ThumbShift: Modulating Perceived Object Properties through Dynamic Thumb Repositioning

Jian Zhang* — University of Melbourne
Gavin Buckingham† — University of Exeter
Wafa Johal‡ — University of Melbourne
Jarrod Knibbe§ — The University of Queensland

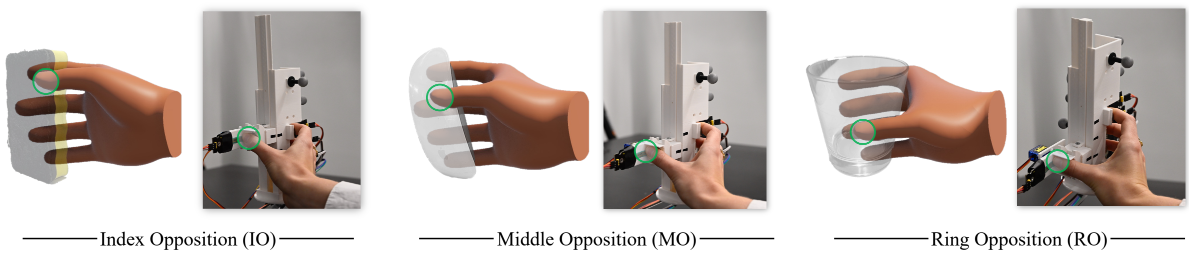


Figure 1: Top: Index Opposition, Middle Opposition and Ring Opposition of the thumb are commonly used poses when grasping objects of different properties. Bottom: ThumbShift changes the users' pose to alter the perception. The green markers show different positions of the thumb in these poses.

Abstract

Inspired by the observation that humans naturally adjust finger configurations based on object size and weight, we present ThumbShift, a novel haptic controller that physically moves and rotates the user's thumb to render subtle shifts in finger collaboration and affect whole-hand grasp perception. Unlike prior work focused on grasp type or global haptic feedback, our approach uniquely targets finger collaboration variation through localised, real-time finger repositioning during grasp – enabling Dynamic Digit Positioning (DDP) to modulate haptic and perceptual experience. Results of our user studies show that while size perception changes only slightly, by about 5%, in a two-alternative forced choice (2AFC) task, perceived weight shifts significantly—by approximately 19%—in magnitude estimation tasks. We also report on the influence of mass centre position which extends the weight perception changing ability to about 56%, and how finger force distribution works in altering users' perception. These findings demonstrate that dynamic thumb movement can reconfigure force distribution across the hand and substantially alter haptic experience. By highlighting the underexplored role of digit motion in object perception, our work opens new directions for perception-aware haptic devices in VR, AR, and physical interaction design.

Index Terms: visuo-haptic perception, virtual reality, perceptual illusion, pseudo-haptics

1 Introduction

When interacting with objects of various sizes and masses, fingers collaborate in different positions and contribute different forces (pressure and friction) to create a steady grasp [41]. When grasping objects with extremely small width (e.g., a piece of paper or a pen) usually only the thumb and the index finger are involved, each providing relatively nominal forces. As objects get larger and heavier (e.g. a cup of water or a baseball), greater perpendicular forces are required to counteract the gravitational force pulling the object downwards. Thus, more fingers are included in the vertical grasp, each providing more force, and the thumb moves downwards, in the direction of the little finger, to better oppose and balance these forces [43, 30].

Decisions about how to grasp an object are often made before contact, guided by expectations about its weight and balance [38]. Users anticipate the required finger orientations and force distributions based on prior experience. However, this initial plan continues to evolve after contact. As users hold the object, they adapt their grasp in response to its actual physical properties (sometimes changing, e.g. a bottle being filled with water)— such as shifting weight or torque — to maintain stability and control. This ongoing adjustment highlights how grasping is not a fixed action but a dynamic process that responds to feedback during the hold itself. These adjustments reflect an intuitive motor strategy, optimized to support varying physical demands through collaborative finger movement, and form the action counterpart to our size-weight perception [28].

Size perception, and associated size illusions, have received much attention in the VR controller literature (e.g., [6, 17, 60]). These devices have sought to understand and exploit the limits of users' size perception, in order to convince the user they are holding objects that are, for example, smaller or larger than the actual device they are holding. These works have shown how virtual objects can be, e.g., 28.7% larger and 4.3% smaller than their physical counterparts without the user noticing [60]. Leveraging these discrepancies allows interaction designers to either (a) use physical items from the real world as proxy haptic props in virtual reality, or (b) potentially increase the scope of use of physical controllers they are building. It is still underexplored how these perceptual limits can be influenced by the active haptic controllers.

In contrast to size perception, weight perception receives comparatively little attention for controller design. On the one hand, there have been a number of devices that simulate force on the hand when grasping (e.g., [11, 12]) – these devices inherently allude to weight, though their primary focus remains size. On the other hand, there have been a range of devices that move their center of mass during interaction (e.g., Shifty [58], Transcalibur [49], etc.), causing dynamic rebalancing of the users' grasp. To date, however, these works have targeted user experience and improved immersion, but have not yet taken a fundamental approach to understanding weight perception and the potential implications for simpler controller designs.

In this work, we explore limits and illusions for size and weight perception for controller design in virtual reality. Based on the observations around finger poses and force distributions in grasping,

*e-mail: jianzhang10@student.unimelb.edu.au
†e-mail: g.buckingham@exeter.ac.uk
‡e-mail: wafa.johal@unimelb.edu.au
§e-mail: j.knibbe@uq.edu.au

we examine whether size and weight perception can be altered by directly repositioning and reorienting the fingers during interaction. We start with the assumption that size-weight perception is a closed loop system – that assumptions about the object inform the planned grasp configuration and expected force delivery, but that the resultant pose and force once in contact with the object is fed back, through kineasthesia and proprioception, to update our understanding of the final size and weight. As such, we hypothesise that reorienting our fingers, and the resultant force redistribution, should alter our size and weight perception.

Inspired by this, we propose an approach to render haptics for objects of different sizes by changing grasping features via finger repositioning and redirecting. We construct a fixed-size controller, that can directly and dynamically move the user's thumb and change its orientation with respect to the other fingers. We conducted a series of psychomotor studies to understand whether these thumb changes influence the perception of size and weight. Simultaneously, we also consider the impact of the relative weight distribution of the controller. Our results show that reorienting and repositioning the thumb has a significant, yet negligible, impact on size perception, but a significant and large impact on weight perception. From this, we propose Dynamic Digit Positioning as a means of altering (primarily) weight perception through a more mechanically simple controller mechanism.

We make the following claims[1]:

- Dynamic Digit Positioning is a simple mechanism that can be used to exploit size-weight perception in controller design.
- Dynamically changing the thumb's positioning and orientation can alter virtual object weight perception by approximately 19%.
- Coupling dynamic thumb positioning with dynamically altering the centre of mass of the controller can further alter object weight perception, up to approximately 56%.

2 Related Work

Researchers have been concentrating on providing haptics in VR via active and passive controllers. Some mechanically reflect the exact properties of the virtual objects (active controllers, e.g., [11]) while others use proxy objects and visual illusions to render them (passive approaches, e.g., [6]).

When visuo-haptic illusions are applied within perceptual limits, users are considered unlikely to notice their occurrence. This makes studying these limits crucial to their success.

