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A Review for Researchers and Developers

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Tactile Weight Rendering: A Review for Researchers and Developers

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(Survey Tutorial Paper)

***Abstract*—Haptic rendering of weight plays an essential role in naturalistic object interaction in virtual environments. While kinesthetic devices have traditionally been used for this aim by applying forces on the limbs, tactile interfaces acting on the skin have recently offered potential solutions to enhance or substitute kinesthetic ones. Here, we aim to provide an in-depth overview and comparison of existing tactile weight rendering approaches. We categorized these approaches based on their type of stimulation into asymmetric vibration and skin stretch, further divided according to the working mechanism of the devices. Then, we compared these approaches using various criteria, including physical, mechanical, and perceptual characteristics of the reported devices. We found that asymmetric vibration devices have the smallest form factor, while skin stretch devices relying on the motion of flat surfaces, belts, or tactors present numerous mechanical and perceptual advantages for scenarios requiring more accurate weight rendering. Finally, we discussed the selection of the proposed categorization of devices together with the limitations and opportunities for future research. We hope this study guides the development and use of tactile interfaces to achieve a more naturalistic object interaction and manipulation in virtual environments.**

***Index Terms*—Haptic interfaces, tactile weight perception, virtual reality, weight rendering.**

I. Introduction

OVER the last decade, the usage of haptic interfaces has gained considerable attention in various applications, such as teleoperation [1], virtual reality (VR) training [2], [3], and neurorehabilitation [4]. Haptic interfaces are mechatronic devices that can modulate physical interaction between a human and their surroundings by displaying kinesthetic cues, i.e., information on the position of and the forces acting on a limb, and tactile cues relating to sensory information from the receptors of the skin [5]. These interfaces can guide or restrain the user's movements and render the physical properties of an object, such as friction, temperature, stiffness, roughness, and weight [6]. Among these physical properties, weight is particularly relevant because it mediates the initial phases of object interaction and the forces applied for grasping and lifting objects [7], [8]. Notably, the addition of weight rendering has been shown to improve the interaction with virtual objects, e.g., improving the task performance during VR assembly tasks [9] and in teleoperation scenarios [1]. Rendering the weight of tangible virtual objects has benefits beyond enhancing performance, e.g., weight haptic rendering is associated with enhanced motor learning of tasks involving objects with complex dynamics [4], [10]. It has also been shown to have a positive effect on the sense of embodiment and ownership in VR [11], which in turn are associated with better performance [12], [13].

Initially, the weight of virtual objects was rendered via kinesthetic haptic devices by applying forces to the limbs or fingers using grounded mechanisms [14], [15]. However, some of these studies pointed out reduced sensitivity compared to actual weights [14] and that simulated weights were perceived as "*too artificial*" by the users [16]. In addition to specific device limitations, the absence of tactile feedback, known to contribute to the perception of weight [17], [18], might be behind these limitations, as suggested by [14]. Psychophysical studies have shown that the provision of kinesthetic information results in less accurate detection of small weights compared to tactile information, as well as lower discrimination between masses up to approximately 200 g [19], [20]. Furthermore, it has been shown that the combination of both sensory sources yields better discrimination and detection accuracy than isolated stimuli [14], [19], [21]. These results highlight the importance of tactile stimulation in weight perception and the need to provide multisensory haptic information to achieve accurate and compelling weight rendering.

Researchers have explored tactile displays for weight rendering to achieve such a multisensory stimulation or provide an alternative to kinesthetic haptic devices. These devices can display tactile stimulation to simulate weights using a variety of approaches. For example, numerous works used asymmetric vibrations through vibration motors to induce a pulling sensation

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that can modulate the perceived weight of an object [22], [23]. Another approach is to reproduce the natural skin stretch of the fingerpad upon lifting an object [24], [25].

