Using Amplitude-modulated Pseudo Forces to Control Human Movement

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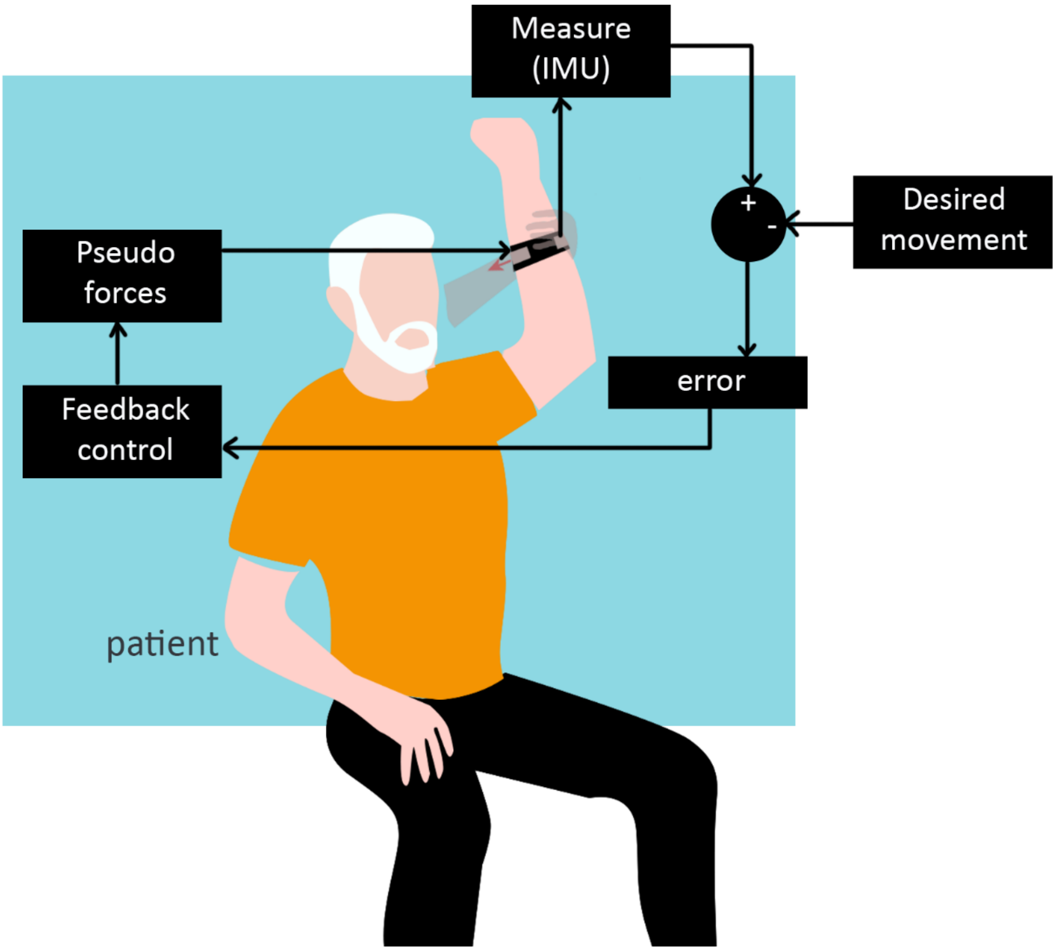

TU Delft

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by

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***Abstract*—Humans perceive a pulling or pushing sensation when subjected to an asymmetric vibration. This so-called pseudo force has great potential to guide human movement. Previous research has exclusively focused on the effect of pseudo forces in open-loop environments, in which the user's joint angular velocity cannot be corrected. As the latter is essential for providing movement guidance, this paper proposes the first closed-loop system in the field of pseudo forces, using amplitude-modulated pseudo forces as haptic feedback. With this feedback, the user was assisted in moving with a specific target angular velocity. In a human factors experiment, the amplitude-modulated stimuli were compared to constant-amplitude stimuli. The results showed that amplitude-modulated pseudo forces significantly decreased the error between the user's and the target angular velocity when continuous movement in the desired direction was achieved. Therefore, the study demonstrated that amplitude-modulated pseudo forces can effectively guide human movement, representing an essential step towards developing a wearable movement guidance device.**

I. Introduction

Physiotherapy is generally executed by a physically present therapist. This presence enables the therapist to give not only audiovisual instructions, but also provide direct movement guidance using human-to-human touch, controlling two key components of movement: direction and joint angular velocity. These tactile cues are unique in that they directly engage the patient's motor learning system [1], contrary to auditory or visual feedback for which the brain is needed to convert the incoming information to an outgoing movement.

To provide physical movement guidance, the therapist and the patient need to be in the same location. The pandemic exposed very clearly that co-location is not always possible or desirable. Moreover, remote movement guidance is a solution to save time and money for both the therapist and the patient.

The existing haptic movement guidance systems can be classified into two types: grounded and ungrounded [2], [3]. Grounded systems can produce realistic reaction and external forces by placing fulcrums on the ground and human arm, such as the Phantom Omni [4] and SPIDAR [5]. They can display a wide range of forces and other tactile cues, but their applications are limited since the working area depends on the device's size [3]. Ungrounded systems are not limited to a specific workspace. Common ungrounded haptic movement guidance devices are robots generating physical forces, like the upper-limb exoskeletons Skelex [6] and EksoVest [7]. These devices serve well for motion assistance, but are inconvenient to use as they are cumbersome and expensive [8]. So, the need for a low-cost, light and ungrounded tactile feedback system providing movement guidance arose.

In 2005, a new and promising phenomenon with great potential in remote movement guidance was introduced; the perception of pseudo forces by inducing an asymmetric vibration [9]. These pseudo forces give the sensation of directional pushing or pulling, using a different acceleration pattern in the opposite direction [10]. In the years following the introduction of this phenomenon, researchers developed multiple systems and signals to create it, further exploring the possibilities and applications of pseudo forces. This progression included reducing the device's weight and size, leading to the development of some lightweight haptuators capable of providing clear directional cues [11]–[14]. These haptuators are very promising to be used in a wearable movement guidance system. However, until now, the haptuators were only evaluated in an open-loop environment, in which the user's joint angular velocity was not monitored or corrected. As controlling the joint angular velocity is essential in providing movement guidance, the aim of this research is to develop the first closed-loop system in the field of pseudo forces, using amplitude-modulated pseudo forces as haptic feedback.

Therefore, a system was assembled with a haptuator and inertial measurement unit as key components, both controlled by a microcontroller. Two types of amplitude feedback were developed and evaluated during a human factors experiment. The results of this experiment are used to answer the question of whether amplitude-modulated pseudo forces can effectively guide human movement.

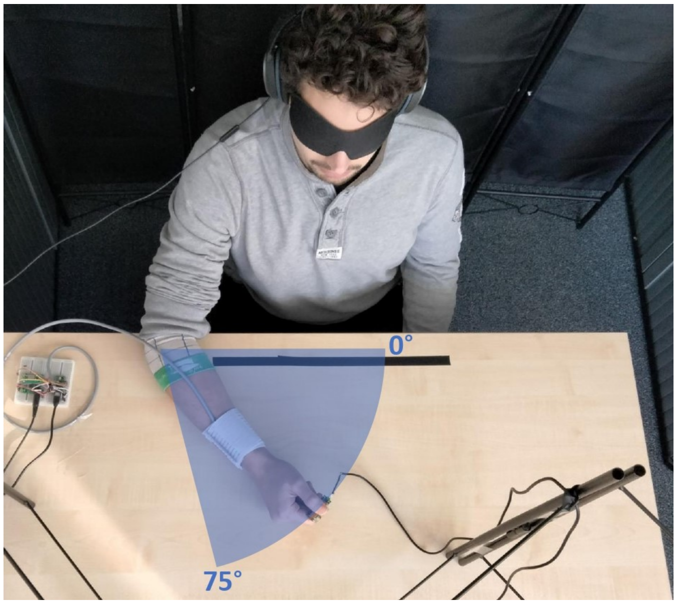


Figure 1: The angular trajectory participants were free to rotate in.

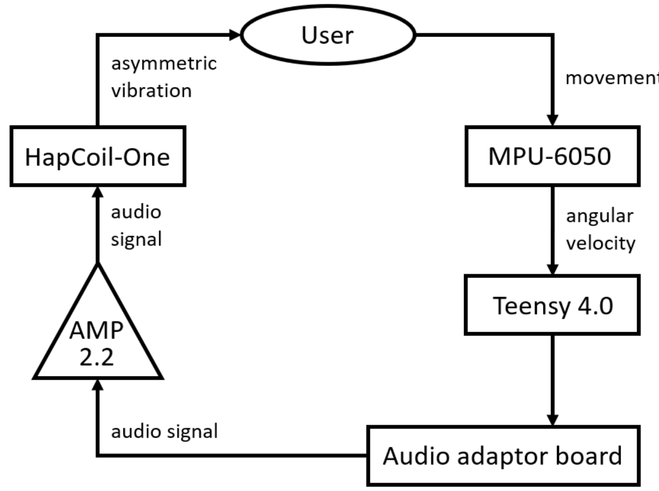


Figure 2: Schematic overview of the closed-loop system. Haptic feedback was provided by amplitude-modulation of the asymmetric vibration.

