Tendon Vibration for Creating Movement Illusions in Virtual Reality

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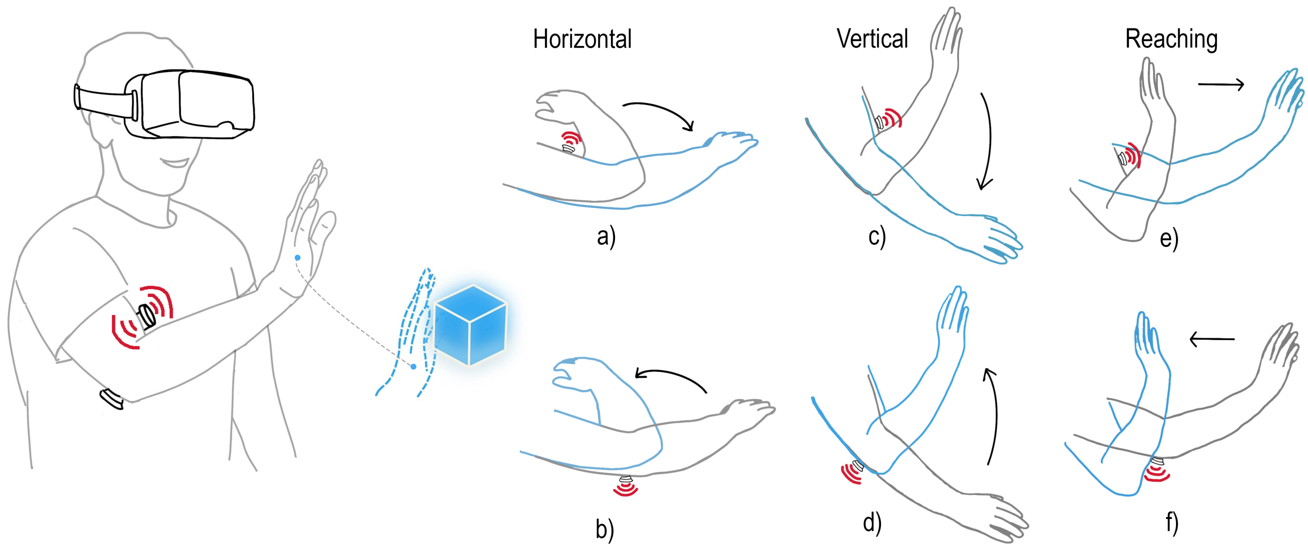

Figure 1: On the left: Vibrating muscle tendons with motors on the skin can create a movement illusion of the virtual hand moving faster-than-actual towards a reached cube. The three movement types investigated in Studies 1 and 2 are Horizontal (a, b), Vertical (c, d), and Reaching (e, f), covering two movement directions each, where vibrating the biceps tendon (a, c, e) creates an illusion of extending the arm from the elbow, while vibrating the triceps tendon (b, d, f) induces an illusion of flexing the arm.

Abstract

Tendon vibration can create movement illusions: vibrating the biceps tendon induces an illusion of extending the arm, while vibrating the triceps tendon induces an illusion of flexing the arm. However, it is unclear how to create and integrate such illusions shown in neuroscience to interaction techniques in virtual reality (VR). We first design a motor setup for tendon vibration. Study 1 validates that the setup induces movement illusions which on average create a 5.26 cm offset in active arm movements. Study 2 shows that tendon vibration improves the detection thresholds of visual motion gains often used in VR interaction techniques by 0.22. A model we developed in Study 2 predicts the effects of tendon vibration and is used in a biomechanical simulation to demonstrate the detection thresholds across typical reaching tasks in VR.

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CCS Concepts

• **Human-centered computing** → **Virtual reality**; *User models*; *Empirical studies in HCI*.

Keywords

Virtual Reality, Hand Redirection, Tendon Vibration, Movement Illusions, Detection Thresholds

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1 Introduction

Vibration of muscle tendons can induce and change the sensation of movement on the body part connected to that muscle. In other words, tendon vibration can create movement illusions. The movement illusion induced by tendon vibration works by activating muscle receptors similar to how they activate when the muscle stretches, thereby creating an illusion of stretching it. For example, vibrating the tendons of the biceps near the elbow creates an illusion of stretching the biceps and hence extending the arm; vibrating the triceps creates an illusion of bending the arm (Figure 1). Tendon vibration has been extensively studied in neuroscience. However, to apply it in virtual reality (VR), stimulating the muscle tendons with vibration motors should reliably induce the illusions during active movements and integrate effectively with visual motion gains of the hand across three-dimensional reaching tasks.

In neuroscience, tendon vibration has shown to induce a movement illusion of flexing and extending the elbow. However, the illusions are produced using a range of different types of vibration motors, stimulation parameters with the motors, and ways to fix the motors on the skin. Furthermore, the illusion has been shown to work reliably only without an active movement of the same limb (e.g., on a static arm [19] or passively moved arm [9]). Research in haptics and VR has demonstrated that vibration motors on the skin can increase the detection thresholds of visual motion gains during active movements [20, 21, 24, 32]. However, the observed effect is general inaccuracy in the perception of the limb position caused by noise in the sensory system [13], and not a controllable illusion (e.g., of flexing or extending the arm). Therefore, it remains unclear how vibration motors could reliably induce an illusion during such active movements involved in the use of VR. We design a motor setup and the first study to address this question.

Movement illusions are particularly useful and also widely used in interaction techniques for VR. Movement illusions in VR are typically produced by changing the visual feedback of the user's body parts. For example, visual motion gains have been applied to the virtual hand reaching into the distance (e.g., Go-Go [35]), reaching to an object on the left or on the right (e.g., Haptic Retargeting [3]), or reaching higher up for ergonomics (e.g., Ownershift [15]). As tendon vibration can induce movement illusions, it has the potential to improve such techniques and open possibilities for new types of techniques. Studies in neuroscience typically create an illusion of flexing or extending the elbow only in horizontal movements and on an arm rest [6]. These are used to minimise the interference caused by muscle work, such as the gravity (e.g., when lowering the arm down the biceps both work and stretch whereas in a horizontal extension only triceps work), and using the shoulder (e.g., when reaching the arm forward the biceps stretch from the elbow but shorten from the shoulder). Therefore, it is unclear how tendon vibration could be used to control the detection thresholds of visual motion gains in such three-dimensional reaching tasks typically seen in VR. We design the second study and a biomechanical model to address this question.

The overall goal of this work is to introduce tendon vibration as a technique for inducing movement illusions in VR and demonstrate its potential. To find how to use tendon vibration to induce an illusion during active movements, we first design a motor setup based on the working principles of tendon vibration from neuroscience, and in Study 1 investigate the extent to which the motor setup can induce offsets in such movements that are involved in the use of VR. To enable VR researchers to use tendon vibration for movement illusions, we investigate in Study 2 how it influences the detection thresholds of visual motion gains, and develop a model that predicts the interference of other muscle work on the thresholds, as well as demonstrate this effect with a biomechanical simulation across three-dimensional reaching tasks.

2 Related work

This work aims to induce movement illusions for HCI in VR by tendon vibration. Movement illusions induced by tendon vibration have been extensively studied in neuroscience. However, many gaps in research remain for transferring the knowledge on tendon vibration from neuroscience to HCI. In this section, we describe the related work in neuroscience and those gaps that need to be addressed in order to apply tendon vibration for movement illusions in VR.

2.1 Stimulation of Tendons with Vibration Motors

Tendon vibration creates proprioceptive illusions, but for simplicity, we call these movement illusions. Proprioception is a sense of body/limb position - statesthesia, and velocity during movement - kinesthesia. Type 1a receptors in muscle spindles and type 1b Golgi tendon organ receptors both contribute to the proprioceptive sense, with type 1a primarily sensing speed of stretch and type 1b sensing muscle load. Tendon vibration can affect both the sense of position and movement velocity by activating these receptors.

Tendon vibration can produce illusions of extremely complex movements. By recording with microneurography (i.e., needles directly inserted in the afferent nerves from the muscle) how the tendons vibrate in actual movements and then playing those back on a static arm has been shown to create so strong and complex movement illusions that the participants can reproduce the letters and geometric shapes they thought their hand drew due to the illusion [e.g., 18]. Such invasive methods are not feasible for VR interaction, and so we are bound by the cost of reducing the resolution of the illusion because of stimulating the entire tendon bundle with motors on the skin.

The motors used for tendon vibration include those that move back and forth and "poke" the skin, and vibration motors. The motors "poking" the skin (e.g., called "electromagnetic shaker" in [10]) require a setup where both the arm and the motor are fixed, so as to keep the distance and hence the strength of poking constant. This does not work for interactive tasks in VR where the motor setup needs to allow the user to move their hand freely for interaction. Vibration motors are thus appropriate actuators for tendon vibration in VR.