A recent review by [26] provides a broad overview of weight rendering approaches and associated limitations. In this review, we aim to build upon their work by presenting a deeper analysis of the weight rendering approaches through tactile stimulation and comparing relevant tactile interfaces to allow researchers and developers to perform an informed selection of the best approach for their needs. To do so, we reviewed studies on human weight perception and the approaches employed to render weight through the tactile sense. We complemented the findings of these studies with other relevant articles using the same approaches for related applications—e.g., object manipulation [25] and mass perception [27]—to gain a better understanding of the capabilities of each approach. Importantly, with the gathered information, we propose a categorization to compare the available tactile interfaces for weight rendering. We considered various criteria, including the approaches' physical properties (i.e., size and mass), mechanical characteristics (i.e., degrees of freedom, workspace, and maximum rendering force), and perceptual features (i.e., weight and direction discrimination threshold). Then, we discussed our findings in the scope of two research questions: *A) Which approaches have been used to render weight through tactile stimulation?*; and *B) What are the main advantages and disadvantages of each approach?*

We hope this review can guide the use of tactile interfaces in diverse domains to achieve more accurate and coherent weight rendering. Doing so could ultimately translate into a more effective integration of tactile stimulation in haptic solutions, potentially improving task performance in VR training and teleoperation, enhancing motor learning in robot-assisted rehabilitation, and providing a more naturalistic interaction with the Virtual Environment (VE).

The remaining part of the article is organized as follows. Section II presents the background knowledge of the sensory mechanisms underlying weight perception, emphasizing the role of tactile information. In Section III, we elaborate on existing approaches for rendering the weight of objects through tactile stimulation. In Section IV, we present the results from the comparison across those approaches based on the physical, mechanical, and perceptual characteristics of the tactile interfaces utilizing them. We then discuss the review's findings and the comparison, together with possible opportunities and directions for future research in the field, in Section V. Finally, the outcomes and implications of our study are summarized in Section VI.

II. Background

This section presents background knowledge on measurement methods in weight perception studies, the mechanisms for weight perception, and the role of cutaneous information on human weight perception.

A. Measurement of Perception

The field of psychophysics governs understanding of the relationship between physical attributes of stimuli and their corresponding perception. Two key concepts relevant to this review are the measurement of *absolute threshold* (Detection Threshold, DT) and *difference threshold* (Differenz Limen or DL). The absolute threshold represents the minimal stimulus intensity required for human perception, while the difference threshold signifies the amount of change in a stimulus needed for a *Just Noticeable Difference* (JND) [30], [31]. Notably, the *Weber Fraction* (WF), which denotes the proportionality of stimulus change to its initial magnitude, is another essential term. This fraction is defined as $c = \Delta\phi/\phi$, where $\Delta\phi$ is the change in magnitude and ϕ is the starting magnitude of the stimulus [32]. Although this value is considered constant, it has been observed to drastically increase as the magnitude of the stimulus gets closer to the absolute threshold [31]. Another metric worth mentioning is the *Point of Subjective Equality* (PSE), used to indicate the point at which the magnitude of a stimulus in a specific condition is perceived to be of equal intensity as that of a reference condition.

Numerous experimental methods can be found in the literature to measure these thresholds, such as the method of constant stimuli, the method of adjustments, or the method of limits. Multiple variations arise from them, using adaptive procedures and other paradigms based on statistics and signal detection theory. In-depth review and explanation of psychophysical methods are provided in [30], [31].

B. Perception of Weight and Contribution of Tactile Cues

When humans grasp, lift, and hold an object with their hand, the gravity acting on its mass creates a downward force (i.e., weight). For a successful lift or hold in the air, this weight should be stabilized with the friction force between the contacted skin and object, actively controlled by the grip force; see Fig. 1 for a schematic of these forces for a precision grasp.

During lifting, humans perceive the object's weight by combining information from multiple sensory systems, predominantly somatosensory and visual ones [26]. The somatosensory system processes tactile cues, perceived through the skin receptors, and kinesthetic cues, sensed by the proprioceptors in muscle spindles or tendon organs. Furthermore, studies have shown evidence of the interplay between the two, where tactile mechanoreceptors responsible for skin stretch also contribute to kinesthetic cues by conveying information about joint angles [33], [34]. Even before lifting begins, individuals gauge an object's heaviness by scrutinizing its appearance. Upon touch and grasp, they acquire tactual information, such as contact shape, texture, temperature, and friction. During lifting, they perceive skin deformation, joint positions, and forces acting on muscles. Integrating all this sensory information by the central nervous system forms the basis for estimating an object's weight [33], [35].