Some studies have concentrated on applying illusions on active controllers to render haptics with lower costs and simpler designs. We begin by presenting mainstream haptic device designs and technologies, highlighting the role that illusions play in their feedback. We discuss the possibility of applying illusions with grasping poses in haptic devices.

2.1 Haptics in VR

Recent research has increasingly focused on enhancing high-resolution haptic feedback for virtual reality (VR) interactions. Much of this work centres around handheld and wearable devices, which are portable and resemble the commercial VR controllers currently in use. Notable examples include wearable controllers designed for grasping rigid objects [11, 12], axisymmetric devices for interacting with pseudo-cylindrical shapes [27], and multi-degree-of-freedom controllers tailored for irregular or asymmetric object manipulation [32]. Despite their potential, these devices remain largely specialised, often bulky, heavy, and cumbersome to use.

In contrast, grounded and encounter-based haptic systems deliver on-demand tactile feedback precisely when needed, allowing users to remain otherwise unencumbered. Examples include commercially available systems like Touch[2] and Omega[3], as well as experimental prototypes such as inFORM featuring [21], ShapeShift [50], and REACH+ [25]. These devices are often mechanically complex, bulky, expensive, and necessitate a step towards infrastructuring that makes them impractical for everyday use.

As a result of these high-resolution active controllers remaining complex, specialist, and bespoke, research has also been exploring opportunities for leveraging haptic illusions to enhance or extend the functionality of physical feedback systems and to make use of real-world objects around the user. The illusory work has basically one of the two focuses: *where* the object is, or *what* the object is.

Illusions of *where* have been heavily influenced by approaches such as redirected touching [35] and haptic retargeting [2]. These applications of illusions seek to guide the user's physical hand towards a proxy object that is spatially decoupled from its virtual counterpart. Examples include redirecting controller buttons [59, 26], enabling users to grab objects placed around them [14], and attempting to retarget random, unscripted reaches [13]. From work on these illusions, we have come to understand the spatial *haptic coverage* of a physical object – the area within which it can provide haptic feedback for virtual objects [15].

Illusions of *what* the object is largely explore the extent to which one physical object can be perceived like another. These illusions aim to convince users they are interacting with an object with one property (for example, a heavy hammer), while they in fact interact with a physical object with a different property or, at least, with an object with a different magnitude of that property (e.g., a lightweight bottle).

For example, illusions have been used to simulate factors in interaction such as geometry [54], force feedback [36], stiffness [48] and texture [8].

In a visuo-haptic system, simple physical devices can express various shapes with edges, curves, and surfaces [3, 4]. The method was further developed by Zhao et al. [61] to extend haptic retargeting to complex, arbitrary shapes. Bickmann et al. [7] showed that haptic feedback can be created by illusion without grasping any physical prop and developed a haptic illusion glove that can provide haptic feedback for various virtual objects such as a cup, a hammer, and a water can.

2.1.1 Size Perception in Haptic Rendering

In addition to the devices that can directly alter the physical size stimuli (e.g. CLAW [12], X-Rings [27], etc.), illusions of size in haptic interaction often rely on visual distortion to alter perception. Kim et al. [33] introduced a fixed-size haptic controller that uses finger repositioning to create the illusion of dynamic size change. This allows users to perceive changes in object size with proper visual feedback.

Studies have also shown that the perceived size of physical objects can be influenced by changing the visual representation of those objects in VR [6, 60]. Yang et al. [57] demonstrated that the illusion of size change could be induced not only through direct hand interaction, but also when manipulating virtual tools such as chopsticks. These illusions are effective because they obscure the mismatch between visual input and proprioceptive feedback, creating the compelling sense that the user is interacting with the virtual object—when in fact they are interacting with *something else*, potentially located *somewhere else*.

2.1.2 Weight Perception in Haptic Rendering

While manipulating size perception in VR is relatively straightforward, the simulation of weight remains a considerable challenge [29, 39]. Unlike geometry or texture, weight involves force-based feedback, which is difficult to replicate without actuators or added mass. Approaches such as leveraging vibration (e.g. Grabity [10]), skin deformation (e.g. HapTip [24]) and force feedback [23] have been explored.

Recent work has also considered an actuator-based approach. For instance, Shifty [58] is a dynamic haptic device that expresses convincing different weights by continuously shifting the internal weight distribution across the device. Based on a similar approach, Transcalibur [49] demonstrates how weight distribution is perceived by users and, thus, what they come to believe about a resulting objects' shape.

[1] We adopt a Popperian philosophy, whereby contributions should be claims that are falsifiable.

[2] 3D Systems, USA - formerly Phantom from Sensable Technologies

[3] Force Dimension, Switzerland

Researchers have also explored pseudo-haptic techniques to simulate varying weights. Maehigashi et al.[42] demonstrated that adjusting the brightness, material, and size of virtual objects can lead users to perceive different weights. Similarly, it has also been proven that weight perception can be altered with a mismatch of virtual and physical sizes, as the expectation of force applied in grasping is influenced by the visual feedback [28]. Yet, despite these efforts, developing lightweight, low-power, and high-fidelity systems for expressing weight in VR remains an open and compelling challenge.

2.2 Finger Poses and Grasping

Multi-finger grasping is a complex coordination of digits, and change of grasping force magnitude induces coordinated changes of force and moments on all fingers [44]. Adjusting the hand's grasp requires complex computations that process the object's dimensions, orientation and environment [31]. Castiello et al. [9] have shown that users tend to use the thumb and index finger to grasp objects of small sizes (0.7 cm) and whole hand prehension for large objects (8 cm). Santello et al. [47] have also revealed that force distributions of all digits are altered by the object's geometries, weight, and mass centres. Amis et al. [1] estimated the force distribution on all fingers grasping objects of different sizes. From index finger to the little finger, the resulting proportions are: 30%, 30%, 22%, and 18%. The proportions didn't significantly change with the object sizes, which is reasonable because the finger locations were almost the same and the grasping features didn't change.

These studies show that users tend to change the grasping configurations to alter the force distributions on fingers, and thus adjust to different target objects being grasped. Assuming users' index fingers contribute almost 100% of the thumb-opposing force in grasping small lightweight objects and the proportion decreases when the objects are larger and the grasping type changes to the whole hand prehension, it is of great value to attempt to inversely trigger the illusion of holding objects with different sizes by altering grasping finger force distributions.

3 Dynamic Digit Positioning

We propose and explore dynamically repositioning the users' fingers and, thus, the relative force distributions during grasping as a mechanism to change object size and weight perception. We call this technique *Dynamic Digit Positioning* (DDP).

According to the GRASP taxonomy [20], in most common whole-hand grasps the thumb is located within a range from opposite to the index finger (Index Opposition, IO) to opposite to the ring finger (Ring Opposition, RO) (e.g., see Figure 1). Other than in some exceptional grasping scenarios, such as holding a pen (a Fixed Hook grasp) or a pair of chopsticks (a Tripod Variation), the majority of whole-hand grasps occur within this index-ring-finger opposition range and thus can be simulated by DDP of the thumb. The GRASP taxonomy summarises how each grasp type corresponds to a force distribution and is related to the mass and size of the target object, further supporting DDP as a potential approach for altering size and weight perception through dynamic repositioning of pose and force distribution.