Tendon vibration can in principle be applied to any muscle tendon. However, the access to the muscle tendon from above the skin and hence the effectiveness of the produced illusion, varies across the body. The biceps and triceps near the elbow are relatively easy to target, but the tendons above the wrist (e.g., to bend and extend the wrist [29]) and the ankle (e.g., an illusion of swaying the entire body or the floor beneath [31]) have also been studied. Moreover, the degrees of freedom on the near joint influence the efficacy. The elbow in relation to the upper arm has only 1 DoF, whereas the wrist and shoulder have more. Therefore, the elbow joint is one of the most-studied joints for movement illusions by tendon vibration. We also target the elbow joint, as that is crucially involved in VR object manipulation tasks.

Anatomically, there are three muscles involved in elbow flexion and two in extension, as presented in Figure 2. Biceps brachii (here and generally referred to as biceps) is the muscle primarily responsible for flexing the elbow. There are two other muscles involved in elbow flexion. One is brachialis which is a smaller muscle located on the upper arm underneath the biceps brachii. The other is brachioradialis, which is located on the forearm. Two muscles are involved in elbow extension. Triceps brachii (here and generally referred to as triceps) and anconeus. The anconeus is a small muscle located on the elbow. Its primary function is to rotate the forearm and it is also sometimes considered to be a part of the triceps instead of being its own muscle. Therefore, biceps and triceps are the muscles targeted in the studies of tendon vibration, including this work, in order to induce movement illusions of the elbow for flexing or extending the arm.

Although these working principles of inducing movement illusions of the elbow by vibration motors on the skin are known, related work uses a range of different types of vibration motors, stimulation parameters with the motors (e.g., vibration frequency and amplitude, onset and duration of the vibration), and ways to place and fix the motors on the skin to target the tendons. Therefore, it remains unclear what kind of a motor setup allows active movements of the elbow joint and yet works reliably for inducing the illusion in VR.

2.2 Illusions During Active Movements

Most work on tendon vibration in neuroscience is done on static joints or passive movements of the joints, and in constrained settings. With commercially available vibration motors, tendon vibration has only been shown to reliably work without an active movement of the same limb (e.g., on a static arm [19] or passively moved arm [9]), or by constraining the arm movement with a support (e.g., an arm rest [6]). Illusion during unsupported, active movement is necessary for using tendon vibration in VR.

Tendon vibration on a passive or inactive arm has been shown to induce movement illusions for both directions (i.e., flexing and extending the elbow) [9]. However, during active arm movement, tendon vibration only amplifies the performed elbow flexion or extension (i.e., more flexed or more extended). Active movement of flexing a joint is performed by contracting a muscle (termed the agonist muscle), while the opposite muscle stretches (termed the antagonist muscle). Therefore, tendon vibration in principle can work on the stretching, antagonist muscle, which is inactive or less active, creating an illusion of the movement being faster-than-actual. Studies show accordingly, that participants undershoot

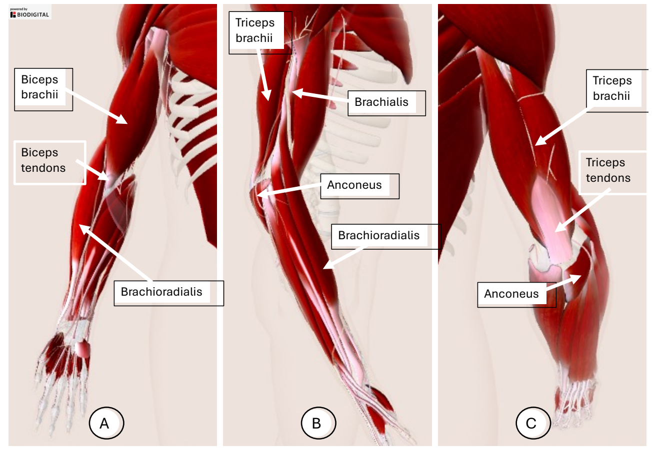

Figure 2: The arm muscles from the front (a), side (b), and back (c), highlighting the muscles involved in elbow flexion and extension. Arrows indicate the muscle tendons targeted in tendon vibration for arm movement illusions. Muscles are depicted in red, with tendons shown in lighter pink or white at the muscle terminations.

their active movements as a result of vibrating the antagonist muscle [e.g., 6]. However, vibrating the agonist muscle does not cause an overshoot but only inaccuracy caused by noise in the sensory system. Moreover, the undershoot effect with active movement has only been found in experiments that use an arm rest.

In the field of haptics and VR, Hagimori et al. [21] find changes in the perceived angle of the elbow during active movements to both directions. However, they used vibration motors on the palmar and dorsal (back of the hand) side of the wrist, not the biceps and triceps. While they provide convincing reasoning for this motor placement and its effects on vibrating the tendons involved in elbow flexion and extension, the three works they cite for it are not available in English, and the setup seems anatomically implausible. First, no muscles involved in elbow extension connect to the wrist. Second, brachioradialis is the only muscle that connects the upper arm (from underneath the triceps) to the wrist and participates in elbow flexion, but its primary function is to rotate the forearm (e.g., so that the palm can be turned up or down). In addition, the brachioradialis (like visible in Figure 2A-B) is connected on the side of the wrist near the thumb (hence its name, radialis, which is the forearm bone on the thumb side). Thus, the motors of Hagimori et al. [21] on the palmar and dorsal side of the wrist are unlikely to stimulate the tendons for elbow flexion. Therefore, the found effects on perceived changes in the elbow angle cannot be due to tendon vibration of the muscles involved in flexing or extending the arm, but likely due to noise, similar to vibrating the agonist muscle.

It remains unclear whether vibrating the muscle tendons with motors can be used to create controlled illusions during active movements (and hence influence the outcome of the movement, such as undershooting a target), or only noise (such as inaccuracy in targeting).

2.3 Tendon vibration with Visual Motion Gains

Movement illusions are particularly useful and also widely used in interaction techniques for virtual reality (VR), such as hand redirection [3, 5, 15, 30, 35, 48]. The illusions in VR are typically produced by changing the visual feedback of the hand. In contrast, studies in neuroscience often use blindfolded tasks to isolate the effects of tendon vibration. Therefore, it is unclear how movement illusions induced by tendon vibration interact with visual illusions typically used in VR, for instance to select or manipulate virtual objects.

In VR studies of movement illusions, visual motion gains have been applied, for instance, to map the virtual hand vertically higher or farther than physical hand for a more ergonomic reach [15, 30], exponentially farther to reach distant objects [35, 48], or horizontally to left and right to match the distinct locations of a virtual and physical object in order to provide tactile sensations from grasping (e.g., the arm [3] or the fingers [5]). Visual motion gains have also been used to create illusions about a virtual object's weight [41] and resistance of a knob [14]; a slower perceived movement speed can induce an illusion of more effort needed to move the objects and hence increased weight or resistance. These VR interaction techniques using redirection are usually evaluated by measuring the detection thresholds of the extent of the illusion, for instance the amount of physical-to-virtual motion gains. As tendon vibration creates a movement illusion about the speed of the flexion or extension, it has the potential to influence the detection thresholds of visual motion gains.

This has been studied in haptics and VR. Most notably, Hirao et al. [24] aimed to influence the detection threshold of visual motion gains during an active movement of vertically flexing the elbow (similar to Figure 1d). While they found an effect in increasing the thresholds, it was not directional, that is, both agonist and antagonist muscle stimulation increased the threshold in a similar manner. Hence, they conclude that "use of tendon vibration as noise on somatosensory information might be more practical for visual illusion than precisely controlling the effect" and add that a possible cause to this can be using a single strap to attach both motors around the upper arm, which might have made a vibration to resonate also to the opposite muscle. Other works on visual motion gains include Hagimori et al. [20], but they used wrist stimulation (and hence the found effects must be due noise) and Ogawa et al. [32], who used tendon electrical stimulation which influences actual motions instead of an illusion. Therefore, it is unclear how detection thresholds of visual motion gains in VR could be improved with tendon vibration.

2.4 The Illusion in Three-dimensional Tasks

Most studies in neuroscience use horizontal movements (like those in Figure 1a-b) to create an illusion of flexing or extending the elbow joint by vibrating the biceps and triceps tendons (and passive movements) of the arm. Using horizontal and supported movements eliminates two possible factors influencing the illusion. The first one is gravity, which could in particular influence vertical movements (such as those on Figure 1c-d). It has been suggested that only information from the stretching (the antagonist) muscle is used for inference [6, 7]. In vertical elbow extension, the biceps perform an eccentric contraction, stretching under tension as it controls the lowering of the arm, therefore acting against gravity. It is unclear from the literature what we should expect of biceps vibration during this movement. The second factor is shoulder involvement. In such horizontal and vertical movements (as in Figure 1a-d) the shoulder muscles might work, but their stretch is static. However, in a reaching movement (such as in Figure 1e-f) the elbow extends and the biceps thus stretches, while the front of the shoulder flexes and the biceps thus shorten. It is unclear if and what kind of bias this may cause to the effects of tendon vibration on movement illusions. In VR interaction tasks, as described above, movements are often three-dimensional with more degrees of freedom from the entire arm. Therefore, the effects of tendon vibration are crucial to understand in such movements in order to apply it for HCI in VR.