The role of each sensory information on perceived heaviness and how they are incorporated have been active research topics for nearly two centuries, dating back to the early psychophysical experiments conducted by Weber [32]. He observed a significant discrepancy in weight discrimination between actively lifting objects by hand and passively perceiving them through cutaneous sensation when the hand was resting on a table. He found that active lifting was more than twice as precise, and this ability

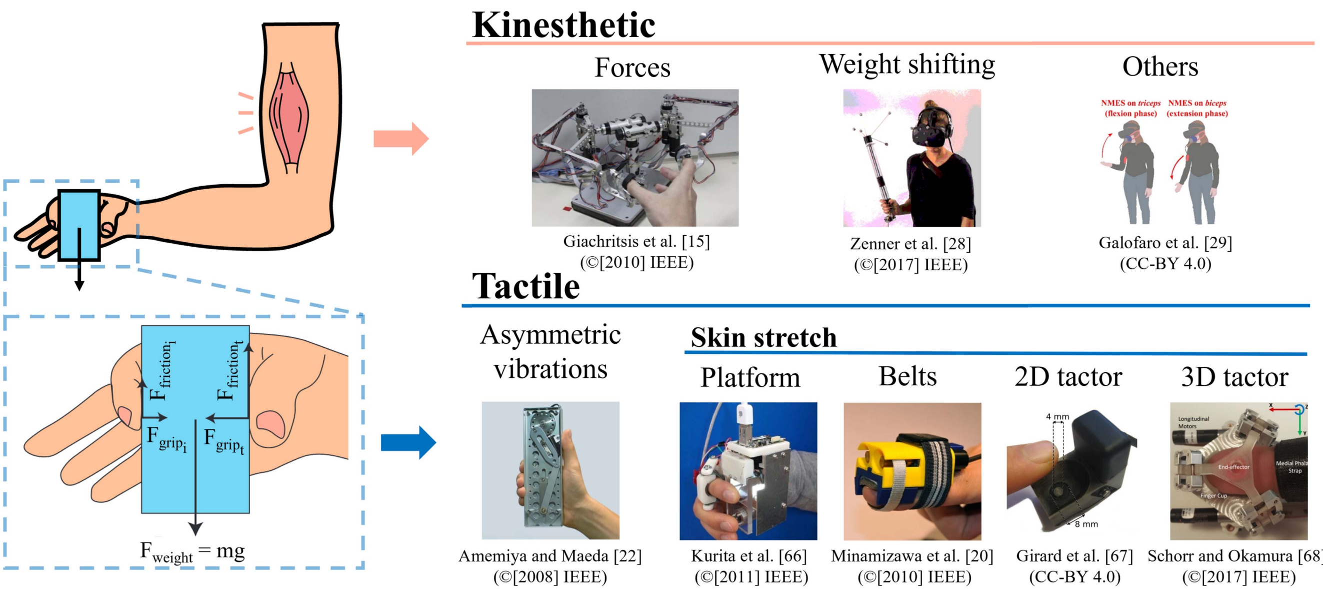

Fig. 1. Somatosensory mechanisms involved in weight perception and the overview of the weight rendering approaches utilizing each perceptual mechanism. Kinesthetic approaches render weight by applying forces upon the limbs [15], shifting the center of mass of the object [28], and other techniques, like neuromuscular electrical stimulation [29]. Tactile approaches rely on skin stimulation through asymmetric vibrations and skin stretch, further subdivided based on the stretch-inducing mechanism into flat surfaces, belts, or tactors actuated in planar/tangential or 3 DoF translational movement. The schematic at the bottom left represents holding an object in the air through the precision grasp. The gravity, g, acting on the object mass, m, creates a downward force, F_{weight}. This force is stabilized by friction forces on the thumb, $F_{friction_t}$, and index fingers, $F_{friction_i}$, controlled by corresponding grip forces, F_{grip_t} and F_{grip_i}.

TABLE I
SUMMARY OF RESULTS FROM STUDIES THAT EVALUATED THE EFFECT OF PHYSICAL FACTORS ON THE PERCEIVED HEAVINESS (I.E., WEIGHT)

Factor		Responsible Sensory System	Effect on Perceived Heaviness
Biomechanical conditions	Muscle fatigue	Kinesthetic	When fatigued, perceived heaviness increased due to over-estimation of contraction forces and increased effort [37].
	Flexor sensitivity	Kinesthetic	Lifted objects were felt heavier when the sensory nerves were anesthetized [38].
	Grasp configuration & style	Kinesthetic, tactile	Objects were perceived as heavier when lifted with two fingers vs. five, with a narrow grip vs. a wide grip, and with a small vs. large contact area [39].
	Lifting method	Kinesthetic, tactile	Weight discrimination accuracy was improved with active lifting vs. reflexive holding [17].
Object properties	Volume	Kinesthetic, tactile, visual	Smaller objects were perceived as heavier than larger objects [40].
	Density	Visual	Denser looking objects were perceived heavier [41].
	Shape	Kinesthetic, tactile, visual	Objects with more compact shapes were perceived as heavier than less compact shapes with same weight and volume [42].
	Surface roughness	Tactile	Smoother objects were perceived as heavier than rough ones [43].
	Temperature	Tactile	Cold objects were perceived as heavier than warm ones [44].