II. Materials and Methods

A. Movement description

The movement selected for the human factors study was a combination of internal-external shoulder rotation and elbow flexion-extension. The participants were instructed to slide their right hand over a table in the direction they felt being pushed or pulled towards while their elbows rested in a fixed position. This movement was selected for its negligible effect on muscle fatigue over multiple repetitions and because it is limited to a horizontal plane.

Every trial started with the forearm paralleling the frontal plane of the upper body, calibrated as 0°. The trial was automatically stopped at an angular distance of 75° or manually stopped when this endpoint was not reached after 80 seconds. Participants were free to rotate in the trajectory between 0-75° while using their elbow as a pivot, as illustrated in Figure 1. The starting point at 0° was preferred over a starting point in the middle, as the latter would reduce the trajectory by half. Besides, there is already extensive proof for the functionality of pseudo forces to guide users in a specific direction from a standstill [9]–[18], so that was not part of this research.

B. Hardware

The tactile amplitude feedback was provided by a haptuator (HapCoil-One, Actronika). The haptic feedback loop was controlled by a microcontroller (Teensy 4.0 Development Board), programmed using the Arduino IDE. The microcontroller was connected to an audio adaptor board, generating the asymmetric waveform. The frequency of this waveform was equal to the resonance frequency of the haptuator (65 Hz), while the amplitude was constantly modulated by the microcontroller during amplitude-modulated feedback trials. The output signal was amplified by an amplifier (Visation AMP 2.2), with a gain of 1.9, after which the signal actuates the haptuator.

Also connected to the microcontroller was an inertial measurement unit (MPU-6050). It used its internal gyroscope to measure the angular velocity around the x-axis in its local frame, which was digitally sent to the microcontroller via I^2C. Figure 2 displays a schematic overview of all electrical components and their interaction with the user in the proposed closed-loop system.

C. Software

Besides initialisation, the Arduino program on the microcontroller consists of three main functions; filter the raw angular velocity data (ω_{raw}), implement the amplitude feedback, and enable the Turning Test.

1) Filter angular velocity: In the main loop, the gyroscopic data from the inertial measurement unit (IMU) was communicated to the microcontroller at a sampling frequency of 19 Hz. These values were converted from radians to degrees, after which they were stored. Since the amplitude modulation was applied to real-time angular velocity data, noisy data would lead to a noisy amplitude. Therefore, a causal filter was implemented to ensure a smooth change in amplitude during modulation, using a window of 16 data points (0.84s). As the filter was applied in real-time, the average was only based on previous data points, inducing latency. Also, the acceleration and deceleration peaks were flattened due

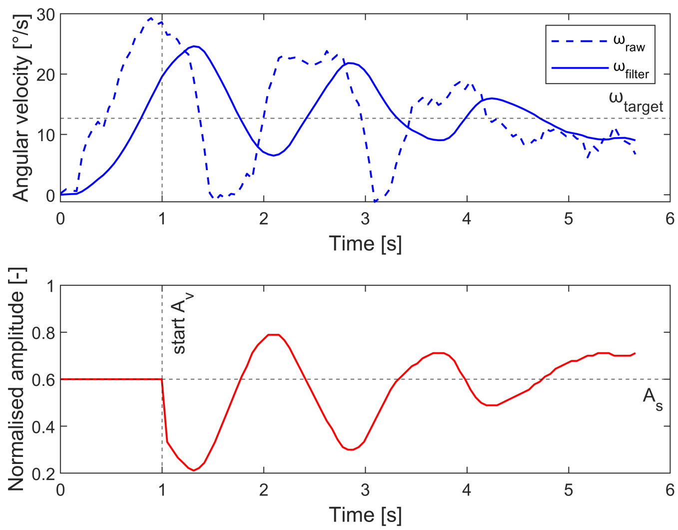


Figure 3: Correlation between angular velocity and amplitude.

to the averaging. The top graph in Figure 3 shows an example of the raw and filtered angular velocity, including the resulting latency and flattening.

The angular distance was calculated by integrating ω_{raw} over time starting from the initial orientation. This was used as input for an internal stop function, activated after an angular distance of 75°.

2) Amplitude feedback: The amplitude-modulated feedback was modelled as a linear damper system, with as input the filtered current angular velocity ($\omega^{t}_{\text{filter}}$) and as output the amplitude. The goal was to regulate the angular velocity of the user so it matches the target angular velocity (ω_{target}). This was achieved by applying a "damping force" based on the error between the $\omega^{t}_{\text{filter}}$ and ω_{target}.

In the main loop of the software, this model was implemented using the following equation:

$$A^{t+1}_{\text{v}} = A_{\text{s}} + \frac{\omega_{\text{target}} - \omega^{t}_{\text{filter}}}{\omega_{\text{target}}} * (1 - A_{\text{s}}) \quad (1)$$

The variable amplitude (A_{v}) was determined by a starting amplitude (A_{s}) and the normalised error between ω_{filter} and ω_{target} multiplied by a scaling factor. A_{v} was limited to a range of [0, 1]. The ω_{target} was participant dependent, explained in more detail in Section II-G.

This research evaluated two A_{s} values: 0.8 and 0.6. The variable amplitudes based on these two A_{s} values are referred to as $A^{0.8}_{\text{v}}$ and $A^{0.6}_{\text{v}}$, respectively. For the trials without amplitude-modulated feedback (control group), the amplitude was set to remain constant throughout the trial:

$$A^{t+1}_{\text{c}} = A_{\text{s}} \quad (2)$$

To compare these constant amplitude (A_{c}) trials with the A_{v} trials, the same A_{s} values were used, denoted as $A^{0.8}_{\text{c}}$ and $A^{0.6}_{\text{c}}$.

The effect of the amplitude-modulated feedback is visualised in Figure 3. Shown is that the A_{v} holds an inverse relation to ω_{filter}. The starting time of the A_{v} was set to be one second after the start of vibration, incorporating reaction time and first acceleration. A pilot study revealed that users were often above ω_{target} at this point in time. Still, it was reasoned that the time delay was preferably longer than too short, preventing the amplitude from overshooting before users had the chance to accelerate.

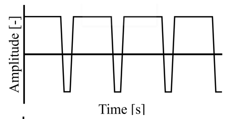
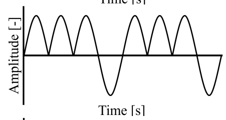
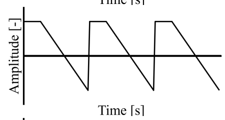
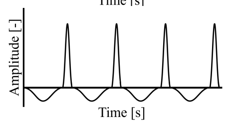
3) Turning Test: Besides the primary goal of evaluating if amplitude-modulated pseudo forces can be used to guide human movement, this study also examined directional discrimination while moving. While previous research only investigated the usage of pseudo forces to distinguish directional cues from a standstill [9]–[14], [17], [19], this research evaluates the response of in-motion participants to a sudden inversion of the vibration direction. In the initialisation, this Turning Test could be invoked, turning on two checkpoints in the main loop. These checkpoints were sufficed when the participant reached a certain angular distance. The first checkpoint was at 60°, followed by a checkpoint at 30°. If a checkpoint was reached, the asymmetric vibration direction was inverted on the next point in time (52ms).

D. *Input signal selection*

Research has not yet evaluated which input signal yields the most evident direction cue for the HapCoil-One haptuator. The four asymmetric vibration input signals developed for light (<50 g) electronic devices were compared in a pilot study. This included Rekimoto's square wave [11], Tanabe et al.'s asymmetrically modified sine wave [12], Culbertson et al.'s step-ramp [13] and Sabnis et al.'s powers of sinusoids [14]. These input signals were evaluated for different duty cycles and frequencies. The duty cycle represents one of the following ratios: on-off [11], positive-negative peaks [12], [14] or step-ramp [13]. For all input signals, the haptuator's resonance frequency (65 Hz), and the device's initially applied frequency were tested. Table I provides an overview of the input signals and conditions tested.

A two-person pilot study evaluated the input signals under all their conditions. Based on how evident the direction cue was starting from a standstill, a numerical rating ranging from one to ten was assigned to each

TABLE I: Overview of the signals and conditions tested on the HapCoil-One haptuator in this research. Indication letters: dc=duty cycle, f=frequency.