3.1 ThumbShift: a Novel Haptic Controller that Physically Moves and Rotates the User's Thumb to Render Subtle Shifts in Finger Collaboration

Repositioning and redirecting fingers cannot be realised with passive haptic proxies and, thus, we designed an active haptic device to move and rotate the users' thumb in real-time. Using this device, we applied several psychometric approaches to understand the impact of Dynamic Digit Positioning of the thumb on user's perception of objects' size and weight.

We present our haptic device ThumbShift, which changes the way fingers collaborate with each other in full-hand grasp in VR, moving and rotating the thumb to alter haptic perception. The design of ThumbShift is shown in Figure 2, demonstrating two major mechanisms of the device: a stepper motor (28BYJ-48) moving the thumb position with a gear and gear rack, and a servo motor (SG90) rotating the thumb

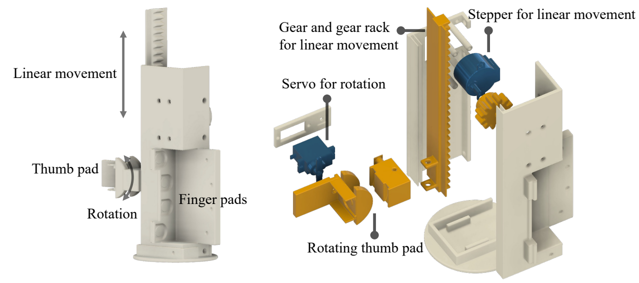


Figure 2: ThymbShift: A VR haptic device that physically moves and rotates the user's thumb to render subtle shifts in digit collaboration and affect whole-hand grasp perception. The blue highlighted parts show the motors, and the orange highlighted parts show the moving mechanisms.

direction. Thin-film pressure sensors can be mounted on each finger pad on the controller.

The distance between the contact surface of the thumb and the contact surface of the other fingers is 6.0±0.1 cm. The height of the controller is 18.2±0.1 cm (up to 25.4±0.1 cm with the gear rack stretching out). The error of linear movement of thumb is less than 0.3 cm and the error of rotating thumb direction is less than 3°. The linear movement speed is approximately 0.9±0.2 cm/s and the rotation speed is approximately 400° per second (and thus the time used to rotate the thumb can be ignored in the study). The speed change when applying grasping force on the device was negligible, due to the device's low mass. The mass of the controller is 223 grams (for comparison, the Meta Quest 3 Touch Plus controller weighs ∼115 grams with battery) and the height of the mass centre is between the Index Opposition level and Middle Opposition level as shown in Figure 5. The controller was connected with long jumper wires (about 40 cm), to ensure free, unrestricted movement of the controller, and to reduce any effect of 'anchoring' on size and weight perception.

To study perception in different configurations of thumb position and orientation, the controller is programmed to move the user's thumb along the surface to three designated locations: Index Opposition (IO), Middle Opposition (MO), and Ring Opposition (RO), as well as three designated orientations: Radial Tilt, Neutral, and Ulnar Tilt (as shown Figure 3). Both the Radial Tilt and the Ulnar Tilt are 10° from Neutral. The linear movement positions IO, MO, and RO were selected to change the finger taking the majority of force in collaboration with the thumb. The distance between two adjacent positions (i.e. IO to MO, MO to RO) is around 2.3 cm. Similarly, by rotating the thumb pad by 10 degrees from the Neutral orientation (around the thumb), the thumb opposes a different finger and so the force distribution changes. For example, if the thumb is in Middle Opposition (i.e., directly opposite the middle finger), rotating by 10° radially puts the thumb in Index Opposition and 10° in the ulnar direction places the thumb into Ring Opposition. Additionally, the biomechanical radial and ulnar rotational range of the thumb is quite restrictive [5] and so the rotation is limited to 10 degrees.

Except for the motors and fastening hardware, the other parts of the controller were 3D printed with polyethylene terephthalate glycol (PETG). Along with the virtual scene of Unity, the control system is built on Arduino UNO R4 Wifi.

4 User Studies

To investigate if perception can be altered through Dynamic Digit Positioning (DDP), we conducted a series of user studies using ThumbShift, organized into two phases.

In Study 1, we examine whether size and weight perception changes based on how an object is grasped. We study this in both a static condition – where the device reconfigures the user's grasp prior to any grasp force being applied (and then remains static during the grasp) – and a dynamic condition – where the thumb pad moves after grasping, altering the distribution of pressure during the holding phase.

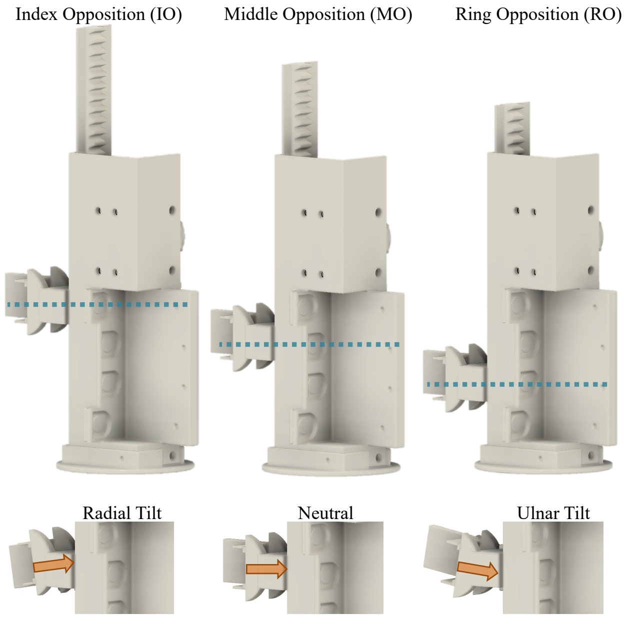


Figure 3: Configurations of the ThumbShift. The thumb can be moved to 3 positions and rotated in 3 directions.

Based on the results of Study 1, Study 2 focused more deeply on weight perception in dynamic conditions. Specifically, **in Study 2 we examine whether (a) the interaction between perceived size and weight can be leveraged to extend the effective rendering range of ThumbShift, and (b) whether subtle changes to the device's center of mass further influence the perceived weight.** We tested various visual object sizes together with different mass centre positions, to assess their combined impact on weight perception with a new group of participants.

4.1 Experimental Design

The participants hold ThumbShift with their right hand and a standard VR controller with their left hand to respond to questions in the study interface. The participants weren't aware of the appearance or design of ThumbShift before the study (the device was hidden upon entry). They were only told it's a device that expresses different sizes and weights.

We applied the two-alternative forced choice tasks described in previous studies [6, 17] to estimate the size perception. The participants compared the size between the virtual and physical objects and chose between "virtual smaller" and virtual larger". As reported in the previous studies, the size illusion of full hand grasp ranges from 5.4 cm to 7.32 cm for a 6 cm physical object [6], which is close to our designed grasp width of ThumbShift (6.0$\pm$0.1 cm). Therefore, the sizes of our virtual objects range from 4 cm to 8 cm with a 0.5 cm step (4.0 cm, 4.5 cm, 5.0 cm, 5.5 cm, 6.0 cm, 6.5 cm, 7.0 cm, 7.5 cm, 8.0 cm).