2.5 Summary of the Open Questions

To summarize, there are four major gaps presented above in the present knowledge on tendon vibration that need to be addressed in order to reliably induce movement illusions in VR. The open questions are about (1) how to set up the vibration motors for tendon vibration in order to induce movement illusions in VR, (2) how may the illusion be reliably controlled during active movements, (3) how may the illusion improve the detection thresholds of visual motion gains in VR, and (4) how may the improvements generalise to free three-dimensional movements of the arm.

3 Tendon Vibration Setup

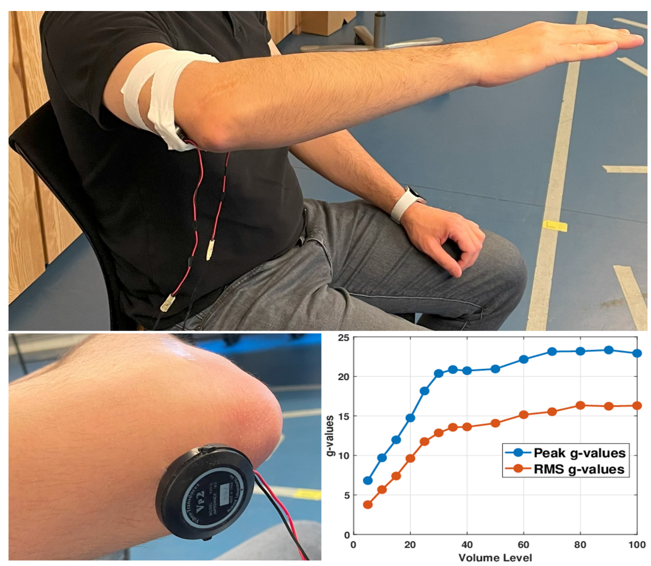

Figure 3: On the top: The motors (VP216) attached both on the biceps and triceps with sports tape crossing higher up on the arm. On bottom left: A motor attached on the triceps with a double-sided tape. On the bottom right: The magnitude of the vibrations as per our technical evaluation of the VP216 at different system volume levels. The two lines represent the peak values and RMS values of the stimulus. The acceleration values are for the axis perpendicular to the skin.

The success of inducing movement illusions by tendon vibration depends on vibration motors, their output described by the stimulation parameters, and motor placement, including their attachment method. The purpose of this section is to describe the design of the motor setup that is used in Studies 1 and 2, and allow the research community to implement the setup for their own studies and designs.

3.1 Vibration Motors

Three main classes of vibration motors are Voice Coil Actuators (VCA), Eccentric Rotating Mass (EMS), and Linear Resonant Actuators (LRA). VCAs offer certain key advantages for stimulating muscle tendons over the other vibration motors. They provide more haptic control when compared to the other two types due to their high acceleration rate, constant force over their stroke, and low hysteresis. They have a wider operation bandwidth as compared to LRAs and provide faster response times in comparison with ERMs.

Two of the most widely used VCAs in haptics are the Haptuator Mark II (Tactile Laboratory, Canada) and the VP series (Acouve Laboratory Inc., Japan). Although related work has used both vibration motors for tendon vibration, it is unclear which works better for creating the illusion. Both actuators effectively cover the haptic bandwidth of human sensations, but their distinct shape and power affect the stimulation characteristics.

Mark II has a longer cylindrical shape and VP216 (the smallest of the VP series) has a larger round, coin-like shape. This means, that due to its round shape and higher weight (49g), VP216 can facilitate a stronger uniform contact and wider vibration distribution as compared to the long and narrow shape and lower weight (8.7g) of Mark II. The VP216 has a higher impedance rating of 16Ω compared to 4Ω for Mark II, and can thus deliver significantly higher vibration amplitude. The shape of Mark II also implies that placement will make the main vibration force direction parallel to the skin. For the VP216 the main vibration force direction is perpendicular to the skin, which matches the stationary setups from neuroscience that produce "poking" of tendons at a fixed arm position. We chose the VP216 due to its force direction.

3.2 Stimulation Parameters

The most important parameters to consider for inducing the illusion are the vibration frequency, amplitude, and contact surface size. Previously, a range of vibration frequencies has been shown to induce proprioceptive illusions, but 80-120 Hz frequency seems to be most commonly reported for producing robust effects [6, 37]. Much lower frequencies of 10-30 Hz (the natural firing rate of 1a afferents during movement) have also been shown to produce illusions precise enough to allow for symbol recognition [2]. However, the same study showed that increasing the frequency step-wise by 20 Hz at a time modulated the perceived speed of the movement by increasing it correspondingly. Therefore, it seems that higher frequencies produce a more intense movement illusion. After piloting with frequencies between 20Hz to 100Hz in 20Hz increments, we found 80Hz and 100Hz to produce similar movement illusions. Since previous work in haptics used 80Hz [24], we chose that as the stimulation frequency in our setup.

The amplitude means the physical travel of the motor moving back and forth. Therefore, it relates to the force exerted by the motor vibrating in a direction perpendicular to the skin. Previous work using motors that "poke" the skin recommend an amplitude between 0.2 to 0.5mm [26, 39]. However, to compare with similar studies [24, 31], it is more common to express the amplitude as acceleration. The mechanical range of 0.2 to 0.5mm can be expressed as acceleration force from 2.58g to 6.44g, which provides us with guidelines for minimum and maximum acceleration force. However, the stronger the force, the greater the risk of it causing discomfort. In piloting with this range, we found the acceleration force of 4g to be strong enough to likely induce the movement illusion and yet not cause discomfort.

The contact surface size between the skin and the motor may also influence the strength of the movement illusion. Verrillo [46] concluded that because a larger motor may stimulate more of the tendons, it is also more likely to activate the receptors involved in inducing the illusion. Correspondingly, Ohshima and Shimada [33] investigated a range of contact surface sizes ($\phi 5\,mm$, $\phi 10\,mm$, $\phi 15\,mm$, $\phi 20\,mm$) for stimulating the biceps brachii, and found that increasing contact surface increased the range of perceived arm extension and vividness of illusory sensations. The VP216 (smallest in the VP series) comes with a diameter of $\phi 43\,mm$ and hence should provide a large enough size to robustly induce the illusion. This was also confirmed in our pilots with the adjustments of the frequency and force as described above.

3.2.1 *VP216 Technical Evaluation.*

We performed a technical evaluation of the VP216 to determine the vibration amplitude in the recommended mechanical displacement range of 0.2-0.5mm [26, 39].

The following formula [22] can be used to translate the mechanical amplitude range (*App*) into acceleration in g force that the motor output is measured in:

$$g_{\text{force}} = \frac{A_{pp} \cdot (2\pi f)^2}{2000 \cdot g}$$

where g is the acceleration due to gravity ($g \approx 9.81\,\text{m/s}^2$).

According to the formula above, a 0.2mm amplitude with 80Hz frequency would produce approximately a 2.58g force acceleration, and a 0.5mm at 80Hz would produce a 6.44g force acceleration. Therefore, we use this range for vibration amplitudes. In the technical evaluation, we delivered the 80Hz sine wave signal to the VP216 motor at 14 different volume levels that determine the amplitude of the audio signal (from 5% to 100%) and measured the produced acceleration using an MPU (GY-522, with MPU 6050 chip), which has a 3-axis accelerometer and 3-axis gyroscope. The outcome accelerations at each volume level were recorded for five seconds at a sampling rate of 200 Hz. The acceleration values along the axis perpendicular to the skin are provided in Figure 3, and we used it to determine which signal amplitude level results in the desired acceleration force. For example, a system volume level of 24.7% would produce approximately 4g of acceleration force.

3.3 Motor Placement and Attachment

Muscle spindles (1a afferents) are distributed throughout the contractile mass of the muscle (the muscle belly, between the tendons), while the golgi tendon organs (1b afferents) are located in the tendons at the end of the muscle where they attach to a bone. Both of these receptors contribute to the proprioceptive sense. Therefore, to induce the illusion of flexing (or extending) the elbow, the motors could be placed anywhere from the middle of the triceps (or biceps) to their ends at the elbow joint. After the piloting, we found that the effect of the motor placed farther away from the elbow was not as effective in inducing the illusion. In our final design, we chose to keep the motors as close to the elbow as possible without letting the motor on the bicep side of the arm contact the forearm when flexing it.