Researcher(s)	Input signal	Tested conditions
Rekimoto, 2013 [11]		dc: 3-1, 5-1, 9-1, 15-1, 23-1 f: 65, 125
Tanabe et al., 2016 [12]		dc: 2-1, 3-1, 4-1, 5-1, 6-1 f: 65, 75
Culbertson et al., 2017 [13]		dc: 1-1, 1-2, 1-3, 1-4, 1-5 f: 50, 65
Sabnis et al. 2021 [14]		dc: 1-7 f: 40, 65

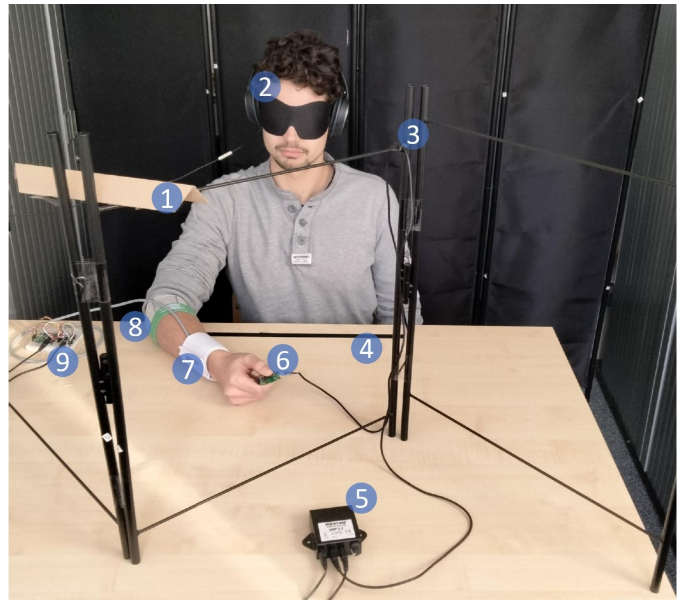


Figure 4: Experimental setup in a closed room, with: (1) camera standard, (2) headphones and eye mask, (3) frame, (4) kinaesthetic tape, (5) amplifier, (6) haptuator and level, (7) IMU and bandage, (8) sleeve and (9) microcontroller.

condition. Eventually, the asymmetrically modified sine wave with a duty cycle of three-to-one and a frequency of 65 Hz was selected due to its highest rating score.

E. Participants

A total of 19 healthy young adults without sensory disorders were recruited to participate in the experiment of this study. Two participants did not respond to the asymmetric vibration, regardless of the amplitude exerted on them. Since these participants had no data to process, they were excluded. The average age of the remaining 17 participants was 26±1.4 years, 9 male, 8 female. Their hand dominance was determined with the Edinburgh Handedness Inventory [20], from which one participant was classified as left-handed and the other 16 as right-handed. All participants provided informed consent before participating. None of them was involved in this research.

F. Experimental setup

A picture of the experimental setup used in this study is presented in Figure 4. The setup was inspected and approved by the safety manager of the 3mE faculty at the TU Delft. Participants wore noise-cancelling headphones and eye masks to cancel out audiovisual cues, and a sleeve around the elbow to smooth the elbow pivoting. A frame was used to place the camera standard and to attach the haptuator's audio cable, so it had a free range of motion. The kinaesthetic tape indicated the initial orientation of the participants' forearm for every trial. The IMU was attached proximally to the wrist with medical-grade double-sided tape. A bandage was wrapped around the IMU and a part of the wire to guarantee long-term attachment. The haptuator was placed between the distal two phalanges of the index finger and the thumb to ensure the asymmetric vibration direction was tangential during the rotational movement (Figure 1). Small interparticipant variations in grasping were observed, attributed to anthropometric variations and preferences in grasping. Placement on the fingertips was preferred over more proximal attachment locations, as a pilot study revealed this yielded a higher response rate than more proximal attachment locations. This outcome is in line with studies of Duan et al. [18] and Culbertson et al. [13], who explain this phenomenon by the higher sensitivity of mechanoreceptors in glabrous skin compared to hairy skin [21]–[23].

To ensure the asymmetric vibration direction remained primarily in the horizontal direction, the participants' forearm pronation and supination was monitored with a level attached to the haptuator. The experimental trial was disqualified if the bubble crossed the black line entirely, corresponding to an inclination of ±10°. The researcher monitored the bubble during all trials. Eventually, no trials had to be excluded based on this criterium. Furthermore, sandpaper was attached to the haptuator to avoid slipping.

G. Experimental protocol

The full experimental protocol lasted approximately one hour, including reception, instructions, consent provision, familiarisation and experimental phase. It was approved by the ethics committee of the TU Delft. The participants were seated on a chair in front of a table with adjustable height. Before the start of the experiment, the participant information was read to the participant, explaining the experiment's purpose and procedure briefly. This was followed by obtaining written informed consent from all participants, after which they were asked to remove all jewellery from their right hand. The table was adjusted to a height where the angle between the table and the upper arm was 145°, using a digital inclinometer.

The experiment comprised two consecutive phases: a familiarisation phase lasting 10 trials and an experimental phase enduring 24 trials. During the familiarisation phase, the participants got acquainted with the setup, vibration and pulling sensation. It was also stressed that the direction of the pulling sensation could switch at any time, which was executed once during familiarisation. Furthermore, the amplitude at which the participants had the most evident direction cue (resulting in the highest joint angular velocity) was selected. For every participant, the A_v and the A_c were normalised about this optimal amplitude. During the last four trials of the familiarisation phase, the average angular velocity (ω_default) of each participant was determined at their optimal amplitude. During a pilot study with four participants, it was observed that they exhibited varying angular velocities despite being exposed to identical asymmetric vibration amplitudes. As such, employing the same amplitude-modulated feedback for all users to achieve a certain ω_target was unfeasible. Instead, the ω_target was adjusted in proportion to each participant's ω_default. Two ω_target values were selected for evaluation: one at 75% and the other at 50% of the participant's ω_default.

The 24 trials in the experimental phase were divided into three classes: 12 trials with A_v, six trials with A_c, and six trials with a Turning Test. The conditions of each trial were determined by the amplitude, ω_target and whether an inversion was invoked. Table II displays an overview of all trials in the experimental phase. The trials were executed in a randomised order, but the same sequence was applied for every participant.

At the end of each trial, participants were asked to return to the starting position. Then, the conditions for the subsequent trial were initialised and uploaded to the microcontroller, after which the microcontroller was manually activated. In total, the time between two trials was approximately 30 seconds. After every six trials, the participants were provided with a two-minute break. Breaks were primarily intended to prevent sensory overload but were also used to discuss anything unclear. All the experiment instructions were provided through the headphone.

TABLE II: Overview of all trials executed in the experimental phase.

	Conditions			
Class	Amplitude	ω_target	Inversion	Trials
Variable amplitude	$A_\text{v}^{0.8}$	75% of ω_default	No	3
		50% of ω_default	No	3
	$A_\text{v}^{0.6}$	75% of ω_default	No	3
		50% of ω_default	No	3
Constant amplitude	$A_\text{c}^{0.8}$	-	No	3
	$A_\text{c}^{0.6}$	-	No	3
Turning Test	$A_\text{c}^{1.0}$	-	Yes	3
		-	No	3

H. Data processing

A fundamental requirement for the proposed closed-loop system with amplitude-modulated pseudo forces is to induce a continuous movement in the desired direction. To assess whether the movements performed during the trials conformed to this requirement, all A_v and A_c trials were divided into three categories based on the participant's movement pattern:

1) Wrong: Trials in which the participant moved consecutively in the wrong direction $\geq$1.5 seconds.

The time criterion of 1.5 seconds was selected based on observations of the experiments. Values below this criterion were considered attempts to find the correct direction, and those above were considered significant movements in the wrong direction.

2) Intermittent: Trials in which the participant stopped $\geq$2 times.

3) Correct: Trials that were not categorised as *wrong* or *intermittent*.

Only trials categorised as *correct* were incorporated to further assess the efficacy of amplitude-modulated feedback, as they fulfilled the fundamental requirement of being a continuous movement in the desired direction. *Wrong* trials and, to a lesser extent, *intermittent* trials would considerably impact the error from the ω_target, as they exhibited a partially negative angular velocity or partially zero angular velocity, respectively. Regarding the A_c trials, using ω_target is misleading since such trials did not have a ω_target conditioned. However, to compare A_v and A_c trials, they must be related to the same reference point, which in this case, is the ω_target.

For the *correct* trials, the efficacy of amplitude-modulated pseudo forces was assessed using two metrics, the mean absolute error (MAE) and the mean absolute percentage error (MAPE). MAE provided valuable information about the absolute difference between the ω_raw and the ω_target in degrees per second. However, it did not consider the relative size of the error in relation to the ω_target. MAPE did take into account this relative size of the error, but a limitation of this metric was the potential for generating excessively large percentage errors for lower ω_{target} values. Consequently, using both MAE and MAPE provided a comprehensive understanding of the efficacy of amplitude-modulated pseudo forces.