To estimate the weight perception, we used a magnitude estimation method similar to previous studies (e.g. [52]). The participants orally reported the weight they perceived in the form of a number. The participants were told there was no limit to the range of numbers. They may use whole numbers, decimals or fractions. They should try to make each number match the intensity with which they perceive the sensation. Their reported answers were recorded by the researcher.

While the static conditions simulate the poses interacting with passive objects, perception can be further influenced by dynamic motion (e.g. Yamamoto et al [56] and Kim et al [33]). Therefore, we studied both static and dynamic conditions as to better understand the effects of Dynamic Digit Positioning.

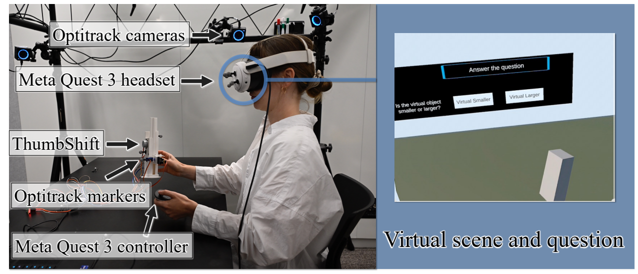


Figure 4: The experimental settings for the user studies.

4.2 Apparatus

In addition to ThumbShift, we used a Meta Quest 3 HMD with the Optitrack motion capture system for tracking the controller and the headset. Seven Prime 13W cameras were placed around the table and set at a tracking frequency of 240Hz (see Figure 4). We designed rigid tracking bodies of different shapes to incorporate the tracking markers which were attached to the tracked objects. These markers did not interfere with the participants' range of motion or object interactions (they were mounted above the device to be grasped). The VR scene was built in Unity 2022 on a laptop PC (13th Gen Intel i9-13900HK 2.60GHz, 32.0GB RAM, NVIDIA GeForce RTX 4090 GPU, Windows 11 Pro).

4.3 Study 1: Does Changing the Grasp Configuration Impact Size and Weight Perception?

We first study the static and dynamic conditions when the users hold the object with different grasp configurations. As the relative force distribution across the fingers changes as grasped objects get larger and heavier, we expect that dynamically altering the grasp to cause force redistribution will directly impact size and weight perception. This is further supported in virtual reality through the inclusion of corresponding visual cues.

4.3.1 Experiment Procedure

Upon recommendation from our local ethics committee, the participants were limited to being in VR for approximately 45 minutes for study 1.

In the static condition, participants experienced the three thumb positions (index opposition - IO, middle-opposition - MO, and ring-opposition - RO) with the three rotation directions (Radial Tilt, Neutral and Ulnar Tilt). The order of the configurations were randomised. With each thumb configuration, the participants compared the physical size with 9 virtual sizes one by one (in a random order) for the 2AFC tasks and then performed the magnitude estimation for weight perception (with the virtual size the same as the physical one), resulting in 10 tasks for every thumb configuration. The device stayed static during the tasks. The device was lifted and put down for each question.

The participants initially grasped the controller lightly, without lifting it, putting their thumb in MO (their fingers were guided by the experimenter). The controller then repositioned the thumb pad into the next orientation and then position. If the target position was the MO position itself, the thumb pad instead moved either upward or downward (randomly) and returned to MO.

Once the thumb reached the target position and direction, participants were then asked to lift the controller and were free to move it within a designated safe area (a space above the table, measuring approximately $50cm^3$ where there was no risk of collision). During the lifting, the participants were given 5 seconds to respond to a 2AFC question or a magnitude questions with the controller in their left hand. The data was considered invalid if the participants used more than 5 seconds (all data points are valid in practice during the study).

In all our studies, the virtual object was only shown when the participants were answering the 2AFC and the magnitude estimation questions, and was invisible at all other times.

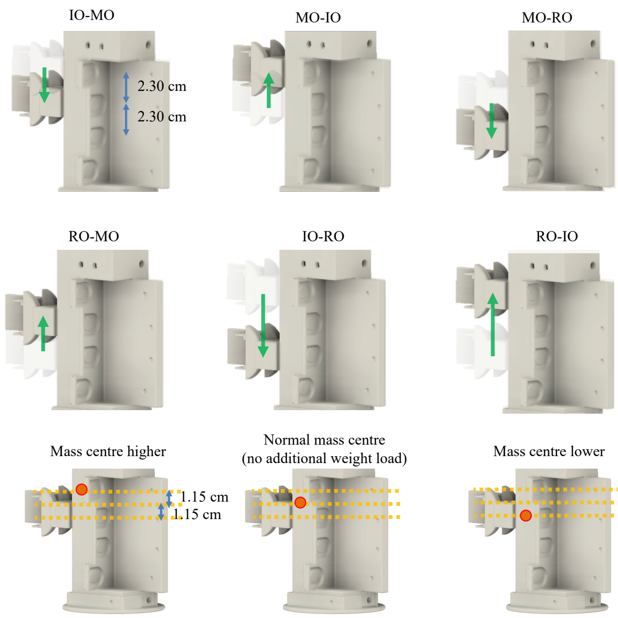


Figure 5: Dynamic configurations of the ThumbShift. The thumb is moved to different positions in 6 sequences, and the mass centre can be moved up and down with an additional weight load attached to ThumbShift.

When the participants finished answering all 10 questions for the current configuration, they placed the controller back on the table, and the controller moved back to the MO position. Next, the controller moved to the next target position and orientation. During this thumb pad movement, participants performed a distraction task — a Stroop task [53], which required them to select an option that matched the font colour, rather than the colour in which the word was displayed. In total, there were 3 positions × 3 directions for the static conditions.

For the dynamic condition, the thumb moved before every question and the users answered the questions right after the movement. There was no distraction task in this condition, as participants were intended to be aware of the reconfiguration. The thumb position changes in six sequences: IO-MO, MO-IO, MO-RO, RO-MO, IO-RO and RO-IO as shown in Figure 5. The time consumed to move to a close-by position is approximately 2 seconds and the full range movements (i.e. RO-IO and IO-RO) took approximately 4 seconds.

The whole dynamic condition was divided into 3 sections for each thumb orientation (orientations are in a random order). The thumb pad oriented to the correct angle before the participants grasped the controller and lifted it into the air. After confirming the lift, the thumb pad moved in six randomised sequences (IO-MO, MO-IO, MO-RO, RO-MO, IO-RO, RO-IO). It stayed at each point for the participants to perform the 2AFC task or the weight estimation task (the participants had 5 seconds to answer, and the data would be invalid if they exceed the time limit, which didn't happen in the study). After answering, the controller moved the thumb pad in the next sequence while the participants held it in the air (without putting it down, different from the static condition).

In each thumb orientation, the participants first answered the 2AFC questions for all the virtual sizes in every sequence, and then answered the magnitude estimation questions for weight perception in every sequence. There were 6 sequences × 3 directions for the dynamic conditions and again 10 questions (nine 2AFC questions and one magnitude estimation question) for each unique configuration.

4.3.2 Participants

We recruited 30 right-handed participants for study 1. The recruitment information was posted on a public university website. Fifteen participants identified as females, fourteen as males, and one as non-binary. Their ages ranged from 18 to 40 and the average age was 24.4 (SD=4.6). There were 8 participants who claimed they had no prior experience in VR, while 19 claimed some experience and 3 claimed good experience. The study was approved by the Ethics Board of the university. Each participant received a gift card with the value of 12 USD as compensation for participating in the experiment.