to discriminate masses through voluntary muscle exertion was called "sense of force". Subsequent research highlighted the dominance of centrally generated motor commands in weight perception; a comprehensive review of these studies can be found in [36].

While the proprioceptive sense has been consistently shown to play a crucial role in weight perception, various physical factors, e.g., biomechanical conditions and object properties, were also found to influence perceived heaviness [26], [36]. For a concise summary of these factors, the relevant sensory systems involved, and their impact on perceived heaviness, please refer to Table I. As indicated in this table, using different grasp conditions—e.g., wide vs. narrow—and lifting methods—e.g., active vs. reflexive holding—alter the perceived heaviness of objects, underscoring the important contribution of the tactile sense in weight perception. However, the integration mechanism of tactile and proprioceptive senses for making heaviness judgments is still an active research topic.

One of the early investigations into the contribution of tactile cues during a grasp-and-lift motion was conducted by Johansson and Westling [45]. The authors measured the grip forces of participants while manipulating small objects with different weights and surface frictions via pinch grasps. They showed that the participants' grip forces changed proportionally to load forces to overcome forces counteracting the intended manipulation. This balance between the grip and load forces was adapted based on friction to provide a small safety margin to prevent slips. They also demonstrated through experiments with local anesthesia that this adaptation occurred through cutaneous cues. In a subsequent study [46], they recorded afferent responses via microneurography when participants did the same grip-and-lift task, and they found activity in all four skin mechanoreceptors at different points. Fast adaptive (FA) I units were triggered during the object gripping and force oscillations during the holding phase. Slow adaptive (SA) I units responded during gripping and showed continuous firing during the static holding. As for the FA II units, they fired upon changes in contact or motion. Finally, the SA II units showed considerable sensitivity to skin deformation induced both by grip and load forces, indicated by an increased firing rate with force magnitude. These findings evidenced the contribution of skin receptors, particularly SA II units, to the sense of weight.

The contribution of tactile cues in weight perception was further proved by Jones and Piateski [18]. They conducted an experiment where participants produced forces with different muscle groups of the arm in the presence and absence of tactile stimuli and matched them using the corresponding muscle group in the other arm, always in the presence of tactile stimuli. Without tactile stimuli, participants tended to underestimate the reference forces for all muscle groups, with an increased effect of the perceptual detriment as weight increased. Similarly, in a recent study, Park et al. [47] observed that a rendered mass at the fingers was perceived to be heavier when tactile stimuli were present than in the condition with only kinesthetic feedback. Matsui et al. [21] attempted to measure the contribution ratios of tactile information and kinesthetic information to the perception of forces, obtaining a 16-28 % contribution of tactile information for a force of 1 N, and 37–55 % for a force of 0.3 N. However, this study only accounted for kinesthetic information from the finger and the hand since the rest of the arm was immobilized. The authors also noted that tactile and kinesthetic stimuli were only partially isolated. Recently, van Beek et al. [19] addressed the limitations of the study of Matsui et al. by utilizing a kinesthetic grounded robot to render the applied forces. Users pinch-grasped a manipulandum attached to the device's endpoint, under which force sensors were located. For isolating tactile and kinesthetic stimuli from each other, a pair of thimbles were worn to compress the finger and prevent tactile stimulation, while a padded finger rest was used to block kinesthetic information. The authors conducted multiple experiments to determine the DT, JND, and PSE under kinesthetic, tactile, and combined stimuli conditions upon presented weights. The authors reported that the combined condition yielded the lowest JND and DT, while the DT for the tactile condition was lower than the kinesthetic condition. Interestingly, while the provision of tactile information resulted in lower JNDs—i.e., provided more reliable information—compared to kinesthetic information for masses below 200 g, both information sources were roughly equally reliable for larger weights.