It was hypothesised that the error decreased towards the end of the trajectory for A_{v} trials, as the participants had more time to adjust their angular velocity based on the amplitude feedback. Therefore, the trajectory was divided into three parts: 0-25°, 25-50°, and 50-75°. For every part, the MAE and MAPE were calculated. The error outcomes were employed to test the null hypothesis that amplitude-modulated pseudo forces did not significantly reduce the error between the ω_{raw} and the ω_{target} compared to constant-amplitude pseudo forces. The alternative hypothesis suggested that the classes were significantly different.

Trials categorised as *wrong* were investigated for a correlation with either time or angular distance. Following the methodology applied to identify *wrong* trials, all time instances and angular distances at which the participant switches from the correct to the wrong direction, followed by a consecutive movement in the wrong direction for $\geq$1.5 seconds, were extracted from both A_{v} and A_{c} trials. These instances are referred to as false inversions.

Furthermore, a confusion matrix was constructed to evaluate the participant's response to the sudden inversion of the asymmetric vibration direction during Turning Test trials. Additionally, the null hypothesis was tested that the participant's angular velocity at the instance of checkpoint crossing was equal for both responders and non-responders to an inversion, with the alternative hypothesis indicating that one of both groups had a higher angular velocity than the other. The Mann-Whitney U test was selected for all statistical analyses in this paper, as it does not assume any specific distribution of the data. Lastly, the participants' individual performance throughout the experiment was investigated by comparing the amount of *correct* A_{v} and A_{c} trials with their Turning Test scores.

III. Results

Table III presents the categorisation of all A_{v} and A_{c} trials. Each of the 17 participants performed three trials per condition, counting up to a total of 51 trials. For each condition, the table showcases the results of all three trials and their summation, displaying the inter- and intra-condition variabilities.

The table reveals that 43% of all A_{v} and A_{c} trials were categorised as *wrong*. The trials in this category were relatively evenly distributed for all conditions, with a slightly higher count for $A^{0.6}$ compared to $A^{0.8}$ and a more notable increase for the lower ω_{target}.

Regarding the *intermittent* trials, there was a difference observed between A_{v} and A_{c}, as they constitute 25% and 14% of the total amount of trials, respectively. Collectively, the *intermittent* trials account for 21% of all trials, with 7% belonging to $A^{0.8}$ and 14% to $A^{0.6}$.

As the *correct* category includes all trials that were not *wrong* or *intermittent*, the trend in this category was opposite to the trend in the other two. For the $A_{\text{v}}^{0.8}$, 41% of the trials were *correct*, while only 19% were for $A_{\text{v}}^{0.6}$. These numbers indicate a clear preference for $A_{\text{v}}^{0.8}$, and thus, further assessment of the efficacy of amplitude-modulated feedback focuses solely on this amplitude.

TABLE III: Categorisation of all trials with variable amplitude (A_{v}) and constant amplitude (A_{c}).

Amplitude	ω_{target}	Trial	$A^{0.8}$ *Wrong*	$A^{0.8}$ *Intermittent*	$A^{0.8}$ *Correct*	$A^{0.6}$ *Wrong*	$A^{0.6}$ *Intermittent*	$A^{0.6}$ *Correct*
A_{v}	75% of ω_{default}	1	6	2	9	8	5	4
		2	7	1	9	7	5	5
		3	6	4	7	8	5	4
		Total	19	7	25	23	15	13
	50% of ω_{default}	1	8	4	5	10	6	1
		2	9	1	7	7	8	2
		3	8	4	5	9	5	3
		Total	25	9	17	26	19	6
A_{c}	-	1	7	2	8	6	4	7
		2	6	1	10	5	4	8
		3	7	1	9	7	2	8
		Total	20	4	27	18	10	23

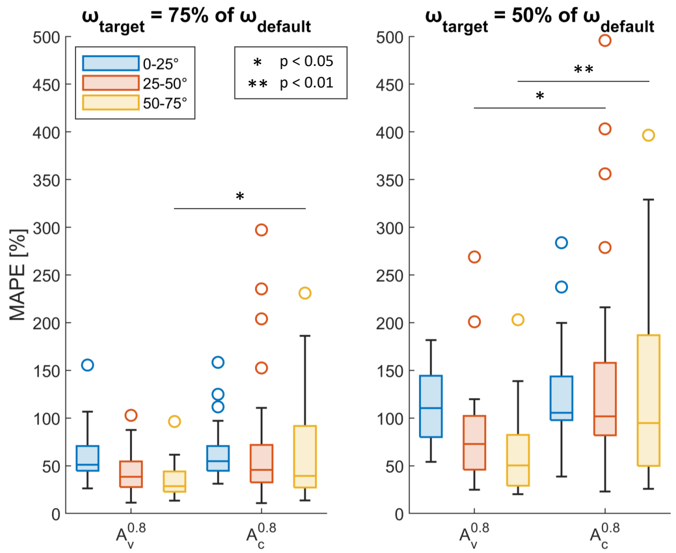


Figure 5: Mean absolute percentage error from the target angular velocity for variable amplitude ($A_v^{0.8}$) and constant amplitude ($A_c^{0.8}$) during three trajectory parts. The boxplots only include the correct trials (sequentially: N=25, N=27, N=17, N=27).

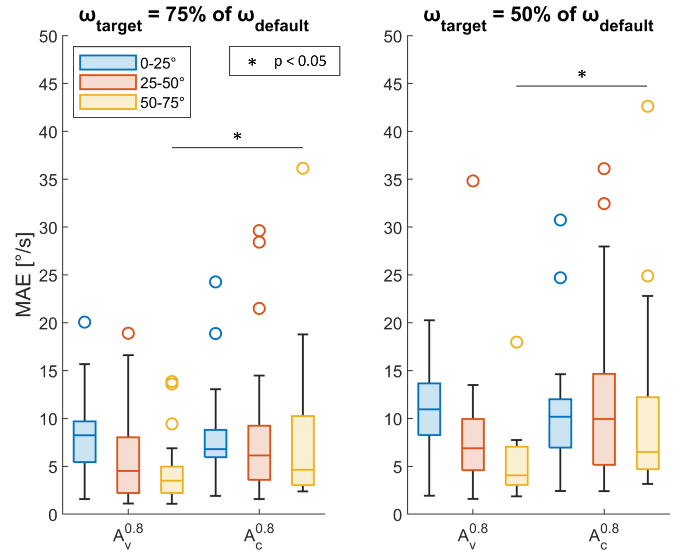


Figure 6: Mean absolute error from the target angular velocity for variable amplitude ($A_v^{0.8}$) and constant amplitude ($A_c^{0.8}$) during three trajectory parts. The boxplots only include the correct trials (sequentially: N=25, N=27, N=17, N=27).

A. Error

The MAPE between the ω_{raw} and the ω_{target} during the trajectory parts 0-25°, 25-50°, and 50-75° is visualised in Figure 5 for both ω_{target} values. In the first part of the trajectory, the MAPE observed for $A_v^{0.8}$ and $A_c^{0.8}$ was very similar. In particular, for the ω_{target} of 75%, where the means and standard deviations of $A_v^{0.8}$ *(Mean=59.8, STD=26.4)* closely matched those of $A_c^{0.8}$ *(Mean=63.5, STD=29.9)*. Also for the ω_{target} of 50%, no statistical difference *(p=0.63)* was found between $A_v^{0.8}$ *(Mean=113.6, STD=36.6)* and $A_c^{0.8}$ *(Mean=125.2, STD=53.1)*. These findings align with expectations, as participants had limited time to adjust their angular velocity based on the amplitude feedback received.

In the middle part of the trajectory, the impact of amplitude-modulated feedback becomes more apparent, particularly for the ω_{target} of 50%, where the MAPE of $A_v^{0.8}$ *(Mean=85.9, STD=58.8)* was significantly lower *(p<0.05)* compared to $A_c^{0.8}$ *(Mean=142.8, STD=115.1)*. For the ω_{target} of 75%, no statistical difference *(p=0.23)* was found between $A_v^{0.8}$ *(Mean=43.4, STD=24.1)* and $A_c^{0.8}$ *(Mean=70.1, STD=71.1)*.

In the final part of the trajectory, the MAPE difference between $A_v^{0.8}$ and $A_c^{0.8}$ was most prominent. For the highest ω_{target}, the amplitude-modulated feedback *(Mean=34.6, STD=18.5)* reduced the MAPE significantly *(p<0.05)* compared to $A_c^{0.8}$ *(Mean=65.2, STD=56.2)*. The effect for the lower ω_{target} was even more apparent, with $A_v^{0.8}$ *(Mean=61.6, STD=46.0)* exhibiting a significantly lower *(p<0.01)* MAPE than $A_c^{0.8}$ *(Mean=127.4, STD=98.2)*.