4.3.3 Results

The proportions of answers in size perception 2AFC questions have been processed similarly to previous studies based on the 2AFC approach [6, 17]. The percentage of selecting "virtual smaller" is calculated for each configuration and the data points are fitted to the sigmoid function:

$$f(x) = \frac{1}{1+e^{ax+b}} \tag{1}$$

The point at which there is a 50% chance of selecting "virtual smaller" is considered the Point of Subjective Equality (PSE); where the virtual object is estimated to be the same size as the physical object (i.e. the participants randomly select from 'smaller' or 'larger', as they perceive the objects to be the same size). The 25% and 75% points, which are used to describe the perception limits in similar psychological studies (e.g., [6, 17, 45]), are correspondingly selected as the upscaling thresholds (UT) and downscaling thresholds (DT) of perception, where the participants become able to accurately determine differences between the physical and virtual objects with 75% certainty.

The results of PSE, UT and DT after fitting in each configuration are shown in Figure 6. Coefficients of determination are all higher than 0.976 and the root mean squared errors are all lower than 0.055 in the fitted curves, indicating satisfying qualities of fit. The smallest perceived size (5.85 cm) appears when the thumb is in Ring Opposition (RO) with Neutral direction, while the largest perceived size (6.19 cm) also appears at RO with Radial Tilt. In the static condition there's only a 0.34 cm range of size perception change (approximately 5.67% of the actual physical grasp size) from the interpretation of PSE. Therefore, **users' size perception does change as a result of the static reconfiguration of the thumb, but by a small amount that seems to offer limited value in VR applications.**

Following standard practices in magnitude estimation analysis suggested in related psychometric work [51, 22], we applied a logarithmic transformation to raw participant estimates to linearize perceived intensities. To account for individual differences in response scaling, we then centered log-transformed values within each participant (as suggested by Cousineau et al. [16]), allowing valid group-level statistical analysis. The normalized data were analysed using a repeated measures ANOVA to examine the effects of the thumb position, thumb

Table 1: ANOVA results for static condition. (SS: Sum of Squares, ddof1: degrees of freedom for the effect, ddof2: degrees of freedom for the error/residual, MS: Mean Square, F: F-value, p-unc: uncorrected p-value, p-GG-corr: Greenhouse-Geisser corrected p-value, η_g^2: effect size, ε: Greenhouse-Geisser estimate)

Source	SS	ddof1	ddof2	MS	F	p-unc	p-GG-corr	η_g^2	ε
position	3.61	2	58	1.81	1.80	0.1739	0.1794	0.0169	0.86
direction	1.23	2	58	0.61	0.61	0.5480	0.5478	0.0058	1.00
position × direction	1.27	4	116	0.32	0.40	0.8113	0.7383	0.0060	0.68

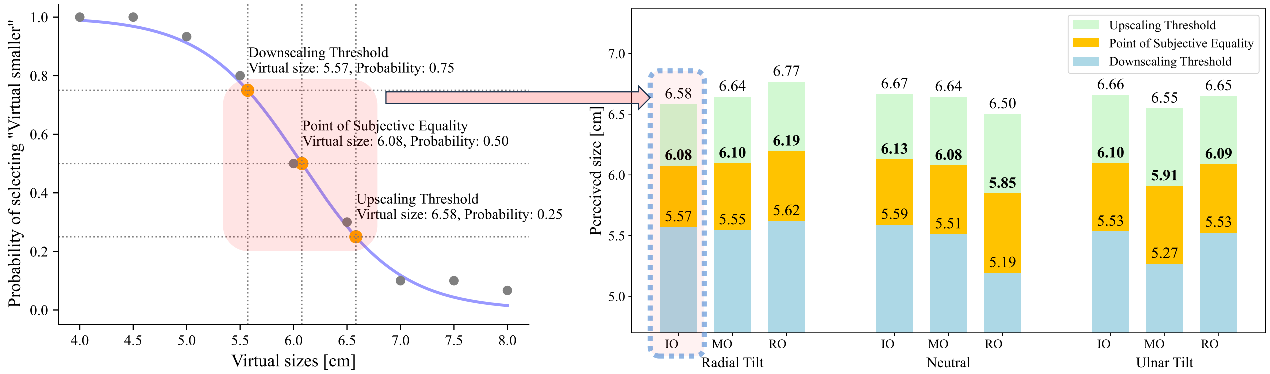


Figure 6: Left: an example of fitting 2AFC results into a sigmoid curve. The horizontal values of the points whose vertical values are 0.75, 0.5 and 0.25 are accordingly the downscaling threshold, point of subjective equality and upscaling threshold. Right: the PSE, downscaling threshold and upscaling threshold in static conditions with different thumb positions and directions are summarised in this figure.

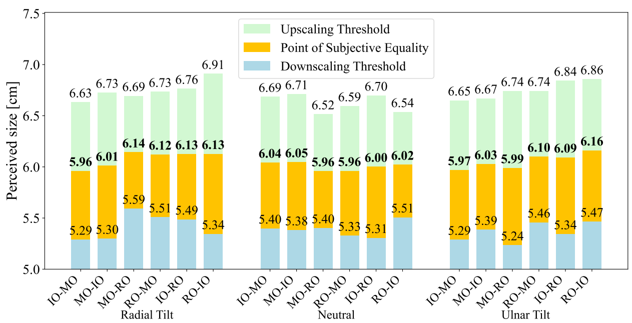
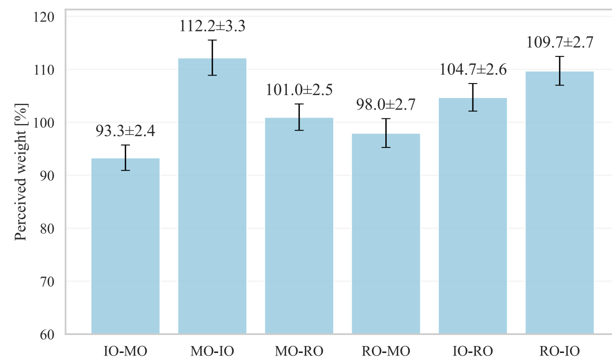


Figure 7: The PSE, downscaling threshold and upscaling threshold in dynamic conditions with different thumb positions and directions are calculated by fitting the 2AFC results into sigmoid curves, and are summarised in this figure.



Source	SS	ddof1	ddof2	MS	F	p-unc	p-GG-corr	η_g^2	ε
sequence	2.26	5	145	0.45	4.73	0.0004	0.0031	0.0673	0.66
direction	0.06	2	58	0.03	0.22	0.8008	0.7987	0.0020	0.99
sequence*direction	0.31	10	290	0.03	0.98	0.4096	0.4096	0.0098	0.33

Figure 8: The weight perception with dynamic thumb repositioning sequences.

direction, and their interaction on the dependent variable. Finally, the data was exponentiated to show the linear changes on weight perception.