Interestingly, while the absence of tactile information decreases the ability to discriminate between small weights, the presence of tactile cues regarding object properties (see Table I) can also lead to misjudging object weight. This perceptual phenomenon, known as sensorimotor mismatch or *weight illusions*, is still being investigated, and its underlying mechanisms are not fully understood. This phenomenon is generally associated with sensorimotor memory [48], [49], which is captured by forward and inverse internal models, predicting the motor commands necessary to lift an object based on prior expectations of its weight and estimated uncertainty [50], [51], [52]. Nonetheless, this perceptual deficiency has been utilized in practical applications for enhancing weight simulation within virtual environments through tactile interfaces [26].

III. Tactile Weight Rendering Approaches

As previously mentioned, weight is perceived via information coming from the tactile and the kinesthetic senses. Multiple approaches exist utilizing either of these senses for creating artificial weight sensation; see Fig. 1. This review focuses on weight rendering approaches through the stimulation of tactile sense. For details regarding weight rendering approaches through kinesthetic sense, interested readers can refer to [26].

To retrieve the existing tactile weight rendering approaches, we searched various scientific databases, namely *Scopus*, *IEEEXplore*, *Web of Science*, *ACM*, and *PubMed*. We aimed for studies whose title, abstract, or keywords would match the query: "*haptic*" AND ("*tactile*" OR "*cutaneous*" OR "*skin*") AND "*weight*". The search was repeated replacing "*haptic*" with approach-specific terms such as "*asymmetric vibration*", "*skin stretch*", or "*tactor*". Finally, we retrieved relevant related studies from the collected studies through forward and backward citation tracking. Two additional studies were included based on the reviewers' suggestions.

Overall, two leading weight rendering approaches through tactile stimulation have been proposed in the literature: stimulating fingertip skin through *vibrations* or *skin stretch*. In this review, we only considered *asymmetric vibrations* among the approaches using vibration stimulation since it is the only one that renders a perceivable force or weight sensation rather than providing a cue proportional to the object's weight. We further categorized skin stretch approaches based on the mechanism that provided skin stretch, whether through the motion of *flat surfaces* or *belts* or *tactors* actuated in planar/tangential or 3 DoF translational movements. It should be noted that in the asymmetric vibration approach, small-scale skin deformations arise from the oscillating movement of the actuator [53]. However, the focus of skin stretch approaches on controlling the large-scale, low-frequency deformations that naturally occur during object interaction [54] sets them apart from those based on vibrations.

A. Asymmetric Vibrations

This rendering approach relies on creating an illusionary pulling sensation that can modulate the perceived heaviness of an object. This illusion is generated by *asymmetric* vibration of an actuator in contact with the skin. The asymmetry is associated with the acceleration profile of the vibration and, consequently, with the forces and displacements induced to the

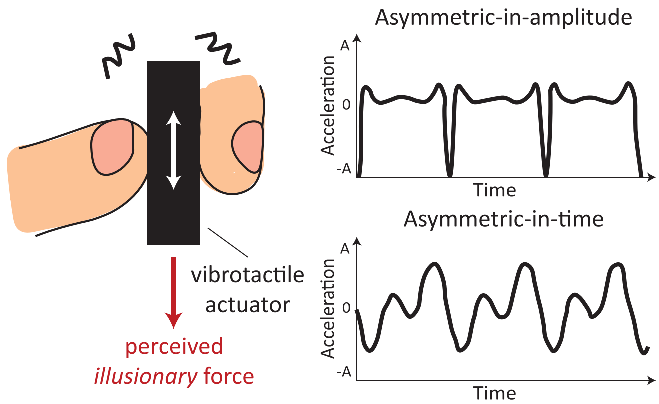

Fig. 2. An illustration of weight rendering through asymmetric vibrations. A vibrotactile actuator moving on the vertical axis is held between the thumb and index finger. The graphs on the right represent exemplary profiles of an *asymmetric-in-amplitude* vibration (top-right) and an *asymmetric-in-time* vibration (bottom-right). The acceleration profiles are adapted from [22] and [57].

skin [22], [53], [55]; see Fig. 2. When the peak acceleration in one direction is larger than in the other, this is referred to as an *asymmetric-in-amplitude* vibration [22]. When the rate of change in acceleration is larger in one of the directions, this is denoted as *asymmetric-in-time* vibration [56], [57]. In these sequences of strong and weak accelerations (either in magnitude or change rate), the strong stimuli are more saliently perceived than the weak ones, resulting in a pulling sensation that increases the perceived weight of an object if the strong stimuli are in the gravity direction [22].