For the attachment of the motors, we first built them a 3D casing, to which we could attach a velcro strap and thereby strap the motors around the biceps and triceps. However, the inflexible velcro seemed to let the motor on the bicep slip too close to the elbow in use (when performing the movements), and its tightness was difficult to adjust. Furthermore, when the arm is rotated (e.g., lifting the elbow to reach left and right), the motors seem to slip slightly to the side of the muscles. Furthermore, as mentioned in previous work [24], attaching the motors with a single strap over both biceps and triceps might cause resonance effects on the opposite muscle. We found this solution fine for prototyping (3D print model for the motor case is availabe [1]), but noticed in pilot testing too weak for distinguishing movement illusions from noise. Therefore, we decided to attach the vibration motors on the arm with two types of tape. First, the motors were positioned on the skin with double-sided cosmetic tape (Figure 3), which is designed to be adhesive to both skin and clothing. Then, the motors are secured one at a time with sports tape, crossing the tapes higher up to avoid the resonance effects (Figure 3).

4 Study 1 - Validating the Movement Illusion

The goal of Study 1 is to validate that our motor setup robustly induces movement illusions in such active movements that are often performed in VR. We use three movements typical in VR, and measure the strength of the illusion as changes in the movements. In this section, we present the study methodology and its results.

4.1 Experiment Design

The experiment follows a $3 \times 3 \times 2$ within-subject design with the main independent variable being the tendon vibration (Antagonist muscle vibration, No vibration, Agonist muscle vibration). The effects of vibration is studied in three movement types (Horizontal, Vertical, Reaching) and two movement directions (Flexion, Extension).

Although the effects of tendon vibration have been shown robust only on the antagonist muscle, we deem it crucial to compare vibrating the antagonist (e.g., biceps for extension) muscle into two baselines: No vibration and vibration of the agonist muscle (e.g., triceps for extension). The reason for this is that if our motor setup induces a movement illusion and hence an offset in the movement compared to the No vibration - baseline, we want to make sure it is not just due to noise that simply vibrating something on the arm could create. If both the antagonist and agonist muscle vibration create similar changes into the movements, then those changes

[1] https://www.printables.com/model/959870-vp216-buckle

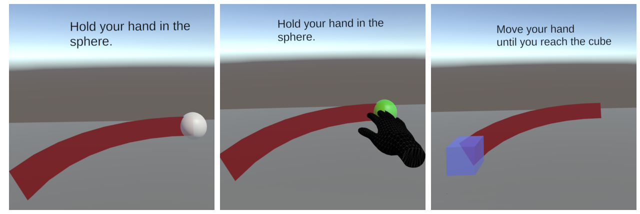

Figure 4: The experiment task in Study 1. Left: The white sphere indicates the starting position and the arc the movement path for the Horizontal movement. Middle: The participant moves the hand to the sphere which turns green to start the Flexion trial, and the virtual hand will be hidden. Right: The participant aims to move their hand to the blue cube, which is the target.

are random, and we cannot use tendon vibration to induce an illusion and a controlled offset (but simply inaccurary due to noise). If the antagonist muscle vibration induces significant undershooting compared to both baselines, then inducing the movement illusion is validated.

We chose to evaluate the effects of tendon vibration in three movement types (Horizontal, Vertical, Reaching). The reason for this is, that these represent the three dimensions of interactive movements in VR, for instance in selecting or manipulating virtual objects. The tendon vibration in our motor setup is intended to induce the movement illusion of flexing or extending the elbow. Thereby, the Flexion and Extension in the Horizontal movement type corresponds moving the hand to the left and right, in the Vertical to up and down, and in the Reaching to near and far, as illustrated in Figure 1.

The experiment was run in three blocks, each corresponding one of the movement types. The order of the movement types was counterbalanced across the participants. Each vibration–movement direction combination within the blocks was repeated 5 times. The order of these trials was fully randomized within the movement type blocks.

The dependent variable in this study is the distance from the endpoint of the movement to the movement target. If the tendon vibration induces an illusion corresponding to the movement direction (i.e., the participant perceives their hand moves faster than it really does), then they undershoot the target.

4.2 Task

The experiment task was to move the physical hand onto a virtual target. As visual feedback contributes to proprioception, the participants received no visual feedback about their hand location during the task.

The task is illustrated in Figure 4. First, the participant sees a white sphere and an instruction to move their hand on it. At this stage, their virtual hand is visible. Once the virtual hand is moved onto the sphere (and after a 0.5 second hover there to avoid accidental start), the sphere turns green, the hand disappears from the view, and the task starts. The participants are instructed to try to follow the displayed movement path (in Figure 4 an arc for Horizontal Flexion), move calmly but continuously, and stop when they believe their hand has reached the target, displayed as a blue cube. After the hand has stopped for 0.5 seconds (movement magnitude less than 5 millimeters), its position is recorded as the endpoint. Vibration stimuli were applied only during arm movement in the task because it takes less than a second to induce the illusion from activation of the motors [17] and overexposure to vibration stimuli (30 seconds or longer) may cause a continuous effect even after it is stopped [38], which might last for several minutes [11].

The movement paths for the task were designed based on the anatomy of the arm. For each movement type, we first determined the extreme ranges of elbow motion. For the Horizontal movement, this is limited by the right hand touching the body (when bending the elbow as fully as possible, the hand touches the left shoulder) on one end, and the arm being fully extended straight ahead on the other. The Vertical movement is limited by the right hand moving in front the right shoulder in full flexion (which is a 52° angle in the elbow according to [45]) on one end, and the entire arm pointing straight down on the other. The reaching movement shared the extremes with the two other types: Hand being in front of the right shoulder in full flexion (as in Vertical) and straight ahead in full extension (as in Horizontal).

The movement paths were constructed based on human anthropometric data [45]. After piloting, we chose to use the average adult measures across genders. The anthropometric maps gave us the average upper arm length, forearm length, hand length, shoulder width, and head-to-shoulder distance. These in turn, allowed us to determine the above-mentioned extreme points of motion.

In two of the movements, the Horizontal and Vertical, the hand moves along an arc. In reaching, it moves along a line. We decided to limit the movements within 80% range of the full motion. This was to avoid the participants noticing the illusion only because they had reached the physical limit of the motion (like touching their shoulder). Therefore, we placed the starting sphere always a 10% (from the total path length) away from the extremes, and the target cube at 10% ± a 5% interval. The target cube position was randomized within this interval to avoid learning effects. This resulted to path lengths (from white sphere to blue cube) of: 26 cm in the Horizontal task, 38cm in Vertical , and 37cm in Reaching (± the 5% interval of the total length).

4.3 Procedure

Upon the start of the experiment, the participant is asked to take a posture similar to the Horizontal movement in order to attach the vibration motors. This is for the experimenter to have access to tape the motors at correct positions on the arm (as in Figure 3). Participants are then instructed to only use the elbow joint to flex or extend the forearm. The VR headset is then adjusted with the experimenter's assistance so that the participants are comfortable but do not see their physical arm from underneath the headset.

Each block (i.e., Movement Type) begins with a calibration phase that adjusts the task's movement path according to the headset position. To do this, the participants were asked to take a relaxed sitting posture, leaning back on the chair, and looking directly ahead.

At the beginning of each block, the participants were given 6 practice trials that represent all of the possible Vibration × Movement Direction combinations in the block's Movement Type. In these practice trials, an additional sphere moving from the starting sphere to the target cube is shown. The participants are instructed to try to move their (non-visual) hand at the same pace with the moving sphere. This procedure was taken to train the participants in calm but continuous movement, preventing excessively fast arm motion, because higher arm movement velocities independent of duration makes the movement illusion less effective, and at high enough velocities negate the illusion completely [9].

Once the practice trials were finished the experiment application moved the participants to the actual trials according to the present movement type. After the blocks of each movement type, the view was re-calibrated, and the next movement type was conducted by repeating the same procedure.

4.4 Setup

The vibration motors used in this study were the Acouve-lab VP216 [1] vibration motors. The stimulus had a vibration frequency of 80Hz and amplitude of 4g. A PAM8610 stereo amplifier [12] was used to drive the motors with a power supply of 12v and 1.5A. The input audio signal came directly from the computer's audio jack; the computer being an Asus Pro Art Studiobook 16 with Intel i7 12700h, 32 GB of RAM and Nvidia RTX 3070ti. The signal sent to the amplifier was generated using an online tone generator [43].

The participants were sat on a chair with a backrest and no armrests. This allowed the participants to perform all the studied arm movements without constraints.

The virtual environment was constructed and run in Unity version 2022.3.18f LTS. We used a Meta Quest Pro VR headset for displaying the virtual environment and logging the data trough tracking the participant's hand movements. The headset was equipped with the additional silicone VR mount to block the view to the real world from underneath it.