In the ANOVA analysis if the violation of sphericity happens, Greenhouse-Geisser correction is applied on p-value. In the weight perception analysis in static condition shown in Table 1, both the position and direction of thumb showed p-value larger than 0.17 and effect sizes less than 0.017, indicating statistical non-significance and small effects on weight perception. Therefore, **the static reconfiguration of the thumb does not have an effect on weight perception.**

The same approaches of analysing the 2AFC and magnitude estimation results from the static condition are applied here in the dynamic condition results.

The psychometric curve in the dynamic condition is well fit, with the coefficients of determination all higher than 0.966 and the root mean squared errors all lower than 0.061. As shown in Figure 7, the size perception is the smallest (5.96 cm) in IO-MO Radial Tilt, MO-RO Neutral and RO-MO Neutral conditions, while it's the largest (6.16 cm) in RO-IO Ulnar Tilt condition according to PSE. **Again, while dynamically repositioning the thumb does change size perception, it is by a small amount (0.20 cm, 3.33% of the physical size), which seems to offer little meaningful design opportunity for VR applications.**

On the other hand, the magnitude estimation results show a significant influence of the sequences on weight perception with the corrected p-value of less than 0.0031 and effect size larger than 0.067. The thumb direction and the interaction effect (thumb moving sequence and direction) have no significant influence (p-values are both larger than 0.40 and the effect sizes are both less than 0.001).

The weight perception is shown in Figure 8 where 100% represents the mean value of each participant's estimation. **Dynamically repositioning the thumb can alter weight perception by up to around 19%.** The estimated weights are larger in MO-IO (112.2%) and RO-IO (109.7%) sequences and lower in IO-MO (93.3%), MO-RO (101.0%) and RO-MO (98.0%) sequences. The weight perception changes the most between the sequences MO-IO and IO-MO with the difference of 18.9% (112.2%-93.3%).

4.4 Study 2: Do Mass Centre, Virtual Size, and Force Distribution Impact Weight Perception?

In Study 1, we examined the impact of finger opposition and thumb orientation on perceptions of size and weight. To find out if other factors also influence the weight perception, we examine how the position of the mass centre influences weight perception (which has been shown to have an impact in prior work [58]). Upon the originally 223-gram controller, a weight load of 93 grams was mounted to move the mass centre from the original position (between IO and MO) to the same level of IO (defined as the "higher" position) and the same level of MO (defined as the "lower" position). Should this have a sufficient impact, this might motivate the inclusion of further internal mechanisms into future devices.

In addition, previous studies have indicated that there is a tight interplay between size and weight perception (e.g. [28]) – weight perception can be influenced by mismatches in object size (through the size-weight illusion). To examine whether size-weight perception further influences weight perception under Dynamic Digit Positioning, in Study 2 we consider the direct impact of virtual size incongruence on weight perception. If there is an impact, this may be another route to further enhance the illusory capability of such devices.

4.4.1 Experimental Procedure

The participants answered only the weight magnitude estimation questions in dynamic condition (i.e. the questions were answered right after the movement and there were 6 sequences of movement). Study 1 indicated the direction had no significant influence and thus we kept it to be neutral in study 2.

At first, the mass centre was manipulated to be either on the higher position or the lower position by adding the weight load. The order of presenting the two mass centre configurations was randomised, and in each mass centre configuration, the order of thumb moving sequences was also randomised. The mass centre wasn't changed before the participants performed the estimation for all the 6 sequences. There were 12 combinations for the different mass centre conditions, including 6 sequences $\times$ 2 mass centre positions.

After the conditions of two mass centre configurations, there were 18 combinations including 6 sequences $\times$ 3 virtual sizes with the additional load removed for the size-weight illusion condition. Drawing on our results from Study 1 (in Figure 6 and 7), we selected three different virtual sizes (5.5 cm, 6.0 cm, 6.5 cm), that participants struggle to differentiate. The orders of presenting the moving sequences and the virtual sizes were both randomised. Each participant performed the task of different virtual objects 3 times. In study 2 the time to perform the tasks including different mass centre conditions and virtual size conditions was about 20 minutes in total.

4.4.2 Participants

Similarly, we recruited 12 right-handed participants for study 2 via a public university website. None of these participants had taken part in study 1. Five participants self-identified as female and seven as male. Their ages ranged from 22 to 33 and the average age was 25.7 (SD=3.3). Three participants claimed to have extensive experience with VR, six claimed some experience, and three claimed no experience. The study was approved by the Ethics Board of the university. Each participant received a gift card with the value of 6 USD after the study.

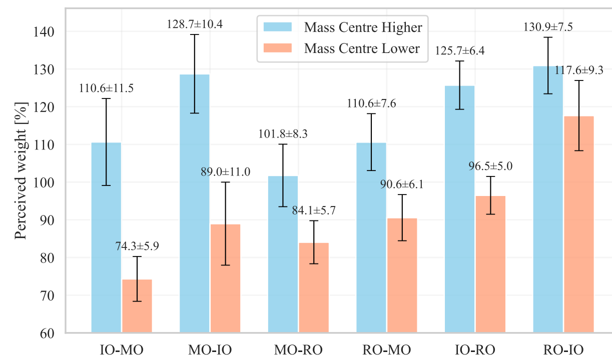
4.4.3 Results

The same analysis of weight perception from study 1 was performed for study 2 results. The ANOVA of the magnitude estimation showed significant effect of both the moving sequences (corrected p-value=0.0086 and effect size=0.156) and mass centre positions (p-value=0.0115 and effect size=0.199) on weight perception, while their interaction effect is not significant (p-value=0.175).

Figure 9 shows how weight perception changes with different mass centre positions. In general, the users perceive the object to be heavier when the mass centre is higher and closer to the index finger and the pattern of how weight perception changes with sequences is similar to previous results.

The FSR readings were filtered and converted through a logarithmic transformation. We could not guarantee stable measurement through the sensors, however, so we include them here only as an approximation of changing force patterns. The FSR readings when the mass centre is higher and lower are demonstrated in Figure 10.

In the size-weight illusion condition, similar to study 1 results, the influence of sequences on weight perception is significant with corrected p-value less than 0.002 and effect size larger than 0.19. The virtual size, however, has not shown significant effect on weight



Source	SS	ddof1	ddof2	MS	F	p-unc	p-GG-corr	η_g^2	ε
mass centre	2.49	1	11	2.49	9.16	0.0115	0.0115	0.1991	1.00
sequence	1.85	5	55	0.37	4.97	0.0008	0.0086	0.1558	0.53
mass centre*sequence	0.43	5	55	0.09	1.60	0.1754	0.2067	0.0409	0.62

Figure 9: The weight perception with different mass centre positions

perception with p-value larger than 0.9 and effect size less than 0.0007. The effect of sequence on weight perception is shown in Figure 11, from which a similar pattern of change to study 2 (Figure 8) is clearly demonstrated. Again, the estimated weights are larger in MO-IO and RO-IO sequences and lower in IO-MO, MO-RO and RO-MO sequences. The average sensor readings from FSR of each finger and each sequence are demonstrated in Figure 12.

5 Discussion

From the user studies, Dynamic Digit Positioning through thumb reconfiguration has an effect on size perception, but the scale of this effect is minimal. Conversely, dynamic thumb reconfiguration during grasping has a meaningful impact on weight perception. Combining thumb reconfiguration with nominal center of mass changes has an even larger impact on weight perception.