One of the first mentions of this effect dates back to Amemiya et al., who designed a slider-crank mechanism to induce a "virtual force vector" [58]. This phenomenon was achieved by the *asymmetric-in-amplitude* vibration of the mass located at the endpoint of the mechanism, whose amplitude and frequency were shown to influence the intensity of the illusionary effect. In a posterior study, Amemiya and Maeda [22] demonstrated that their device could be used to perturb the perceived weight of an object when aligning the vibration in the direction of gravity. They observed that participants only perceived significant differences in weight when the pulling illusion was directed downwards (increased weight) but not upwards (decreased weight). The authors speculated that the strong additive force peaks resulting from the asymmetric acceleration profile were more saliently felt in the downward condition than the brief periods of reduced net force in the upward condition.

Inspired by these works, Tappeiner et al. [59] investigated how well this pulling illusion could be perceived in different directions in the horizontal plane. They used the Maglev device [60], a grounded magnetic levitation haptic interface, driven with an *asymmetric-in-time* vibration, achieved by a sinusoidal waveform with two half-periods of different durations. The authors showed that users could guess the direction of vibrations with an error between 9 and 25 degrees.

To utilize the asymmetric vibration approach for weight rendering in mobile conditions, Rekimoto [61] designed the Traxion device, which weighed only 5.2 g. This development was a substantial improvement over previous solutions, which were much larger and heavier. This device utilized a linear electromagnetic vibration actuator (Force Reactor L-type, Alps Alpine, Japan) capable of inducing a pulling sensation with a much smaller size. By driving the actuator with a pulse-width modulated (PWM) signal, Rekimoto achieved a pulling sensation of 0.292 N with the device when held horizontally, perpendicular to gravity. Inspired by this innovation, researchers began exploring the use of alternative electromagnetic actuators, such as voice coil and linear resonance actuators, for implementing asymmetric vibrations.

Soon thereafter, Amemiya and Gomi [62] investigated the intensity of the pulling sensation elicited by asymmetric vibrations by employing the same actuator as [61] and a voice coil actuator (Haptuator, Tactile Labs, Canada). Their findings revealed that the pulling illusion was most pronounced when the asymmetric vibration signal frequency coincided with the actuator's resonance frequency. Another experiment within the same study showed that the illusion was most intense for the combination of the Haptuator and a driving signal of 40 Hz. Follow-up work by Culbertson et al. [53] carried out the dynamic modeling of this actuator and fingerpad to tune the characteristics of the driving signal. Coinciding with the results from [62], the authors suggested using a driving frequency of 40 Hz for the asymmetric vibration. This frequency generated skin stretch with low relaxation speed and high asymmetry in amplitude, thus theoretically increasing the intensity of the illusion. Moreover, the proposed input signal in [53] consisted of a sawtooth step-ramp signal with a pulse width ratio of 0.3 to produce more asymmetry in the acceleration profile than a square wave signal. These refined model-based parameters were later used in two studies by [23] and [63] on the use of asymmetric vibrations for weight rendering.

One of those studies was performed by Choi et al. [23], who designed Grabity, a haptic device for rendering grip contact and forces, weight, and inertia in a pinch grasp configuration. The device incorporated weight rendering capabilities through a pair of Haptuators aligned with the direction of gravity and driven by the signal proposed by [53]. The researchers demonstrated that the magnitude of the generated virtual forces can be adjusted by manipulating the amplitude of the asymmetric input signal. With their device, they could simulate increasing and decreasing virtual weight variations of up to 0.294 N (30 g). Notably, they observed that the perceived magnitude of the variations was smaller when decreasing the weight than when increasing it, in line with the results of [22].