Figure 6 presents the MAE between the ω_{raw} and the ω_{target}, which followed a trend similar to the MAPE. Between 50-75°, the MAE of $A_v^{0.8}$ *(Mean=4.5, STD=3.2)* was significantly lower *(p<0.05)* compared to $A_c^{0.8}$ *(Mean=7.7, STD=7.5)* for the ω_{target} of 75%. Also for the other ω_{target}, $A_v^{0.8}$ *(Mean=5.3, STD=3.6)* exhibited a significantly lower *(p<0.05)* MAE compared to $A_c^{0.8}$ *(Mean=10.0, STD=8.9)* during the last part of the trajectory.

Two additional observations can be made from the boxplots presented in Figure 5 and Figure 6. Firstly, it is notable that the MAPE and MAE towards the end of the trajectory decrease even in the absence of amplitude-modulated feedback. Analysis of the velocity course towards the end of the trajectory during A_c trials indicated that participants generally reduced their angular velocity towards the end. Since most participants rotated much faster during A_c trials than the ω_{target} (being only 75% or 50% of their ω_{default}), the decrease in velocity towards the end of the trajectory reduced the error between their angular velocity and the target.

Secondly, the boxplots reveal that A_c trials exhibit much more deviation than A_v trials. Especially for the second and third part of the trajectory, with an average standard deviation of 79.5 for A_c, compared to 42.6 for A_v. Thus, using amplitude-modulated pseudo forces decreases the deviation by nearly 50%.

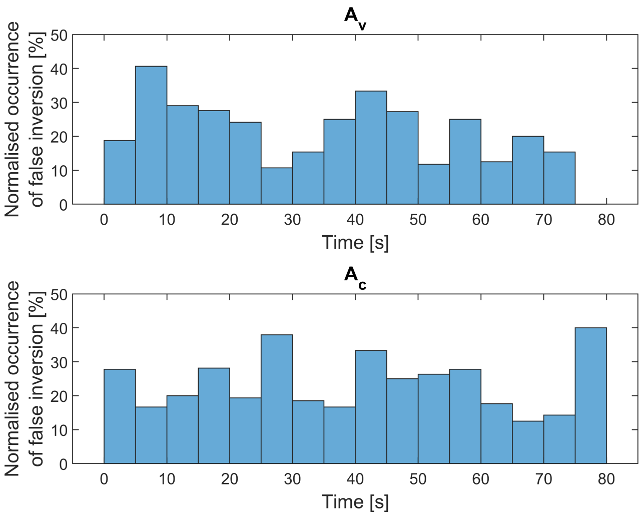


Figure 7: Trial time at which a false inversion occurred, separated for variable amplitude (A_v, N=241) and constant amplitude (A_c, N=168).

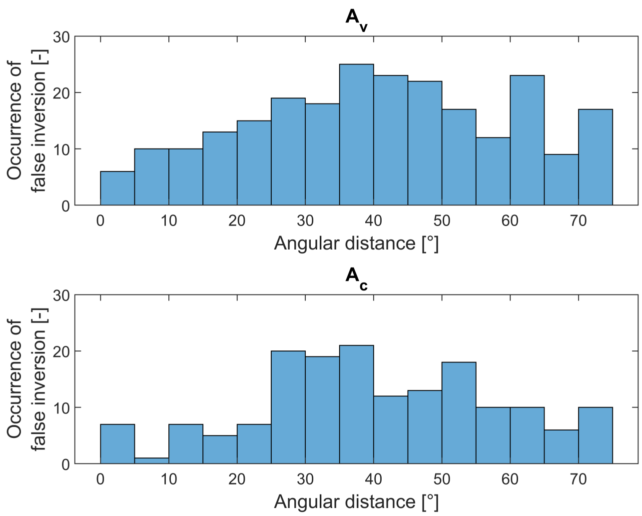


Figure 8: Angular distance at which a false inversion occurred, separated for variable amplitude (A_v, N=241) and constant amplitude (A_c, N=168).

B. Wrong trials

In Figure 7, the relationship between time and the occurrence of false inversions is displayed. To ensure an equal comparison between all time intervals, the number of false inversions in each interval was normalised by the total number of *wrong* trials that were in progress during that specific time interval. The results indicate no increase in false inversions as trial durations become longer for both A_v and A_c.

Figure 8 illustrates the occurrence of false inversions against the angular distance at which they occurred. The findings reveal a notable peak in occurrence within the range of 35-50° for A_v trials, and 25-40° for A_c trials. This observation may indicate a physical boundary resulting from a lack of motor control in the middle part of the trajectory, which will be addressed more in-depth in the discussion section.

TABLE IV: Confusion table showing participant responses to inversion of the asymmetric vibration at the first (N=99) and second checkpoint (N=20).

			Response	
			Inversion	No inversion
Real	First Checkpoint	Inversion	22 (46%)	26 (54%)
		No inversion	16 (31%)	35 (69%)
	Second Checkpoint	Inversion	18 (90%)	2 (10%)
		No inversion	-	-

C. Turning Test

Following the methodology described in Section II-H, the Turning Test involved six trials per participant, including three trials with the inversions turned on and three with it turned off, all at the same constant amplitude: the participant's optimal. The performance of all participants was summarised in two confusion matrices, one for each of the two inversion checkpoints, as shown in Table IV. The rows and columns of the confusion matrix represent the *real* state and the participant's *response*, respectively. Notably, the second checkpoint does not contain any results for the *real* "no inversion" condition since the vibration was not inverted at the first checkpoint during this condition.

Amongst the trials with *real* inversions, there were three trials in which a participant did not reach the first checkpoint before the termination of the trial at 80 seconds. These trials were excluded, remaining 48 trials. For the second checkpoint, 20 trials were included: the 22 trials where the participant responded correctly to the inversion at the first checkpoint, minus the two who did not reach the second checkpoint. The confusion table reveals that out of all the *real* inversions at the first checkpoint, only 22 were followed by a correct *response*, while the other 26 were false negatives. For the *real* trials without inversions, 35 led to a correct *response*, while 16 were false positives. At the second checkpoint, 18 out of 20 trials were followed by a correct *response*, while the other two were false negatives.

During the Turning Test, it was observed that mainly participants with higher angular velocities tended to ignore the vibration inversion. To investigate this relationship, the participant's angular velocity at the instance of checkpoint crossing was plotted versus the correctness of response, as displayed in Figure 9. The boxplots show that the angular velocity of false responders (*Mean=23.6, STD=12.8*) was significantly higher (*p<0.01*) than correct responders (*Mean=15.1, STD=9.9*).

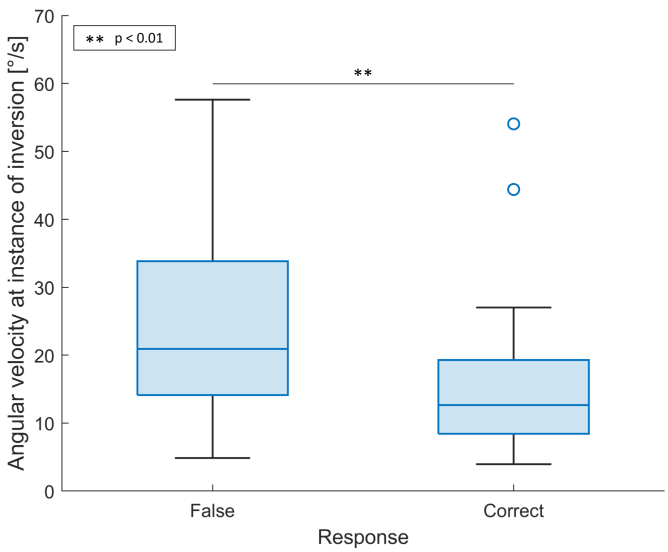


Figure 9: Participant's angular velocity when the checkpoint is crossed, and thus the vibration is inverted. All checkpoint crossings are assigned to a false (N=28) or correct (N=40) response.

D. Interparticipant variability

Figure 10 displays the individual performance of participants in $A_v^{0.8}$, $A_v^{0.6}$ and A_c trials, and the Turning Test. Analysis of the A_v and A_c trials reveals that the same individuals performed *correct* for both the variable and constant amplitude. However, a comparison with the Turning Test trials reveals that most individuals with high *correct* scores in the A_v and A_c trials tended to ignore the vibration direction inversion during the Turning Test, and vice versa.