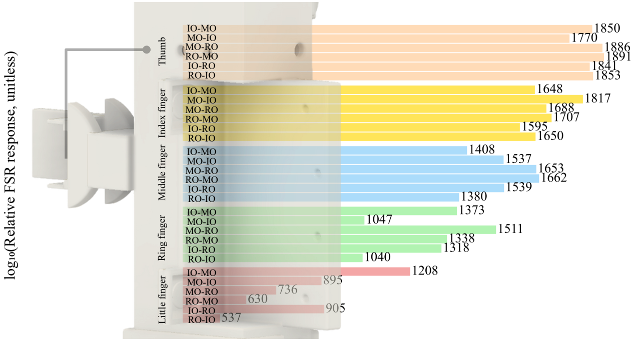
5.1 ThumbShift Enhances Size Perception Accuracy

In both the static and dynamic conditions, the size perception showed only subtle changes from PSE (see Figure 6 and 7). Previous perceptual threshold estimation studies using a 6 cm passive object, 2AFC approach, and whole hand grasping [6, 60] reported upscaling and downscaling thresholds of approximately 7.32 cm and 5.40 cm. While the downscaling thresholds we report here remain similar to those previous studies, the upscaling threshold was smaller, limited to 6.91cm. In total, this contributes to a smaller range of just noticeable differences (upscaling threshold - downscaling threshold) in our studies, indicating the perception of size is more accurate with ThumbShift.

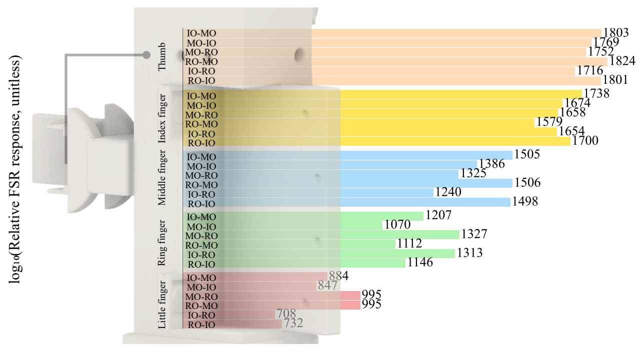
One of the reasons that might lead to more accurate size perception is that the thumb was moved along the surface of the device in our study, contributing more perceptual samples that are integrated into a more accurate perceptual model of the device. In the previous studies, the participants grasped, lifted, and released the physical objects in each trial, giving them only one perceptual point of feedback and, as such, resulting in a less accurate perceptual model of the object and larger upscaling and downscaling thresholds.

Additionally, the users held the same controller in study 1 for a much longer time (around 45 minutes) than reported in previous studies (i.e. around 10 minutes for each physical object [6, 60]), also resulting in the users getting more familiar with the haptic properties of ThumbShift.

The implication of increasing perceptual accuracy over time, perhaps as a result of integration of additional sensory samples, emphasises the need for further consideration of training and learning effects in haptics over time. Even over a short increase in interaction time (10 minutes to 45 minutes), we see an increase in perceptual accuracy. What happens

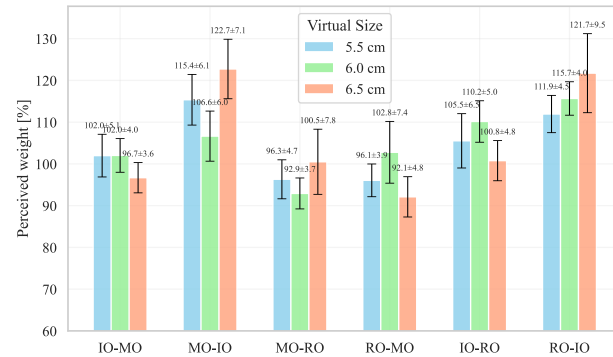


(a) Pressure sensor readings with higher mass centre



(b) Pressure sensor readings with lower mass centre

Figure 10: The pressure sensor readings with higher (a) and lower (b) mass centre. Values plotted are logarithmically transformed FSR outputs, representing relative pressure levels. Note that FSRs produce non-linear responses to force; thus, these readings reflect relative force magnitude, not calibrated force in physical units.



Source	SS	ddof1	ddof2	MS	F	p-unc	p-GG-corr	η_g^2	ε
sequence	1.332	5	55	0.266	8.86	0.000003	0.0022	0.1907	0.36
virtual size	0.003	2	22	0.002	0.11	0.9002	0.8787	0.0007	0.89
sequence*virtual size	0.344	10	110	0.034	1.05	0.4047	0.3539	0.0574	0.16

Figure 11: The weight perception with different virtual sizes

should device use increase to a couple of hours or days? To what extent do our perceptual models reset between uses? Furthermore, in our study, participants did not see the controller prior to interacting with it in VR. Multi-sensory integration is more accurate than kinaesthesia alone [55] and, thus, seeing the controller prior to use may further reduce perceptual limits. These are important avenues for future work.

Given that the perception change is limited to around only 5% (0.34 mm) of the physical width of the controller, the rest of the discussion will focus on the proportionally larger impact on weight perception.

5.2 Dynamic Thumb Position Changes Alter Perceived Weight via Finger Force Redistribution

Unlike the results in the dynamic conditions, there was no significant effect of thumb configurations on weight perception in the static conditions, which suggests the change of weight perception happens from the contrast of perception between two different thumb positions and the process of stablising the grasp when the pose changes.

By examining the FSR readings in Figure 12, the perceived weight is largest in the sequences with lower pressure readings on the middle finger, ring finger, and little finger (i.e., when the thumb is opposite the middle or index finger, the pressure readings on the lower fingers decrease, and the perceived weight of the device increases). This indicates that weight perception is strongly related to the force contributions from the middle, ring, and little fingers, broadly echoing what we see in the literature (e.g., [1]).

Therefore, we assume that one reason for the perceived weight increasing in MO-IO and RO-IO conditions is that the relative force, and associated strain, exerted on the index finger increases. The stabilising effect of the lower fingers is also reduced in this scenario. The sequence IO-RO also results in a relatively heavy weight perception compared with IO-MO and RO-MO, suggesting the lower relative strength of the ring finger in opposition to the thumb also impacts weight perception. These patterns of the weight perception are verified in both study 1 (see Figure 8) and study 2 (see Figure 11) with different groups of participants, showing the effectiveness of the experiment and analysis methods.

Another potential reason for the weight perception to change is that a sense of downwards slippage is introduced when the thumb moves towards the index finger in MO-IO and RO-IO. Similar slipping mechanism on fingers has been designed in SpinOcchio [34] without examining the weight perception. By holding the device vertically, the dynamic sequences MO-IO and RO-IO simulate a slow slipping of objects in grasp (accordingly taking around 2 seconds and 4 seconds), which can create an illusion of slipping, or additional downward pressure cues, due to heavy weight. This possibility also explains why the weight perception doesn't change in the static conditions. The sequence IO-RO is an exception here, where the slippage illusion doesn't happen but the weight is also perceived heavier. Therefore, the weight perception may be changed due to the combined effect of the change of force distribution and the illusion of slippage.