Later on, Tanaka et al. [63] presented their DualVib device, a handheld device designed for rendering a *dynamic mass* moving inside a container, such as a fluid or particles. The authors used asymmetric vibrations to render the forces of the moving mass using the actuator and driving signal from [53], denoted as force feedback. In their design, they strategically positioned two Haptuators beneath the thumb and index fingers of the users to enhance the pulling sensation. Additionally, two electromagnetic vibration actuators (Haptic Reactors, Alps Alpine, Japan) were positioned on the palm for rendering the fine vibrations arising from the collisions of the dynamic mass with the container's inner surface, denoted as texture feedback. This distinction in actuation sites aimed to improve the perception quality of these two types of vibration stimuli. In their main experiment, participants were asked to distinguish between combinations of three different rendered materials (textures) through acoustic vibrations and three different mass levels rendered through asymmetric vibrations, both in isolation and combined. The participants were only capable of identifying conditions with an accuracy of $43.6 \pm 15.1\,\%$ for the combined one. A deeper look into the results showed that the combined condition yielded a mass discrimination accuracy similar to the force-only condition. However, for material discrimination, the accuracy of the combined condition was closer to that of the texture-only condition. These results, together with the overall higher accuracy of the combined condition, suggest that asymmetric vibrations and texture feedback could be combined, or in terms of the authors, "without mutual interference" [63].

A limitation pointed out in both studies above was the relatively small strength of the pulling sensation [23], [63], despite using the refined signal and actuator by [53], [62]. Considering WF values around 0.9–0.12 for weight perception with real objects [17] and the mass of the devices, 65 g and 151 g [23], [63], the reported 0.294 N (30 g) for the maximum shift in perceived weight with this approach would allow rendering at most five different perceivable weights. Shifts in perceived weight of similar magnitude have been reported in other studies using similar actuators, like the study from Rekimoto [61], who measured a perceived force of about 0.292 N. Similarly, Amemiya [64] measured the change in the perceived weight of an object when vibrating asymmetrically, obtaining an increase of 0.196 N (20 g). These results indicate the need for more powerful actuators or optimized vibration patterns to increase the strength of the illusion.

More recently, Tanabe et al. [55] provided further guidelines and observations about the usage of asymmetric vibrations, such as the minimum application time, the time until users develop perceptual adaptation to vibration, and further emphasis on designing the setup with a matching signal and actuator. Notably, the authors observed that the illusion was more strongly perceived when applied tangentially to the skin rather than in the normal direction. The reason for this reduction in the strength of the illusion was attributed to the overall reduced sensitivity to skin displacements in the normal direction [65] and the smaller range of the skin deformations in the normal direction compared to the tangential direction. In a follow-up study, Tanabe and colleagues created a voice-coil actuator of their own. They designed the output acceleration profile as a sinusoidal superimposed with its second harmonic with different phase shifts, resulting in various types of asymmetries [56]. The novelty introduced by the authors was the estimation of the combined fingertip and actuator transfer function per participant to ensure the accurate realization of the desired acceleration profile. By doing so, the authors observed that the pulling illusion was more strongly perceived when the resulting acceleration profile was asymmetric-in-time, with responses close to the chance rate for asymmetric-in-amplitude acceleration profiles. This result was further verified for different frequencies in a follow-up study, which also confirmed the relevance and suitability of signals close to 40 Hz to induce the pulling sensation [57].

B. Skin Stretch

The second approach for rendering weight through tactile stimulation is inducing fingerpad deformations, replicating lateral (frictional) forces during object lifting. This form of stimulation is widely known as skin stretch. Skin-stretch devices for weight rendering can be categorized based on the mechanism providing skin stretch, whether through the motion of *flat surfaces* or *belts* or *tactors* actuated in planar/tangential or 3 DoF translational movements. Several studies employing these approaches for weight rendering are discussed in the following paragraphs.

1) Skin Stretch Through Flat Surface Motion: One mechanism to provide skin stretch for simulating weight in virtual environments is moving a flat surface in contact with the skin; see Fig. 3(a) for an illustration. Although such methodology has been used for rendering textures [69] or understanding finger deformations [70], Kurita et al. [66] were the first ones to utilize it for weight rendering. Their one-DoF box-shaped device was held in a pinch grasp and worn through a pair of rings attached to the device. The transparent surface beneath the index fingertip was actuated vertically through a motor. During this motion, a camera captured the finger contact surface to calculate the fingerpad eccentricity, i.e., deformation. The virtual weights were rendered by controlling the position of the surface such that the measured fingertip deformation matched the average fingertip eccentricity profiles obtained by Mukai et al. [71], who measured the fingertip eccentricity of different participants while holding different weights. It should be noted that these average deformation profiles were used to simulate weights without accounting for differences in skin properties. The system was evaluated in an object identification experiment, in which participants grasped and lifted the device. On each trial, the device rendered the weight and friction coefficient of one of a set of real objects, which the user was asked to identify afterward. The authors observed that the device could render perceivably different levels of weight and friction, but the perceived values differed from the intended ones. Participants tended to rate the 100 g object heavier than it was, while the 200 g and 300 g objects were underestimated. The authors discussed that such deviations could be attributed to the generalization of the deformation profiles, which did not account for individual differences in skin properties.

