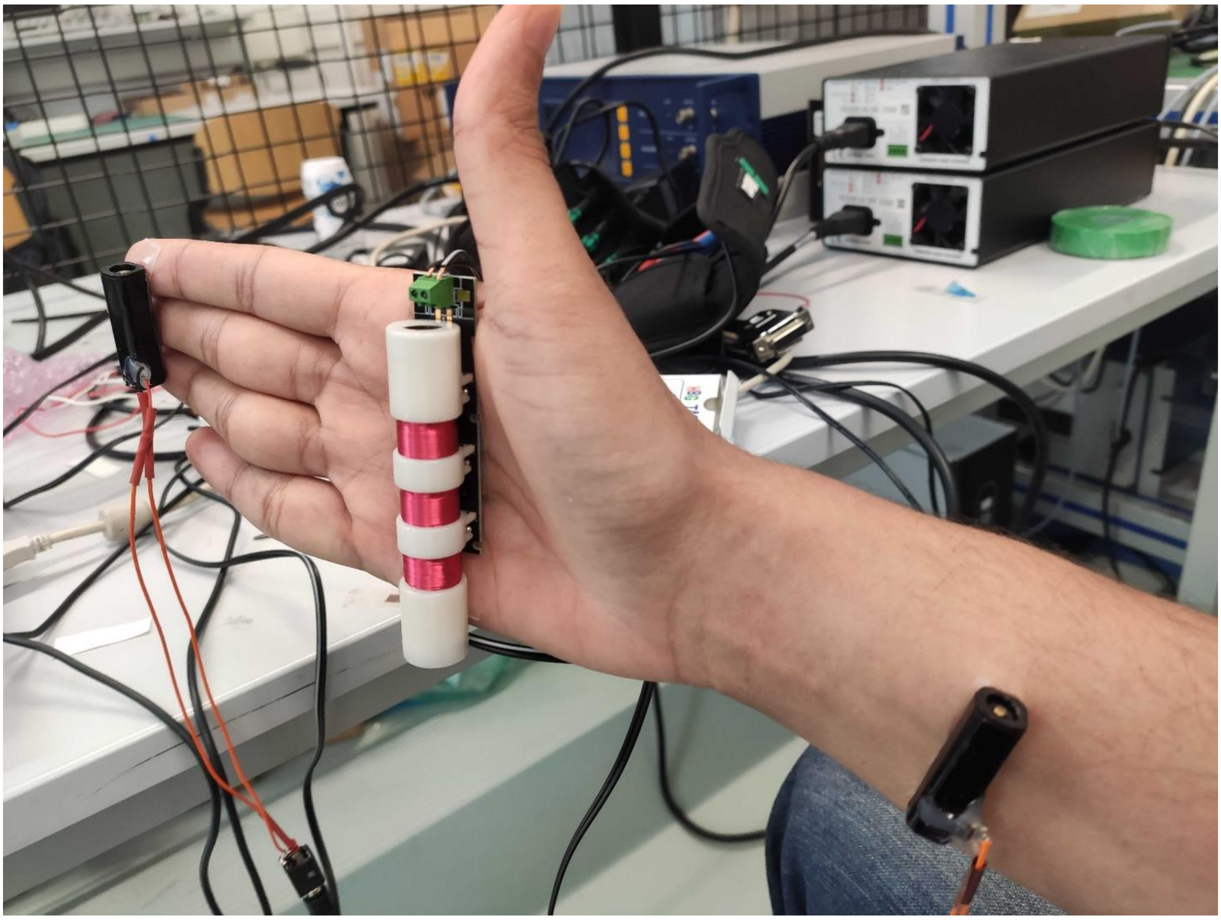
1) Multiple Haptuators:

2) Different methods of fixing haptuators on the skin:
   a) Kinesthetic tape: 3 haptuators connected using kinesthetic tape are shown below. This approach did not work since the haptuator and the skin moved separately.