5.3 Mass Centre Position Alters Weight Perception via Finger Force Distribution

Although previous studies such as Yamamoto et al. [56] and Zenner et al. [58] developed weight-shifting devices, we look deeper into the mechanism of how changes in mass-centre effects the weight perception with pressure sensor data and a much less intense user interaction than waving or shaking the device.

Figure 9 shows the weight perception can be largely altered with different mass centre positions as suggested in previous studies (e.g. Kalus et al. [29]), with an overall larger weight perception when the mass centre is higher and the pattern of weight perception changing with sequences also different. When the mass centre is higher, it's further away from the centre of the palm and, according to our analysis of finger collaboration, the ring and little fingers contribute little force for stabilising the weight, increasing the relative load and strain on the index finger. In the higher mass centre condition in Figure 10 the ring finger force is again showing the opposite pattern to the weight perception, while the force changing on little finger shows less regular patterns and one of the reasons is the mass centre is far from the little finger and the force contribution from the little finger is thus irregular and less impacting. In the lower mass centre condition in Figure 10 the pattern of pressure on the ring and little finger changing with weight perception is less obvious, but there's still, for example, a clear decrease of force when the weight perception is larger in RO-IO.

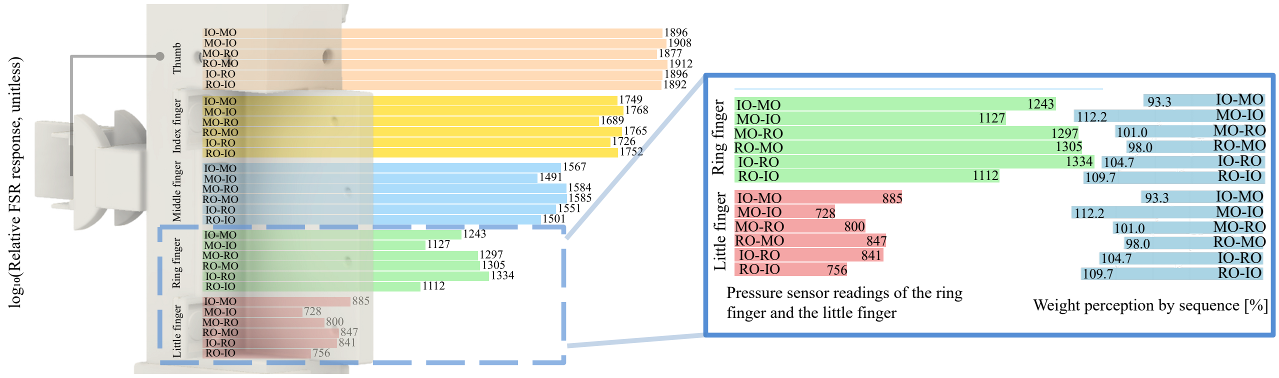


Figure 12: Left: The pressure sensor readings (no additional weight load). Right: The readings of the ring finger and the little finger show an inverse pattern when compared with the weight perception results.

5.4 Implications for VR Haptics

ThumbShift is a novel addition to haptic devices for grasping such as Stuet [32] and TORC [37], showcasing how weight perception can also be altered in grasping with subtle movements of the thumb. The user studies also revealed the potential of Dynamic Digit Positioning for haptics.

The increased accuracy of size perception seen with our device (relative to previous studies [6, 60]) indicates that the ability to exploit illusions of size perception decreases when the users continuously hold the device. This result highlights the potential importance of fully releasing and re-grasping physical devices when aiming for the largest possible range of virtual sizes to be rendered by limited haptic devices. This aligns with the conclusion by Lim et al. [40] according to Weber's Law.

In previous studies, weight perception was a challenging VR haptic field [40] to be altered with complex mechanism (e.g. [23, 19], certain movement of the users (e.g. waving the device in [58], and shaking the device in [56]) and pseudo-haptic approaches (e.g. [18, 46]. These approaches are either costly, bulky, inefficient or limited to certain large-scale user movements. We propose a new method of simply moving the thumb position and orientation in certain sequences to simulate different weights effectively. A single motor with simple design of thumb pads being added to any controller or haptic device in VR/AR can potentially reach the same effect of altering weight perception. And the perception changes happen within the users' hands without being put down, simplifying the user interaction, all the while making it more practical for realistic VR applications.

Furthermore, although already indicated in previous studies [56], we found that moving the mass centre has a large impact on weight perception. In concert with thumb shifting, minimally shifting the center-of-mass can change the perceived weight by more than 56% (heaviest when the mass centre is higher and thumb moves up, i.e. RO-IO sequence, and lightest when the mass centre is lower and the thumb moves down, i.e. IO-MO sequence, Figure 9). This means in our study ThumbShift showed the ability to alter the weight perception by more than half of its own weight (approximately 414 grams to 235 grams, ranging around 179 grams taking the real mass as 100% in the results), demonstrating the ability to be applied in various VR scenes with grasp. Even if the thumb movement is limited within IO and MO positions, the perceived weight can also be changed by around 54% when the mass centre is moved. By simply changing the mass centre and moving the thumb between the IO and RO positions—configurations that result in natural grasp poses found in widely used controllers such as the Meta Quest Touch Plus controller—ThumbShift achieves a weight rendering range that overlaps with, and encompasses, many commonly used grasp types as defined by the GRASP taxonomy [20]. All of this is achieved through only minimal mass-center changes (2.3 cm). This makes ThumbShift a compelling design choice for VR applications.

These insights from ThumbShift and the related studies, once applied in the haptic designs in the community, simplify the challenge of altering the weight perception without complex designs or large-scale motion of the users.

5.5 Future Work

The results of our studies show a more accurate size perception than previous studies [6, 60], highlighting the need for further exploration of the influences of training, learning, and fatigue on perception. Our future works will examine how visual priming and familiarity impact the haptic perception.

In our studies, the device was held vertically with different thumb configurations. We believe the associated perception change is a factor of a change in force distribution across the fingers and a reduction in the stabilising effect of the additional fingers, and the impact of perceived slippage. It's possible, however, that perception changes differently if the device is held differently (e.g. horizontally with the thumb on top or at bottom). In addition, similar to the study of Kim et al. [33], the sense of slippage may also be enhanced through associated visual cues. We expect less effect on altering the perception in horizontal grasps because the thumb movement won't change the force distribution and finger collaboration as much in these poses, but the influence is still to be estimated.

The thumb orientation seems not to be able to influence the weight perception in our study, although altering the direction changes the force distribution and the difficulty of lifting the object. This indicates that thumb repositioning is a much more substantial influence on weight perception. However, the influence of orientation changes across all the fingers remains unknown and warrants further investigation.

6 Conclusion

Given that objects with different physical properties are grasped with different poses, we propose Dynamic Digit Positioning as a technique to alter the grasping pose, and so alter the force distribution across the fingers, and so influence the perception of an object's size and weight. To validate Dynamic Digital Positioning, we designed ThumbShift, a haptic device that redistributes the forces on fingers by moving and rotating the thumb. While the static grasp, thumb direction and size-weight illusion showed minor influence on size and weight perception, the thumb movement in dynamic conditions, together with changes in the mass center of the device, has a large impact on the perceived weight. Based on our user study results, ThumbShift designed with the DDP approach has the ability to alter the weight perception by around 56% (179 grams) and holds the potential to extend this ability in further developments.

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