4.5 Participants

12 people (7 male, 5 female, Mean age: 27.33, SD: 5.5) participated in the experiment. 10 out of them reported having previous VR experience. The experiences of participants ranged from VR gaming to participating in VR user studies, and 3 out of 10 had also developed VR projects, and 3 out of 12 had heard of or experienced tendon vibration before.

4.6 Analysis Method

The dependent variable in this study is the offset between the endpoint of the movement and the target.

To compute this offset, we projected the hand endpoint position on the instructed movement path (i.e., the arc or a line). This allows us to determine the offset angle to the target for horizontal and vertical arcs and straight line displacement to the target for the reaching path. The angle offsets were converted to distance based on the total path length.

The purpose of this study is to validate that our motor setup for tendon vibration can induce systematic offsets in active movements in VR. We use a mixed-effect ANOVA to assess the endpoint

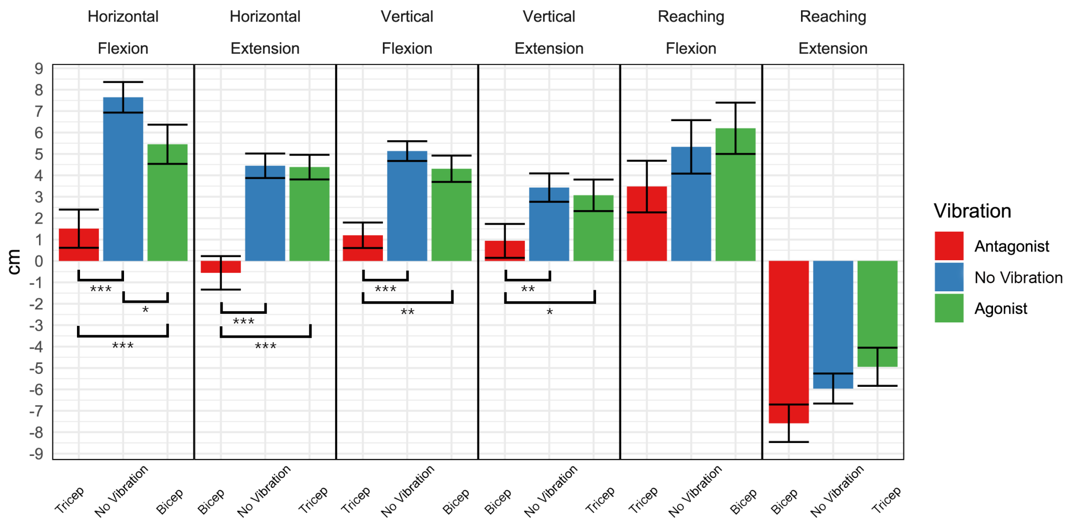

Figure 5: The results of Study 1. The bars indicate the average endpoint offsets in cm across the participants and trial repetitions in each Movement Type, Direction, and Vibration. The error bars represent the standard error. Significance levels are denoted by the following symbols: * for p < 0.001, ** for p < 0.01, and * for p < 0.05.**

offsets across three movement types, incorporating fixed effects of vibration and movement direction and treating participants as a random effect. Bonferroni corrections were applied in the post-hoc comparisons. Trials were excluded if the distance between the endpoint and the target exceeded 40% of the total path length. We incorporated all repetitions in the ANOVA, rather than averaging them for each participant, to account for within-subject variability and enhance statistical power.

4.7 Results

Figure 5 presents the results of Study 1 as the endpoint offsets across all the conditions. Table 1 illustrates the offset values from the baseline to the antagonist vibration condition, which summarizes how much distance tendon vibration could shift the endpoint position compared to the no vibration condition.

4.7.1 Horizontal. Vibrating the antagonist muscles (i.e., triceps during flexion and biceps during extension) induced significant offsets as compared to the baseline conditions (no vibration and agonist). ANOVA results showed significant effects of Vibration ($F_{2,337}$ = 49.43, p < 0.001, η_p = 0.11) and MovementDirection ($F_{1,337}$ = 18.62, p < 0.001, η_p = 0.05) on endpoint offset. No significant interaction for Vibration × MovementDirection ($F_{2,337}$ = 1.65, p < 0.194, η_p = 0.15). For flexion movements, post-hoc test results indicated significant differences for antagonist - no vibration (p < 0.001), antagonist - agonist (p < 0.001), and agonist - no vibration (p = 0.031). For extension movements, there were significant differences regarding antagonist - no vibration (p < 0.001), antagonist - agonist (p < 0.001) and no significant difference for agonist - no vibration (p = 1).

4.7.2 Vertical. The results from vertical movements align with the ones from horizontal movements—antagonist muscle vibration led to significant offsets compared to the no vibration and agonist conditions. Anova results showed significant effects of Vibration ($F_{2,336}$ = 17.84, p < 0.001, η_p = 0.04), MovementDirection ($F_{1,336}$ = 5.23, p = 0.023, η_p = 0.01). No significant interaction for Vibration × MovementDirection ($F_{2,336}$ = 0.84, p = 0.43, η_p = 0.06). Post-hoc tests indicate significant differences in terms of antagonist - no vibration (p < 0.001), antagonist - agonist (p = 0.004) and no significant difference for agonist - no vibration (p = 1) for flexion movements. For extension movements, there were significant differences in antagonist - no vibration (p = 0.007), antagonist - agonist (p = 0.027), and no significant difference between agonist - no vibration (p = 1).

4.7.3 Reaching. Reaching movement results indicate offsets between antagonist and agonist vibration conditions, but no significant effect was found between the three vibration conditions.

	Horizontal		**Vertical**		**Reaching**		**Mean**
	Flexion	*Extension*	*Flexion*	*Extension*	*Flexion*	*Extension*	
Antagonist Vibration	6.14	5.0	3.9	2.50	1.90	1.62	5.26

Table 1: Undershoot in centimeters with antagonist vibration from the baseline of no vibration.

ANOVA results showed significant effects of Vibration ($F_{2,341}$ = 3.7, p = 0.026, $\eta_p < 0.01$) and MovementDirection ($F_{1,341}$ = 198.66, p < 0.001, η_p = 0.37). Significant interaction was identified for Vibration × MovementDirection ($F_{2,341}$ = 3.78, p = 0.024, η_p = 0.02). Post-hoc results indicated there was no significant difference among antagonist, agonist, and no vibration in both flexion and extension movements.

4.7.4 Summary. Through the first study, we validated that our setup for vibrating the antagonist muscle lead to significant target under-shooting during active arm movements. This means that our setup has increased the perceived movement velocity of the hand. We also found that the potency of this illusion could be influenced by the movement types: tendon vibration on horizontal and vertical induced larger offsets compared to the reaching movements.

5 Study 2 - Improving Hand Redirection

The goal of Study 2 is to investigate how a movement illusion induced by tendon vibration integrates with visual motion gains often used in VR interaction techniques, such as in hand redirection. Those techniques are commonly assessed by detection thresholds. Therefore, the measure is whether tendon vibration can make visual motion gains less noticeable. In this section, we present the study and a model we build for both analyzing the data and later for simulating the effects of tendon vibration across reaching movements (in Section 6).

5.1 Experiment Design

The experiment follows a $2 \times 6 \times 3 \times 2$ within-subject design with the main independent variable being tendon vibration (Antagonist muscle vibration, No vibration) across 6 visual motion gains (a baseline of no gain + 5 positive gains). As in Study 1, the effect of vibration is studied in three movement types (Horizontal, Vertical, Reaching) and two movement directions (Flexion, Extension). In contrast to Study 1, the reason for including only the antagonist muscle vibration here is that we are interested in improving the detection thresholds (not countering their effects, which the agonist muscle vibration would attempt to do).

In this study, the participants see their virtual hand. In order to measure the effect of tendon vibration on the detection thresholds, we manipulate the visual motion gains of the virtual hand. Study 1, in alignment with the related work, showed the effect of tendon vibration only on antagonist muscle, that is, increasing the perceived motion velocity. This suggests that the detection thresholds of positive gains could potentially be increased with tendon vibration. Therefore, we only include positive gains that amplify the virtual hand movements in five levels: 1.00, 1.05, 1.10, 1.15, 1.20, 1.25. This range was decided based on previous work on the thresholds of visual motion gains [50]. Therefore, the experiment should provide data on both unnoticeable gains also in the baseline conditions, and in many faster gain levels that will likely be noticed.

The experiment was run in three blocks, each corresponding to one of the movement types. The order of the movement types was counterbalanced across the participants. Each vibration–movement direction–motion gain combination within the blocks was repeated 3 times. The order of these trials was fully randomized within the movement type blocks.

The dependent variable in this study is an answer about whether the virtual hand was moving *faster* or *slower* to the real hand. This is a 2-alternative-force-choice (2AFC) task that is a commonly used in psychophysics to assess detection thresholds. We chose 2AFC instead of 1AFC (a yes/no question) because they are less prone to response biases [36].