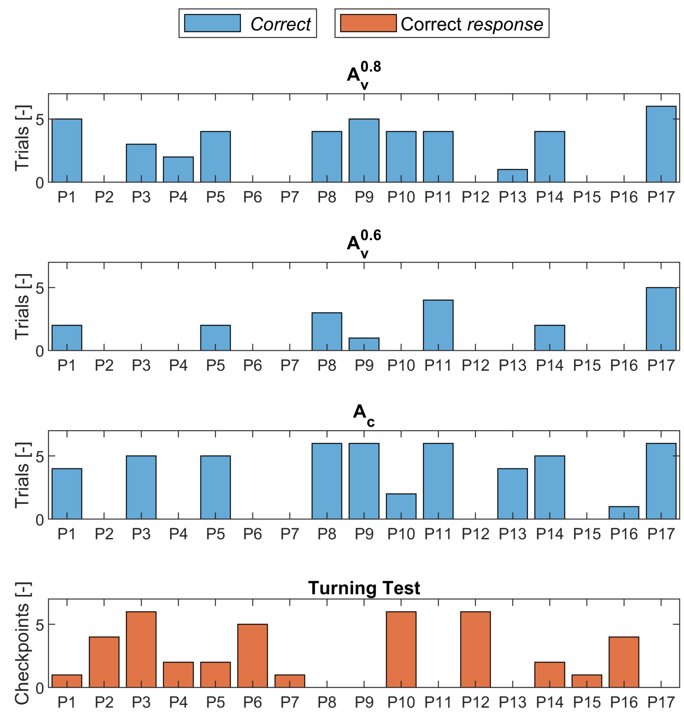


Figure 10: Performance of all participants during variable amplitude ($A_v^{0.8}$ and $A_v^{0.6}$), constant amplitude (A_c), and the Turning Test.

IV. Discussion

This study demonstrated that using variable amplitude-modulated pseudo forces significantly decrease the error towards a ω_{target} as compared to using constant-amplitude pseudo forces. For one of the evaluated variable amplitudes ($A_v^{0.8}$), the MAPE reduced by almost 50% as opposed to constant-amplitude stimuli.

However, these findings were based only on trials that were categorised as *correct*, accounting for just 41% of the trials for the preferred $A_v^{0.8}$. More trials (43%) were identified as *wrong*, while the rest were labelled as *intermittent* (16%). Additionally, the study included a test that evaluated participants' responses to sudden inversion of the asymmetric vibration. Only 46% of the participants responded correctly to the first inversion, of which 90% responded correctly to the second inversion. These results do not align with the open-loop research reporting a correct response rate of more than 88% [9]–[14]. The primary difference was that previous studies investigated the participant's initial ability to distinguish directional cues from a standstill, while this research monitored their movement over a longer period, including in-motion responses to sudden changes in vibration direction. In this Section will be explored whether the observed differences in results can be mainly attributed to this primary difference or whether other influential factors had crucial impact.

A. Training

One factor that expectedly had a large impact on the outcomes of this study, was the approach used to focus on intuitive movement guidance without any learning support. During the familiarisation phase, participants were not given any feedback on the correctness of the direction they were moving in. Also, participants were only subjected to a vibration with a constant amplitude during familiarisation and experienced varying amplitude for the first time during the experimental phase. This sudden amplitude modulation might have confused the participants, mainly because they were not informed of the goal of reaching a constant ω_{target}. This confusion could have led participants to associate the amplitude modulation with either vibration inversion or the sensation of being pulled to a particular angular distance, resulting in *wrong* and *intermittent* trials. This hypothesis was supported by the greater number of *wrong* and *intermittent* trials for A_v compared to A_c, as shown in Table III.

In addition to training on how to use amplitude modulation to reach the ω_{target}, training on how to respond to vibration inversion could also be taught. Users can be notified when inversion is about to occur, allowing them to focus their attention entirely on the sensation and link their perception to the correct action. This training is expected to significantly reduce the number of *wrong* trials and increase the number of correctly identified *real* inversions.

B. Latency

As mentioned in Section II-C, the applied causal filter with a low operating sampling frequency and a large time window induced latency. This latency, referring to the delay between a change in the participant's angular velocity and the corresponding amplitude feedback, is expected to have caused intermittency during A_{v} trials. Since the latency made the participants respond to their past movements, the delayed amplitude-modulated feedback often led to an oscillating movement. This phenomenon affects $A_{\text{v}}^{0.6}$ more than $A_{\text{v}}^{0.8}$ due to the difference in the rate of amplitude variation. For instance, when a participant moved at their ω_{default} in a trial where the ω_{target} was set at 50%, $A_{\text{v}}^{0.8}$ resulted in an amplitude of 0.6, while $A_{\text{v}}^{0.6}$ resulted in an amplitude of 0.2. An amplitude of 0.2 nearly extinguished the vibration, often causing the participants to come to a standstill. In contrast, with $A_{\text{v}}^{0.8}$, a participant had to rotate at twice their ω_{default} before the amplitude dropped to 0.2. The effect of this difference in the rate of amplitude variation between $A_{\text{v}}^{0.8}$ and $A_{\text{v}}^{0.6}$ is apparent in the categorisation table.

Further research is necessary to determine the efficacy of using a filter with a shorter time window or an exponential filter that assigns more weight to recent data. Additionally, it should be investigated to which extent the direct linkage of amplitude modulation to the ω_{raw} affects the perception. This information will enable a well-informed decision regarding how to link angular velocity to amplitude modulation.

C. Experimental setup

Although the researcher did not perceive any physical boundary for the selected combined movement of internal-external shoulder rotation and elbow flexion-extension, some participants reported they did. Based on the hypothesis that a lack of motor control in some part of the trajectory induced such a physical boundary, the occurrence of false inversions was plotted against the angular distance at which they occurred (Figure 8). Although the findings cannot reject the existence of a physical boundary, it is hard to imagine that the boundary was so robust as to cause false inversions. However, there was another factor that might have slightly contributed to the physical boundary: the aux cable transmitting the asymmetric audio signal to the haptuator. The aux cable was attached to the frame at a height of approximately 40cm, with the frame's foot perpendicular to the trajectory's midpoint. As the participant moved away from this midpoint, the cable's weight exerted a slight pulling force towards the trajectory's centre, where the distance to the attachment point was the shortest. In retrospect, it would have been better to lead the aux cable via the participant's wrist and elbow to the table, similar to the cable linking the IMU to the microcontroller.

This study also investigated the correlation between time and the occurrence of false inversions based on the presumption that prolonged trials can lead to sensory overload. This overload may have caused participants to lose the direction cue, resulting in movement in both directions in an attempt to rediscover the right one. Although no indication of desensitisation was found in Section III-B, multiple participants reported they had lost the direction cue after a certain trial duration. Previous studies had already implemented breaks to reduce the impact of sensory overload [10], [13], [19], even though their trials only lasted a few seconds. In contrast, the average trial time in this study was 22 seconds, making sensory overload during a trial more probable. The combination of vibration desensitisation and a physical boundary arising from the experimental movement and the pulling aux cable may have contributed to the high number of *wrong* trials. For everyday implementation in a movement guidance system, the physical boundary can be easily overcome by proper assembly and executing more natural, unforced movements. But the desensitisation to vibration may limit the practical application of the proposed amplitude-modulated pseudo forces in a wearable movement guidance device. Future research is necessary to investigate this phenomenon.

The last experimental setup-related influential factor was the friction force between the participant's hand and the table. Static friction is known to be higher than kinetic friction [24], leading to a velocity overshoot when the participant starts sliding their hand. This occurs because it requires a greater force to overcome the static friction while starting the motion than the force required to maintain the motion. As a result, some participants accelerated towards a higher angular velocity than anticipated. For participants with a low ω_{default}, this overshoot significantly impacted their amplitude modulation. With the ω_{target} set to 75% or 50% of their ω_{default}, the ω_{target} may have been well below the peak velocity during overshoot, resulting in an amplitude drop. This, in turn, caused the participant to come to a standstill, starting the process all over again. The theory was supported by the results of the three participants with a ω_{default} below 5°/s (P7, P12, and P13). For the preferred $A_{\text{v}}^{0.8}$, these participants accounted for 7 out of the 16 *intermittent* trials, a contribution of 44%, despite only comprising 18% of the participants.

The static friction force being greater than the perceived pseudo force and thus inhibiting movement was also expected to be the explanation for the two participants who did not respond to the asymmetric vibration at all. There is substantial evidence that the pseudo force sensation can be attributed to skin displacement and Meissner corpuscles [13], [19], [25]. Expectedly, the transition from skin displacement and excitation of Meissner corpuscles to movement was highly user-dependent. Alternatively, the minor interparticipant variations in haptuator grasping may have also impacted the perception of pseudo forces. A more consistent method for grasping or even attachment to the fingers should be implemented in future studies.

D. Turning Test

As briefly noted, the results of the Turning Test fell below expectations based on previous research. One possible explanation for the underperformance pertains to the first checkpoint for inversion occurring at 60°, near the endpoint of 75° where the vibration terminates. This proximity could have negatively affected the outcome.