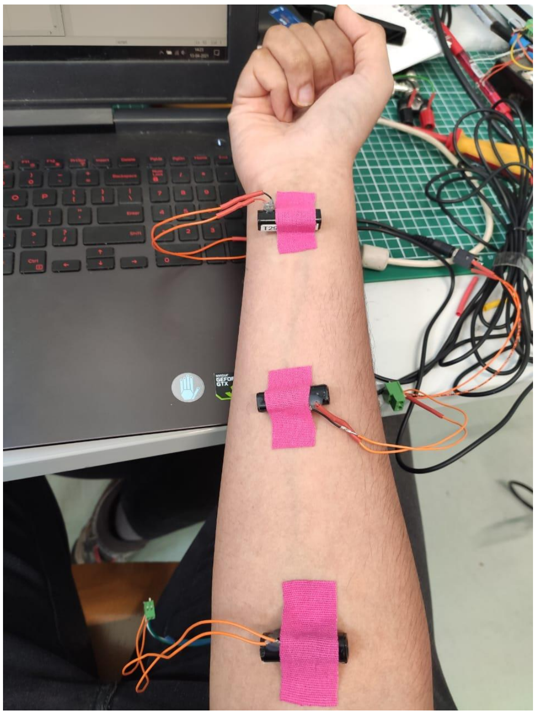


b) Wearable band: haptuator connected using band is shown below. This approach did not work since the haptuator and the skin moved separately.

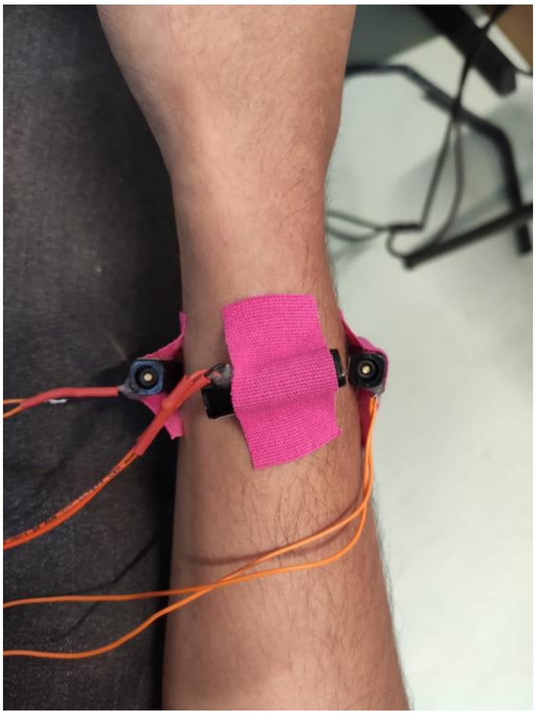
3) Different types of Linear Resonant Actuators: A hapcoil plus and 2 haptuators are seen. Observe the different locations at which the actuators are placed as well.



4) Different types of movement guidance: Primarily, the rotation of the forearm and the elbow flexion-extension (supported + unsupported) were inspected using the pseudo force feedback.



Flexion-extension movement guidance.



Rotational movement guidance.

Final Sleeve

After multiple iterations of locating haptuators at different locations, rendering with different kinds of vibrations and Linear resonant actuators and different techniques to attach the haptuators, we finally designed a sleeve in collaboration with the industrial design department of TU Delft. I would like to thank Lynda and Kasper Jansen for the help during the same.

The entire process of making the sleeve involved multiple iterations of weaving, knitting and making it aesthetic. Moreover, the sleeve contains conductive threads so external wires are not required to actuate the haptuators. 2 IMU pockets are designed to insert the XSens DOTs. These locations are specific to the elbow movements.

[redacted]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2021/05-128A
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-131A

PARTICIPANT INFORMATION SHEET

Title of Research: **Pseudo Forces to guide elbow flexion extension.**

Date: **22nd July 2021**

We would like to invite you to join our research study titled '**Pseudo Forces to guide elbow flexion extension.'** In this letter you will find information about the research. If you have any questions, please contact the researchers listed at the bottom of this letter.

Purpose of the research

Stroke is a leading cause of adult physical disability. Grasping movements and bringing objects to the face are frequently performed and crucial activities of daily living and is needed in eating, drinking. For most of these movements, elbow flexion-extension movement is necessary and therefore it is key to exercise this motion. In-person sessions with a physiotherapist are not always possible due to situations like Covid. We have developed a simple and compact wearable device aimed to give the feel of exercise assisted by a real physiotherapist. The purpose of this research is to evaluate the effectiveness of this prototype to guide the movement.