5.2 Task

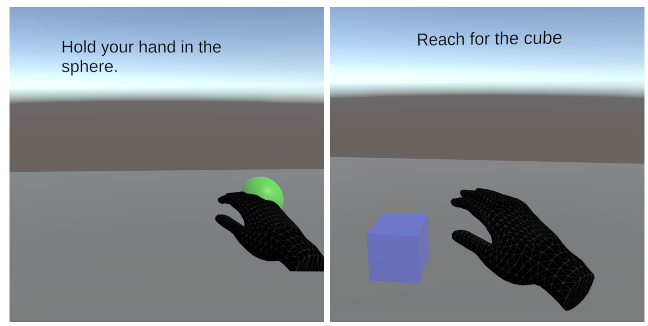

Figure 6: The experiment task in Study 2. After moving their hand to the starting sphere, it turns green (left) and the blue target cube appears. The participant moves the virtual hand to the cube (right), and answers whether they think the virtual hand moved faster or slower than their real hand.

Similar to Study 1, the experiment task for the participants was to move their physical hand onto a virtual target. The task is illustrated in Figure 6. First the participant sees a white sphere and an instruction to move their hand on it. Once the virtual hand is moved onto the sphere, the sphere turns green (after a 0.5 second interval), a target cube appears, and the task starts. The participants are instructed to move calmly but continuously to the blue target cube. Once the virtual hand reaches the target cube, it flashes green, and (after a 0.5 second interval) a question to answer between the two choices about the hand movement appears (Figure 6). The participant then records their answer by pushing a joystick on the their left hand up for a *faster* virtual hand movement, and down for *slower*.

The movement paths in this study, including the starting and end points, were exactly the same as in Study 1. However, the arc/line for the movement path was not shown in this Study, as visual feedback about the hand is given. The hand redirection algorithm for a linear transformation based on gains was adapted from Zenner and Krüger [50].

5.3 Procedure

The procedure was similar with Study 1 in terms of everything else except the conditions in each block. The practice trials here included 3 conditions for each movement type and direction: No vibration and Vibration with No gain, as well as Vibration with maximum gain. The participants were explained that their virtual hand movements are manipulated in some trials in the experiment.

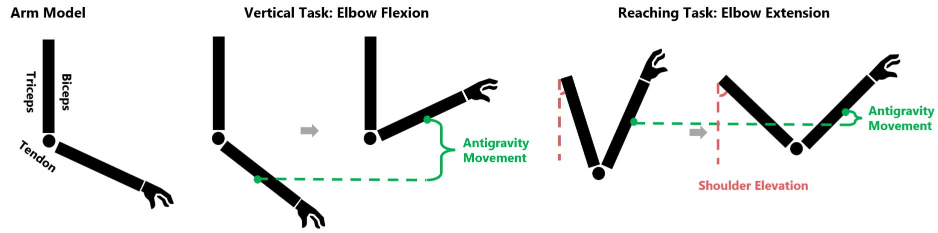

Figure 7: The two-segment arm model. Based on evidence from the existing literature, we hypothesise that gravity and synergistic upper arm movement may influence the effect of tendon vibration in vertical and reaching tasks.

5.4 Setup

The setup was the same as in Study 1, except here the participants held a controller in their left hand in order to answer the 2AFC.

5.5 Participants

18 people (8 male, 10 female, Mean age: 28.39, SD: 4.15) took part in this experiment. 16 out of 18 reported to have previous VR experience. The experiences of participants ranged from VR gaming to participating in VR user studies, 4 out of 10 had developed VR projects, and 5 out of 18 had heard or experienced tendon vibration before (but none participated in Study 1).

5.6 Analysis Method

The dependent variable in Study 2 is the answer to the 2AFC question on whether the perceived virtual hand motion was faster or slower than the physical one. The purpose of our analysis is to assess if and how much tendon vibration can improve the detection thresholds of visual motion gains.

To do that, we build a generalized linear model and use it to analyze the data from Study 2. The model encompasses the three types of movements (horizontal, vertical, and reaching) into a single equation. The benefit of this approach is that we could estimate an overall effect of tendon vibration (and other related factors) across the movement types, rather than producing three different estimations for them. It could further allow us to generalize the findings to different movements that may appear in a real application (as we will demonstrate in Section 6). In the following, we present the model, the related hypotheses, and the data analysis.

5.6.1 Model Hypotheses. The arm can be simplified into two segments (upper arm and forearm), connected by an elbow joint [4] (see Figure 7). The biceps and triceps are situated on the upper arm. Through contraction and relaxation, they generate forces transmitted through the tendons to control elbow extension and flexion. We hypothesize that two main reasons affecting the perception of the movement with tendon vibration across the three movement types (i.e., horizontal, vertical, and reaching) is the gravity and the involvement of the shoulder joint in the motion.

First, during the vertical movement, flexion and extension are influenced by the force of gravity acting on the forearm [47]—we call it the gravity effect, shown in the middle of Figure 7. Specifically, during flexion, gravity hampers the movement, while during extension, it facilitates the movement. This difference could lead to different levels of muscle contraction (to generate different forces), thus influencing the effectiveness of tendon vibration.

Second, during the reaching movement, the shoulder can have different levels of elevation—we call it the shoulder effect, demonstrated in the right of Figure 7. Previous research has suggested that the biceps and triceps can play additional roles, such as a dynamic stabilizer, in addition to controlling elbow extension and flexion [27, 28, 42]. These controls induced by upper arm movements may corrupt the tendon vibration effect. Furthermore, as illustrated in the figure, the gravity effect is also present in such reaching movements.

Due to the potential impact of gravity and shoulder elevation on tendon vibration effects, we will integrate these two components into our predictive model.

Predictor	Description	Values
TendonVibration	The presence of tendon vibration during movements	'with vibration', 'no vibration'
Gain	The applied visual motor gain	1.00, 1.05, 1.10, 1.15, 1.20, 1.25
MovementDirection	The elbow movement	'extension', 'flexion'
GravityEffect	The gravity facilitates, hampers, or is perpendicular to the movement	1, -1, 0
ShoulderEffect	The shoulder joint is elevated, lowered, or stable during the movement	1, -1, 0
(1|Participant)	The participant number is used as a random factor	1 to 18

Table 2: The predictors used for our generalized linear mixed model (GLMM) and their values in Study 2.

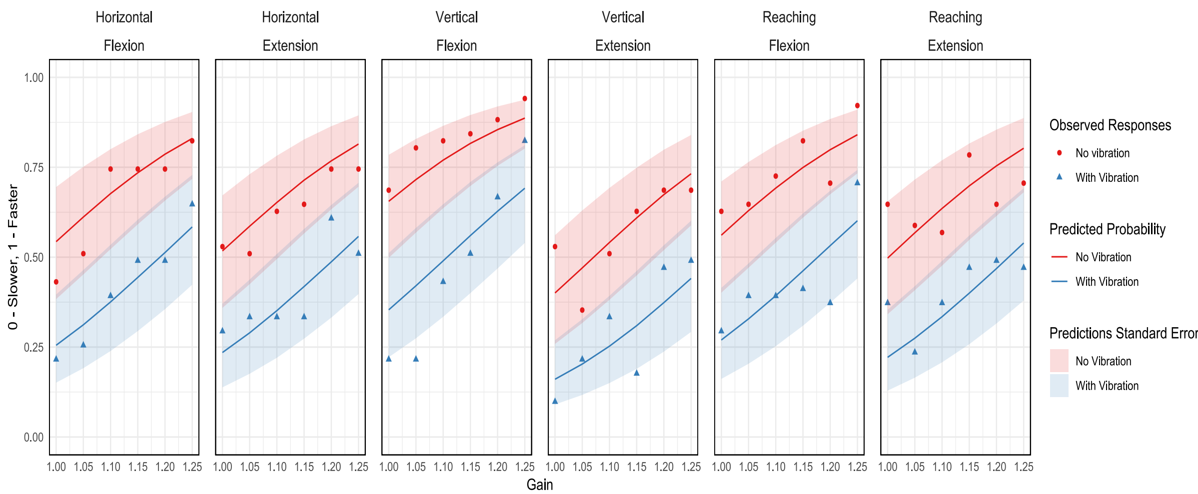

Figure 8: 2AFC results: Observed Responses presented as proportions of the answers across all the participants. The line presents predicted responses based on the GLMM. Standard error bands depict the accuracy of predictions made with the model.

5.6.2 Generalized linear mixed model (GLMM). We built a GLMM that incorporates our hypotheses on how different components may influence user responses across the three movement types: Response ~ TendonVibration + Gain + MovementDirection + GravityEffect + ShoulderEffect + (1|Participant). The predictors and the response are linked by a logistic regression, as Response was either 0 (i.e., the virtual movement is *slower* than the physical movement) or 1 (i.e., the virtual movement is *faster* than the physical movement). The model components and their corresponding values in the second study are shown in Table 2.