Upon passing the checkpoint, the vibration was inverted on the next time instant (52ms), after which the Meissner corpuscles detect the vibration inversion, activating afferent neurons that propagate impulses to the brain at a speed of approximately 50 meters per second (taking 15ms) [26]. The brain processes the nerve impulses to determine the appropriate muscle response to the sensory input (130ms) [27], followed by the propagation of a nerve impulse back to the muscles initiating activation dynamics (25ms) [26], [28].

Given an average angular velocity of 20°/s at the moment of inversion, the total elapsed time of approximately 220ms corresponds to an angular displacement of more than 4° before the participant could react. If a participant with an average angular velocity responded instantaneously, deceleration had to occur within the next 11°, a relatively short distance to decelerate and change direction at that angular velocity. Figure 9 supports the theory by showing that non-responders had significantly higher angular velocities than correct responders.

V. Conclusion

This paper introduced the first closed-loop system for movement guidance using pseudo forces, with amplitude-modulated pseudo forces as haptic feedback. A human factors study demonstrated that these amplitude-modulated pseudo forces significantly decrease the error towards a specific target angular velocity: a reduction of 48.9% compared to pseudo forces with a constant amplitude. In absolute terms, the participants moved 4.0°/s closer to the target angular velocity when applying amplitude-modulated stimuli. However, the majority of trials failed to meet the base requirement for a movement guidance system, which was to induce a continuous movement in the desired direction. This is attributed to a lack of training, latency induced by the applied causal smoothing filter, and a physical boundary and friction force resulting from the experimental setup. Despite these limitations, it is hypothesised that amplitude-modulated pseudo forces will guide the future development of a wearable movement guidance device.

VI. Acknowledgements

I'm very grateful for the guidance I received during my thesis. In particular, I would like to express my gratitude towards Dr. Eline van der Kruk and Dr. Michaël Wiertlewski, whose expertise and critical questions were a huge source of inspiration. Also, thanks to all the participants who dedicated their time to contribute to this research. Special thanks to Maurits Pfaff for sharing his knowledge of soldering, shielding and signal analysis. And last but not least, thanks to my fellow students in the F-wing for sharing this experience with me and keeping me sharp and motivated.

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Appendix A – Hardware Assembly

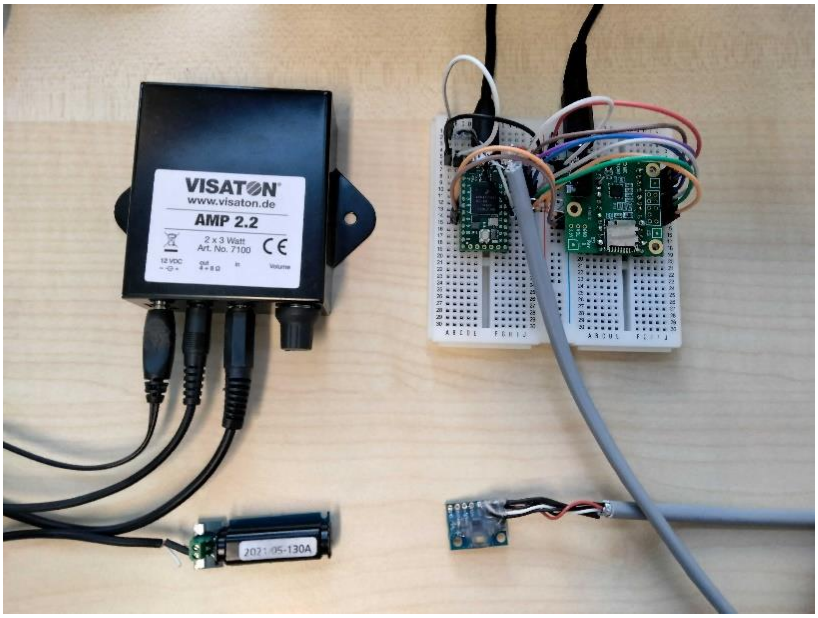


Figure 1: Overview of the hardware used in this research

The hardware used for this experiment is depicted in Figure 1. A Teensy 4.0 microcontroller, audio adaptor board and MPU-6050 inertial measurement unit were connected on a breadboard. Table 1 shows the connections between the three components.

Teensy 4.0	Audio adaptor board	MPU-6050	Function
GND	GND	GND	Connect ground
3.3V	3.3V	VCC	Connect power
7 (OUT1A)	7 (DIN)	-	Send audio data from Teensy to Audio adaptor board
8 (IN1)	8 (DOUT)	-	Send audio data from Audio adaptor board to Teensy
18 (SDA0)	18 (SDA)	SDA	Control data (I^2C)
19 (SCL0)	19 (SCL)	SCL	Control clock (I^2C)
20 (LRCLK1)	20 (LRCLK)	-	Control audio left/right clock
21 (BCLK1)	21 (BCLK)	-	Control audio bit clock
23 (MCLK1)	23 (MCLK)	-	Control audio master clock

Table 1: Connections between the Teensy 4.0, audio adaptor board and MPU-6050

The microcontroller was connected through USB with a laptop. A pre-programmed code in Arduino IDE controlled the microcontroller. The audio adaptor board sent an audio signal to the Visation AMP 2.2 amplifier, which amplified the signal with a gain of 1.9, after which the signal induced an asymmetric vibration at the HapCoil-One haptuator. A 4Ω resistor was put in series with the haptuator, enabling a higher Voltage across the haptuator while staying below its 'rated current' (147.8mA).

Appendix B - Participant Information

Dear potential participant,

You are invited to participate in a research study titled 'Using amplitude modulated pseudo forces to control movement guidance.' This study is executed by Kasper Dols (Master's student at the TU Delft) under the supervision of Assistant Professors Michaël Wiertlewski and Eline van der Kruk. This document will inform you about the research. If you have any questions, don't hesitate to ask one of the researchers. You can find their contact details at the bottom of this document.

Purpose of the research
When subjected to an asymmetric vibration, humans perceive an ungrounded pulling or pushing sensation. This so-called pseudo force has great potential to guide human movement. Currently, only open-loop systems are published, which cannot monitor and correct users when their limb does not follow the desired movement. This research focuses on closing the loop, evaluating if amplitude modulated pseudo forces can accurately control movement.

Procedure of experiment
Once you have decided to participate in this research, you will be asked to come to the mentioned location, where we 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 informed consent form. The estimated time requirement is 60 minutes. We will ask you to provide us with some information regarding your age and sex. In the experiment, your response to two different forms of feedback will be analysed:

1. Response without feedback
2. Response with amplitude feedback

You will be asked to rotate your forearm several times during the experiments. To analyse the movement of your forearm, we stick an Inertial Measurement unit on it with medical-grade double-sided tape. An elastic strap is fixed to your arm to hold the IMU and wires in place (Figure 1). Moreover, you will be holding one haptuator (Figure 2) in your dominant hand. This haptuator will produce vibrations. Finally, you are asked to wear an eye mask and noise-cancelling headphones to cancel audiovisual cues.

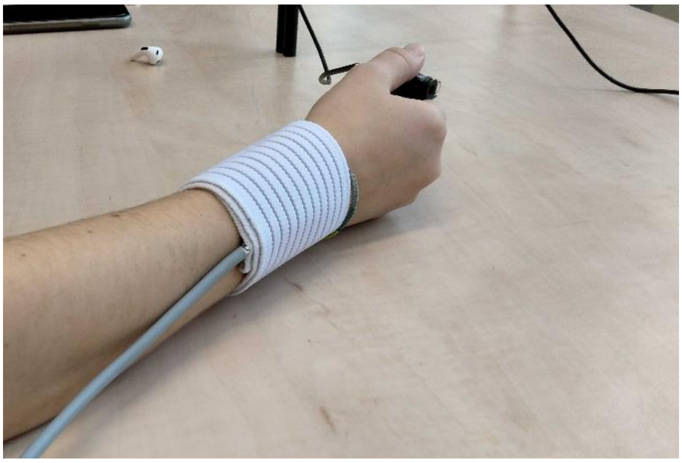


Figure 1: The Inertial Measurement Unit

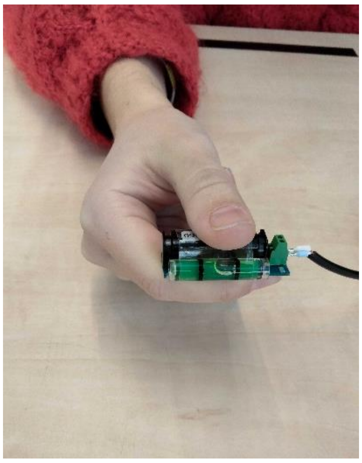


Figure 2: The haptuator

Are you eligible to participate?
We would like you to consider participating in this study if you are a healthy young adult with no sensory disorders in your dominant hand. Please refrain from participating in this study if you have any Covid related symptoms.