What does participation in the research involve?

Once you have decided to take part in this research, you will be asked to come to the mentioned location where our research team will discuss the study with you and answer any questions you may have. If you are still happy to take part, we will ask you to sign the consent form. The estimated time requirement is 1 hour.

We will ask you to provide us with some information regarding your name, age, sex, contact details and basic medical information. There would be 4 experiments which would be conducted to analyse the following parameters:

1. Direction.
2. Response to duration modulation.
3. Response to frequency modulation.
4. Response to amplitude modulation.

During the experiments, you would be asked to perform elbow flexion-extension several times. To analyse the movement of your body we will strap several sensors (Fig 1: Inertial Measurement units) on your bare skin at various locations/ sleeve on the arm., Moreover, we will place single/ multiple vibrotactile actuators to your dominant arm by sticking them with a medical grade double sided tape. These actuators will produce vibrations while moving the arm. Finally, you would be provided with an eye mask and active noise cancelling earphones/ earplugs and ear protection equipment to cancel out background noise.

Fig. 1 The inertial measurement unit.

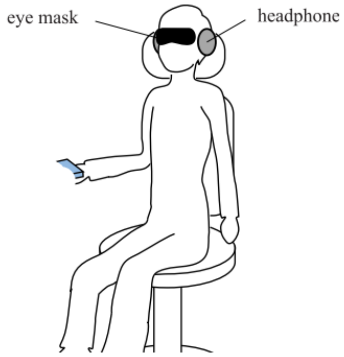

Fig 2. Eye mask and headphone

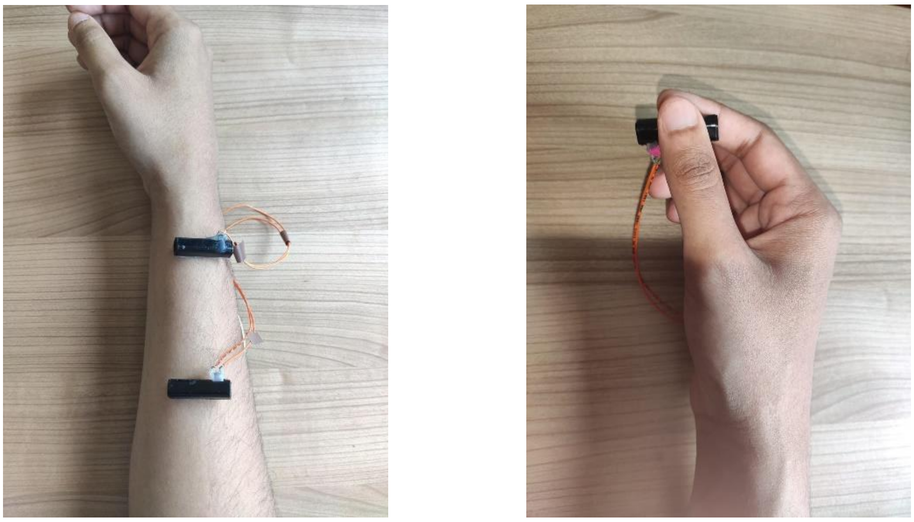

Fig 3. The vibrotactile actuators placed on the forearm and hand using double sided tape.

Are you eligible to participate?

We would like you to consider participating in this study if you are a healthy participant who hasn’t been diagnosed with any damage to the dominant arm for last 6 months. Please refrain from participating in the study if you had a Covid-19 vaccination less than 3 days before you participate.

What are the side effects, and are there any risks in taking part?

It is a non-invasive study. You may experience a minor tingling sensation for a couple of minutes after donning off the haptic actuators used to provide the pseudo force feedback. Moreover, a medical grade double sided tape would be used for placing the inertial measurement units and actuators on your skin. The donning-off of the double-sided tape will be a bit painful but it is temporary and usually lasts for 30 seconds.

What are the possible benefits of taking part?

There are no clear benefits to you of taking part. However, the information we get from this research will enable us to improve the design of the wearable that may help CVA patients to recover better in the future.

Do I have to take part?