5.6.3 Model constraints. The GLMM was built on several assumptions. First, the model assumes a linear combination of the predictors that are transferred through a link function (i.e., logistic regression) without accounting for, for instance, quadratic or interaction effects. Second, the gravity effect and the shoulder effect are not precisely qualified (e.g., elevated 5°), as we only consider the directional impact (i.e., elevated or not), which may lose the granularity if the effect depends on the movement extent. However, our model assumptions are meant to simplify the problem.

5.7 Results

The GLMM achieved $R^2_{cond} = 0.205$, $ICC = 0.030$, $RMSE = 0.456$, $AIC = 4486.133$, and $BIC = 4529.592$ according to model evaluation techniques provided in the `performance` package in R. For comparison, a full model that considers all the interaction effects achieved $R^2_{cond} = 0.226$, $ICC = 0.030$, $RMSE = 0.453$, $AIC = 4475.664$, and $BIC = 4630.877$. Since the full model only brought marginal improvements to the performance, and might achieve this by adding more complexity (as indicated by the increased BIC value), we favored the simpler model. The predictions by the GLMM are summarized in Figure 8.

We first estimated the gain required to achieve a probability of 50% of "faster" response (i.e., the point of subjective equality), based on 10^4 bootstrap simulations. The results are summarized in Table 3. Overall, the tendon vibration increased the subjective equality point of visual motion gain by 0.22 across all movement types compared to the visual-only condition. The exact gain numbers differ in horizontal, vertical, and reaching movements, likely because of the gravity and shoulder effects.

We then used the GLMM to investigate the significance of the effect of TendonVibration, Gain, MovementDirection, GravityEffect, ShoulderEffect on the 2AFC responses.

Results show that all of the predictors, except for MovementDirection (Estimate = 0.108, SE = 0.124, z = 0.869, p < 0.385), had a significant impact on predicting the response outcome. TendonVibration was found to significantly decrease the probability of "faster" response (Estimate = -1.271, SE = 0.074, z = -17.303, p <

	Horizontal		**Vertical**		**Reaching**		
	Flexion	*Extension*	*Flexion*	*Extension*	*Flexion*	*Extension*	
No Vibration	0.97	0.99	0.89	1.07	0.96	1.00	Δ = 0.22
With Vibration	1.19	1.21	1.11	1.29	1.18	1.22	

Table 3: The point of subjective equality estimated by the GLMM.

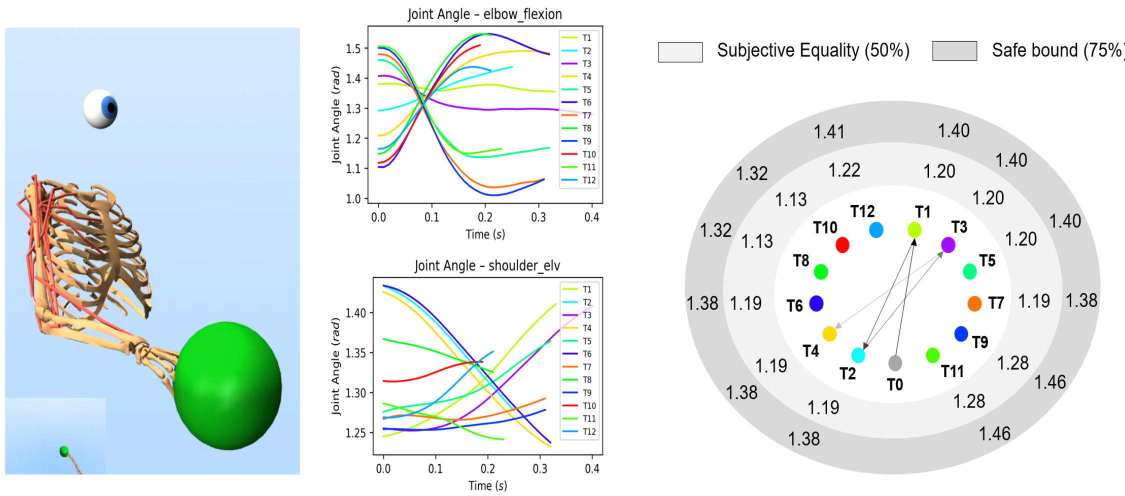

Figure 9: The GLMM from Study 2 was combined with biomechanical simulations to estimate the detection thresholds in an ISO cyclical reaching task. The simulated user completes a series of target-reaching trials in the order of T0 → T1 → T2 and so on. The simulation produces elbow flexion, pointer positions, and shoulder elevation across the trials, which were then converted as predictors (MovementDirection, GravityEffect, and ShoulderEffect) in the GLMM. The predictors allow the GLMM to output the estimated point of subjective equality (50%) and the safe bound where users are likely to not notice the introduced gain (75%). Screenshots taken from User-in-the-Box (UitB) [25].

0.001). This confirms that the tendon vibration makes people less likely to notice a faster visual motion gain. Additionally, the results revealed a positive relationship between gain and the probability of answering "faster" 2AFC response (Estimate = 5.747, SE = 0.435, z = 13.226, $p < 0.001$).

GravityEffect was shown to be another significant effector (Estimate = -0.478, SE = 0.089, z = -5.370, $p < 0.001$). Finally, ShoulderEffect had a statistically significant effect on user responses (Estimate = -0.555, SE = 0.153, z = -3.632, $p < 0.001$). Variability among participants was captured by the random effects for intercept, which indicated notable between-subject differences (Estimate = -5.678, SE = 0.495, z = -11.461, $p < 0.001$).

5.8 Summary

Overall, our GLMM provides reasonable and close estimations of the detection threshold compared to a more complex model that includes all the main effects and their interactions. The model suggests that while users could easily detect movement redirection (i.e., faster or slower) with only visual manipulation with an average subject equity point of 0.98, tendon vibration could boost this threshold by 0.22. These results highlight the promise of applying tendon vibration for movement illusions in VR.

6 Demonstration: How to Use our Results for Pointing Tasks

In a practical interactive application, such as a pointing task, users may employ three-dimensional movements. Study 2 results apply to distinct movements that were investigated in the experiment, while the GLMM derived from it has encoded how important predictors, including MovementDirection, GravityEffect, and ShoulderEffect influenced the effectiveness of our tendon vibration setup. These predictors capture the impact of elbow and shoulder movements, as well as the influence of gravity, across different types of movement. With the GLMM, we can estimate the detection threshold for different movement types in an application if the values of these predictors are known. In this section, we demonstrate how to apply our GLMM with biomechanical simulation to estimate detection thresholds in an ISO cyclical reaching task.

Suppose a user needs to complete an ISO cyclical reaching task with 12 targets, and we are interested in how much visual motion gain we can introduce with tendon vibration so that the redirection is not noticeable by the user. To achieve this, we first need to determine the values of the predictors, including MovementDirection, GravityEffect, and ShoulderEffect for a given movement, as they are inputs for the GLMM to produce a detection threshold estimation.

We decided to use biomechanical simulation to infer the values of these predictors. The benefit of using biomechanical simulation is that it mimics how a real user completes the ISO cyclical reaching task and outputs the movement trajectory information of different joints, without the need to recruit an actual user. We employed an opensource, pre-trained biomechanical model in HCI called User-in-the-Box (UitB) [25]. The model was trained on different tasks, including reaching (or pointing), with deep reinforcement learning. The model produced how different joints move over time in the ISO cyclical reaching task (see Figure 9, middle).

As mentioned, we need to determine MovementDirection, GravityEffect, and ShoulderEffect for each movement as predictors for the GLMM. MovementDirection (either flexion or extension) can be determined by the difference in elbow flexion angles between the initial and final points of movement (Figure 9, middle top). GravityEffect (whether along, against, or perpendicular to the direction of gravity) can be approximate by the difference in the height of the pointer before and after the movement (i.e., start and target positions). To estimate ShoulderEffect (whether the shoulder joint was elevated, lowered, or remained stable), we can calculate the differences in shoulder elevation angles before and after the movement (Figure 9, middle bottom). We deemed the shoulder stable if the angular difference was less than 0.05 radians (around 3°). We repeated this procedure for the 12 movements (corresponding to the 12 targets).

After determining the predictor values for each movement, we fed them with a list of gain values into the GLMM. We generate predicted gain intervals for each participant with 10^4 bootstraps and averaged the 18 participants' results to compute the corresponding gain values regarding their point of subjective equality (50% chances of saying the virtual movement is faster) and the safe bound where users are likely to not notice the introduced gain (75% chances of saying the virtual movement is faster). The prediction results are summarized in Figure 9, right.

Overall, based on the predictions, subjective equality falls within the range of 1.13 to 1.28 visual motion gain, with the upper limit (75%) ranging from 1.32 to 1.41. These results should inform us about how much visual motor gain we can introduce with tendon vibration for each of the 12 reaching movements.