What are the side effects, and are there any risks in participating?
It is a non-invasive study. You may experience a minor tingling sensation for a couple of minutes after releasing the haptuator. Moreover, a medical grade double-sided tape would be used for placing the Inertial Measurement Unit on your skin. Removing the double-sided tape will be a bit painful but is temporary and usually lasts less than 30 seconds.

What are the benefits of taking part?
There are no clear benefits to you for taking part. However, the information from this study provides insightful information on the possibility of using amplitude scaled pseudo forces to control movement guidance.

Do I have to take part?
No, your decision to participate is entirely up to you. 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 participate or withdraw from the study, it will not affect any future interactions you may have with the TU Delft. If you choose to withdraw, the information collected up until that point can be deleted on your request. Please inform any member of the research team straight away if you no longer wish to participate in the study.

Confidentiality of data
This study requires that the following personal data are collected and used: sex, age, and contact details (email). Your sex and age will be used to represent the group of participants, while your contact details will be used for communication. To safeguard and maintain the confidentiality of your personal information, necessary security steps will be taken. Your data will be stored in a secure storage environment at TU Delft, only accessible to the researchers mentioned at the bottom of this document. Personal data will be anonymized before processing.

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 pseudonymized personal data will be retained in accordance with the TU Delft Research Data Framework Policy. Anonymized or aggregated data may be shared with others after the end of the research project. The results of this study will be published in a scientific publication. Your participant number, name, and contact details will never be shared in a publication. The anonymized data will be used for research purposes and future publications based on research only.

Contact details
If you have any complaints regarding the 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 research team, thank you in advance for your possible cooperation.

Kasper Dols (k.c.dols@student.tudelft.nl), +31 6 42519201

Dr. Michael Wiertlewski (M.Wiertlewski@tudelft.nl)

Dr. Eline van der Kruk (E.vanderKruk@tudelft.nl)

Appendix C - Informed Consent Form

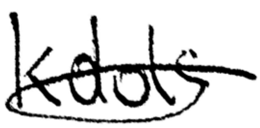
PLEASE TICK THE APPROPRIATE BOXES	Yes	No
Participating in the study		
I have read and understood the study information dated 23th November 2022, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily 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.	☐	☐
Potential risks of participating		
I understand that taking part in the study involves the following risks: • You may experience a minor tingling sensation for a couple of minutes after releasing the haptuator. • Removing the medical grade double-sided tape of your forearm will be a bit painful but is temporary and usually lasts less than 30 seconds.	☐	☐
Use of information		
I understand that after the research study the de-identified information I provide will be used for a scientific publication.	☐	☐
I understand that personally identifiable information, such as my contact details, sex, and age will not be shared beyond the study team.	☐	☐
I give permission for the de-identified motion data that I provide to be archived in a secure drive of the TU Delft so it can be used for future research and learning.	☐	☐

Signatures

________________________ ________________________ ________

Name of participant [printed] Signature Date

I, as researcher, 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.



Kasper Dols 23th November 2022

________________________ __________________ ________

Researcher name [printed] Signature Date

Study contact details for further information:

Kasper Dols (k.c.dols@student.tudelft.nl), +31 6 42519201

Appendix D - Edinburgh Handedness Inventory

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put ++*. If in any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task. Some activities are translated into Dutch for clarity.

PLEASE TICK THE APPROPRIATE BOXES	LEFT	RIGHT
Writing		
Drawing		
Throwing		
Scissors		
Toothbrush		
Knife (without fork)		
Spoon		
Broom (upper hand) *Bezem (bovenste hand)*		
Striking Match (match) *Lucifer aansteken (lucifer)*		
Opening box (lid) *Doos openmaken (deksel)*		

If you are interested, this is how you can calculate your score:

$$Laterality\ Quotient = \left(\frac{R - L}{R + L}\right) * 100$$

With R & L referring to the total number of "+" marked on the right and left side respectively

Interpretation Laterality Quotient:

- Left-handedness = Less than -40
- Ambidexterity = Between -40 and +40
- Right-handedness = More than +40

____________________________	____________________
Name of participant [printed]	Laterality Quotient

Appendix E – Inspection Report

Delft University of Technology
INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies[1].

The first part of the report has to be completed by the researcher and/or a responsible technician.

Then, the safety officer (Heath, Security and Environment advisor) of the faculty responsible for the device has to inspect the device and fill in the second part of this form. An actual list of safety-officers is provided on this webpage.

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. Information on ethics topics, including the application process, is provided on the HREC website.

Device identification (name, location): HapCoil-One**,** IMU (MPU6050)

Configurations inspected[2]: NA

Type of experiment to be carried out on the device[3]: Directing motion by vibration, measuring the angular velocity

Name(s) and job title(s) of applicants(s): Kasper Dols (MSc student), Michaël Wiertlewski (Assistant Professor)

(Please note that the inspection report should be filled in by a TU Delft employee. In case of a BSc/MSc thesis project, the responsible supervisor has to fill in and sign the inspection report.)

Date: 07-11-2022

Signature(s):

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1 Modified, altered, used for a purpose not reasonably foreseen in the CE certification

2 If the devices can be used in multiple configurations, otherwise insert NA

3 e.g. driving, flying, VR navigation, physical exercise, ...

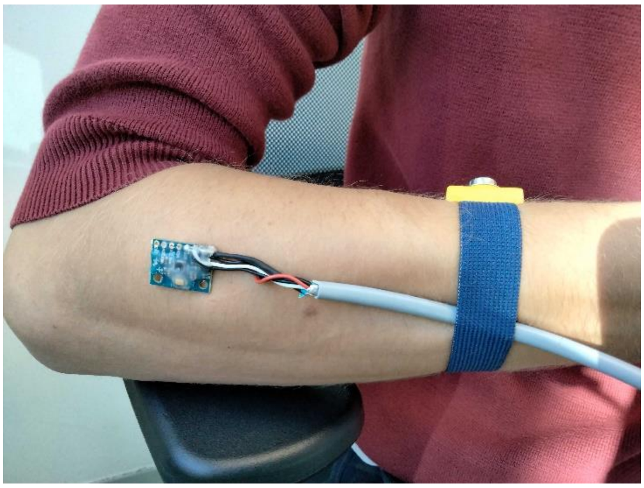
Setup summary

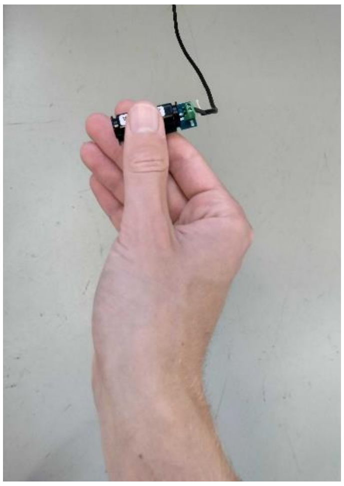
Please provide a brief description of the experimental device (functions and components) and the setup in which context it supposed to be used. Please document with pictures where necessary.

More elaborate descriptions should be added as an appendix (see below).

The picture below shows all devices. A Teensy microcontroller and audio shield are connected on a breadboard (top right), sending a signal via an amplifier (top left) towards the HapCoil-One haptuator (bottom left). This induces an asymmetric vibration at the haptuator. The bottom right displays an MPU6050 Inertial Measurement Unit, sending digital angular velocity output directly to the Teensy.

During the experiment, the Inertial Measurement Unit (IMU) will be stuck on the participant's arm with medical-grade double-sided tape. An elastic strap is fixed to the arm to hold the IMU and wires in place. Moreover, the participant will be holding one haptuator in their hand. All devices run on 5 Volt, and the devices interacting with humans are shielded. The IMU and haptuator are CE certified, having a non-conductive coating and shielding, respectively.





Risk checklist

Please fill in the following checklist and consider these hazards that are typically present in many research setups. If a hazard is present, please describe how it is dealt with.

Also, mention any other hazards that are present.

Hazard type	**Present**	**Hazard source**	**Mitigation measures**
Mechanical (sharp edges, moving equipment, etc.)	X	Vibration, which causes moving device	The amplitude will be in a safe range, so the participants will only experience a minor tingling sensation
Electrical			
Structural failure			
Touch Temperature			
Electromagnetic radiation			
Ionizing radiation			
(Near-)optical radiation (lasers, IR-, UV-, bright visible light sources)			
Noise exposure			
Materials (flammability, offgassing, etc.)			
Chemical processes			
Fall risk			
Other:			
Other:			
Other:			

Appendices

Here, you may add one or more appendices describing more detailed aspects of your setup or the research procedures.

Device inspection

(to be filled in by the AMA advisor of the corresponding faculty)

Name: Peter Kohne

Faculty: 3mE/IO

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical testing, measurements for electrical safety etc.)

Date: 15-11-2022

Signature:

Inspection valid until[4]:

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

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4 Indicate validity of the inspection, with a maximum of 3 years