No, your decision to participate is entirely down to you and if you would like to take part, you will be asked to sign a consent form. Even after you have signed this consent form and agreed to join the study, you are free to withdraw from the study at any time. If you decide not to take part, or withdraw from the study, it will not affect any future interactions that you may have with the TU Delft. If you choose to withdraw, the information collected up until that point will be retained and used in the study; however, no further data will be collected. Please inform any member of the research team straight away if you no longer wish to participate in the study.

Confidentiality of data

This investigation requires that the following personal data are collected and used: **name, gender, age and contact details (email)**. A video recording would be done of the session to for understanding the movement. All the video data would remain confidential. To safeguard and maintain confidentiality of your personal information, necessary security steps will be taken. Your data will be stored in a secure storage environment at TU Delft. Data will only be accessible to **the researchers mentioned at the bottom of this document**. All data will be processed confidentially. Personal data will be anonymized and processed. Whereas health information would be used for representation of the group of participants.

Your name will be linked to a participant number. This participant number will be located on the "informed consent form". The informed consent form will be stored digitally in a separate and secure location. This way, all your details remain confidential. Only the researchers below can know which participant number you have.

The pseudonymised personal data will be retained in accordance with the TU Delft Research Data Framework Policy. Anonymised or aggregated data may be shared with others after the end of the research project.

The results of this study will be published in possible future scientific publications. Your participant number, name, contact details and individual health information will never be shared on publications (master thesis report, scientific publications, reports …) about the research. The anonymized data will be used for research purposes and the future publications based on research only.

Contact Information

If you have any complaints regarding confidentiality of your data, you can contact the TU Delft Data Protection Officer (Erik van Leeuwen) via privacy-tud@tudelft.nl or the Dutch Data Protection Authority (Autoriteit Persoonsgegevens).

On behalf of the researcher(s), thank you in advance for your possible cooperation.

Researcher(s) name and email address(es)

Nihar Sabnis

Dr. Eline van der Kruk

Dr. Michael Wiertlewski

Dr. David Abbink

Informed consent form: Pseudo Forces to guide elbow flexion extension.

Consent Form for study “Pseudo Forces to guide elbow flexion extension”

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated 22nd July 2021, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
Risks associated with participating in the study You may experience a minor tingling sensation for a couple of minutes after donning off the haptic actuators used to provide the pseudo force feedback. Moreover, a medical grade double sided tape would be used for placing the inertial measurement units and actuators on your skin. The donning-off of the double-sided tape will be a bit painful but it is temporary and usually lasts for 30 seconds.	☐	☐
Use of the information in the study		
I understand that information I provide will be used for a scientific publication and presentation of results at scientific conferences.	☐	☐
I understand that personal information collected about me that can identify me, such as my name, age and contact details will not be shared beyond the study team.	☐	☐
I agree that my information can be quoted in research outputs after anonymization (testimonial report).	☐	☐

Future use and reuse of the information by others

I give permission for the acquired motion data, answers given in questionnaires, video and photographic material that I provide to be archived in a secure drive at TU Delft under the CC-BY copyright license after anonymization so it can be used for future research and learning. All identifiable data, such as my name or address, will be removed in the anonymization process. ☐ ☐

Videos and photographs that contain identifiable features, such as my face, will be anonymized by blurring or blackening the identifiable parts.

Signatures

________________________ ________________________ _________

Name of participant [printed] Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Nihar Sabnis 22nd July 2021

___________________________ ____________________ _________

Researcher name [printed] Signature Date

Study contact details for further information:

Nihar Sabnis Dr. Eline van der Kruk

Dr. Michael Wiertlewski

Dr. David Abbink

Date 28-05-2021
Contact person Ir. J.B.J. Groot Kormelink, secretary HREC

TU Delft
Delft University of Technology

Human Research Ethics Committee
TU Delft
(http://hrec.tudelft.nl/)

Visiting address
Jaffalaan 5 (building 31)
2628 BX Delft

Postal address
P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: Pseudo Forces to guide elbow flexion extension in stroke patients
Applicant: Sabnis, Nihar

Dear Nihar Sabnis,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission and additional information to the HREC. This study has now been approved for both healthy participants and recovering patients. Please do make sure that your Informed Consent form for healthy participants is adjusted for only any Personally Identifiable Information you will collect from them.

Best wishes,

Good luck with your research!

Sincerely,

Dr. Ir. U. Pesch
Chair HREC
Faculty of Technology, Policy and Management