While we have demonstrated how to combine our results with biomechanical simulation, there are other ways to apply our results. For example, one could record the exact values of the predictors using tracking systems (e.g., OptiTrack) as a real user moves. Alternatively, one could apply a flat gain of $\Delta = 0.22$, averaged across the three movement directions in Study 2, in addition to the visual-based redirection threshold. However, this approach produces less precise results for individual movements.

To summarize, when we know the exact values of MovementDirection, GravityEffect, and ShoulderEffect for a given movement, we can achieve a more accurate estimation of the detection threshold tailored to the movement. This method can predict detection thresholds not only in the ISO tasks demonstrated in this section but also in other movements that may occur in practical interactive applications.

7 Discussion

We set out to introduce tendon vibration for movement illusions in VR and demonstrate its potential. We presented our tendon vibration setup, conducted two studies to validate movement illusion effects that can improve hand redirection in VR, and developed a model that predicts how tendon vibration contributes to improving the detection thresholds in tasks that appear in real applications. In this section, we discuss the results of our studies, and how future work can extend the understanding and possible usage of tendon vibration.

7.1 Tendon Vibration in VR Applications

Our studies have shown that the tendon vibration setup could increase the perceived movement velocity of the hand (Study 1) and improve the detection thresholds of visual motion gains (Study 2). The strength of the movement illusion may depend on the type and direction of the movement, as well as individual user differences. The average offset between perceived and actual movement was 5.26cm in Study 1, and the average increase in the detection thresholds to visual motion gains was 0.22 across movement types and directions in Study 2.

Therefore, tendon vibration can be useful for applications that require hand redirection and want to make such redirection less detectable, such as for techniques using visual motion gains [3, 14, 41]. Tendon vibration could also be combined with other methods that improve hand redirection detection thresholds, such as redirection during eye blinks and saccades [49], and illusions of rotational force induced by applying pressure to two points on the wrist (i.e., the hanger reflex [44]).

It would have been useful to compare our movement offsets and detection thresholds with previous studies [23, 50]. However, the differences in paradigms (e.g., using a 1AFC vs. 2AFC paradigm), movement tasks (e.g., paths and directions), and gain levels (e.g., focusing on slower-than-real mapping of the virtual movement [23] vs. faster [3]) make direct comparisons difficult.

We observed individual variances in the results of both Study 1 and Study 2. While significant effects were detected regardless of the variance, stronger illusions could be possible to induce if both the visual and proprioceptive cues (from tendon vibration) would be calibrated based on individual differences in perceptive sensitivity. The global movement offsets and detection thresholds presented in our results also include the variance caused by using average adult body as the basis of the measures. Therefore, these offsets and thresholds have potential for further improvement with individual calibration.

While we have demonstrated how to combine our results (Study 2) with the biomechanical simulation there are other ways to use the results and the GLMM in VR applications. We briefly mentioned (Section 6) that the predictors (i.e., movement direction, gravity effect, and shoulder effect) for GLMM can be determined using real motion data of the upper arm (hand, elbow, and shoulder positions). For future work, it would be beneficial to collect a sample of users' motion data during VR interactions and use the GLMM to find detection thresholds for real movements in VR. Besides more accurate detection thresholds for VR applications we could investigate how well the simulation results generalize to different users and targets.

For the use of VR applications in practice, it is also important to consider the possible negative effects tendon vibration could have. Tendon vibration might induce Tonic Vibration Reflex (TVR), a sustained muscle contraction that contributes to muscle stress and fatigue [34]. This can cause irritating sensations. Additionally, prolonged exposure to tendon vibration can cause movement illusions even after the stimulation ceases [38], influencing the usability of this technique. In our controlled studies these negative effects were minimized by performing one type of arm movement at a time, controlling the exposure time of vibration stimulus to the absolute minimum required to induce the movement illusion, and the opportunity to rest the arm between each experiment trial and block.

7.2 Inducing More Precise Movement Illusions

In this work, we showed our tendon vibration setup creates movement illusions of faster-than-actual arm movement speed, which is confirmed in Study 1 by a systematic undershoot in the arm movements. With adjustments to the setup factors we presented (i.e., the type of the motor, the stimulation parameters, motor placement, and attachment method) we could potentially control the strength of movement illusions, and induce illusions of slower-than-actual arm movement that would produce an overshoot to the arm movements.

Tendon vibration working in only one direction: *undershooting* the movements (i.e., increasing the perceived movement velocity in Study 1) is limited to increasing the thresholds of *positive* motion gains (in Study 2). In our Study 1, we did not find an effect between vibrating the agonist muscle and the no-vibration baseline. Therefore, we only focused on positive gains in Study 2, that is, amplifying the movement velocity. This aligns with a previous study [9], which found that the illusion is induced only when the antagonist muscle is vibrated (during active movement). Therefore, the interplay between the antagonist and agonist muscle vibrations to the movement illusion remain interesting for future work. If tendon vibration could induce the movement illusion that produces an *overshooting* of an active movement (i.e., decreasing the perceived movement velocity), it could be used to increase the detection thresholds of *negative* gains.

In our studies, we vibrated the tendons with a single stimulus (i.e., frequency and amplitude), that induces a movement illusion of fixed strength. However, future work can investigate modulating the strength of the illusions by instrumenting different stimulation parameters. For example, Albert et al. [2] found that the perceived velocity of a movement illusion created in a static limb (shown both on the wrist and ankle) increased with higher vibration frequencies. Furthermore, with dynamic frequency modulation, it is possible to induce complex movement illusions that recreates a sensation of drawing geometric shapes (e.g., squares and circles), letters, and numbers [40]. Therefore, tendon vibration could be used to induce precise movement illusions by modulating its strength.

To transfer modulation of the movement illusion's strength in active arm movements, first, a motor setup needs to be investigated, and second, the strength of the illusion during active arm movement needs to be verified (measured similarly to directional offsets in our Study 1). Our motor setup (Section 3) can be used as a starting point. Depending on the desired modulation range of frequencies, specific motors have to be chosen. For each individual frequency, the vibration amplitude has to be kept consistent similar to previous work (0.25mm peak-to-peak for all frequencies 1-100Hz [2, 40]). Each frequency should be technically evaluated (similar to Section 3.2.1) to confirm the vibration amplitude. To create a mapping between frequencies to offsets (strength of movement illusion) a verification process similar to our Study 1 is required. The arm movement speed also influences the strength of the illusion, which the previous work [2, 40] did not need to consider as they investigated movement illusions for static joints. Therefore, the arm movement speed should be introduced as a condition (e.g., slow, medium, fast).

7.3 Tendon Vibration on Other Joints

The tendon vibration setup we presented in this work successfully induced movement illusions in active arm movements based on elbow flexion and extension. This concept can be further applied to create movement illusions during active movement in other joints in the arm: shoulder [16], wrist [40] and fingers [8], or other limb joints in the body, for example, the ankles [31, 40]. Based on previous work [6, 9, 24] it was uncertain if tendon vibration of the elbow induces movement illusions during unrestrained active movements that did not rely on arm support or follow a horizontal movement trajectory. Our work confirmed that it is possible to create movement illusions in such conditions potentially opening up the possibility to investigate tendon vibration for other joints. For example, a neuroscience study on the wrist and ankle joints [40] shows illusions of complex movement patterns without active limb movement when applying tendon vibration. Although the motor setup we presented might not be directly applicable to induce robust movement illusions on other joints, the same factors in the setup (i.e., the type of the motor, the stimulation parameters, motor placement and attachment method) are relevant to consider with any joint, and the specifics of this setup can guide and provide ideas for designing them.

The main reason the elbow is the most-studied joint for tendon vibration in neuroscience [e.g., 6, 9, 19] is due to its accessibility and ability to simplify the movements of the elbow into a hinge joint of 1DoF (extension and flexion). For example, the wrist has more types of tendons due to its greater degrees of freedom (extension, flexion, adduction and abduction) compared to the elbow; additionally, the wrist's smaller size means tendons are packed closer together, making it challenging to apply specific vibrations for movement illusions without inadvertently affecting other tendons responsible for different movements. Therefore it is important to investigate a valid setup for each joint, as expanding tendon vibration for multiple joints and using them in combination could broaden the range of interactions and potentially create more potent illusions.

8 Conclusion

To conclude, we have presented a novel method of using our tendon vibration setup to induce movement illusions, and showed its application to VR. Study 1 verified that vibrating the antagonist muscle with our setup could lead to significant offsets in active movements. Study 2 showcases the potential of our setup in minimizing the detection of hand redirection—it improves the threshold for perceiving visual motion gains by a notable margin of 0.22. Finally, leveraging the collected data, we constructed a predictive model and integrated it with biomechanical simulation, offering insights into estimating detection thresholds of various movements enhanced by movement illusions in reaching tasks.

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