2) Skin Stretch Through Belt Motion: Another way to render weight via skin stretch is by utilizing belt motion. One of the first skin stretch devices evaluated within this context was the Gravity Grabber, developed by Minamizawa et al. [24], [54]. The device utilized two motors that actuated a fabric belt to deform the fingerpad skin in the vertical (normal) and shear (ulnar-radial) directions, as illustrated in Fig. 3(b). When both motors rotated at the same rate in opposite directions, they induced vertical stress on the fingerpad, replicating the sensation of grasp contact and grip forces. Conversely, they produced shear stress when they

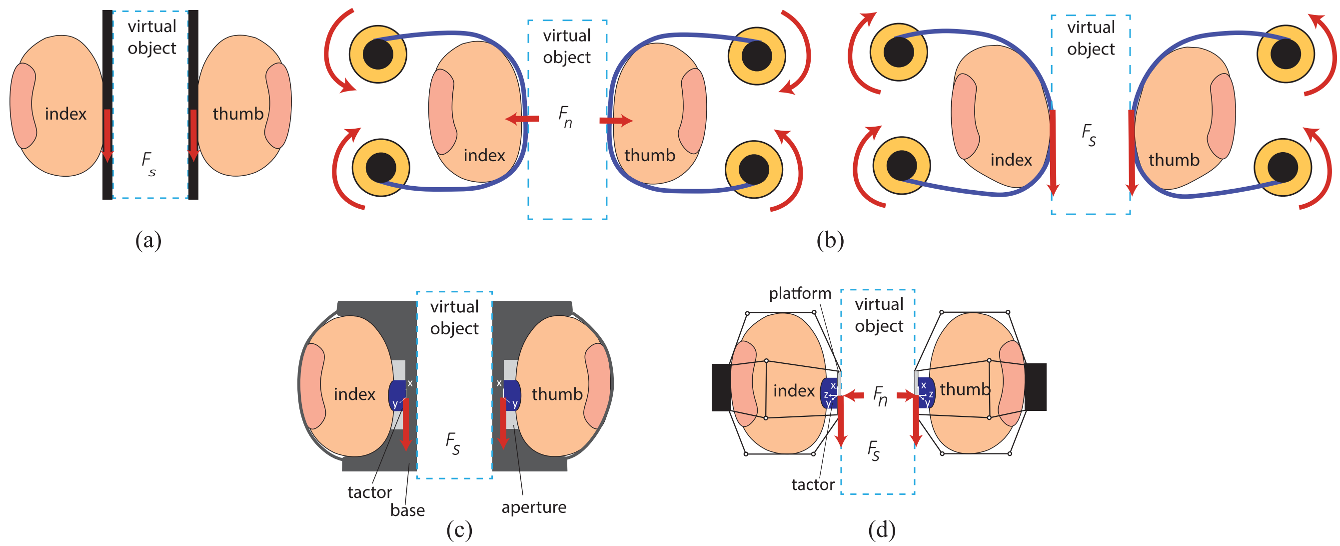

Fig. 3. Illustration of weight rendering approaches through skin stretch. Here, the users grip virtual objects via precision grasp with their thumb and index fingers by wearing or holding the devices. (a) Skin stretch via *flat surface motion*. e.g., [66]. The object weight is simulated by controlling the displacement of the flat surfaces contacted with fingers, creating a shear force toward gravity. (b) Skin stretch through *belt* motion, e.g., [24]. When the motors of a belt rotate in opposite directions and at the same rate, it deforms the corresponding finger only in the normal direction, simulating the normal stress due to grip. When they rotate in the same direction and rate, they deform the fingerpad only in the tangential direction, simulating the shear stress based on the desired weight of the virtual object. They can simultaneously deform the fingertip in normal and shear directions by rotating at different rates. (c) Skin stretch through a *tactor* actuated in planar/tangential movement, e.g., [67]. Each fingerpad rests on the base of the device and contacts the tactor through an aperture at the center. The displacement of the tactor creates a shear force, simulating the weight of an object. (d) Skin stretch via a *tactor* actuated in 3 DoF translational movement, e.g., [68]. The object weight is simulated by controlling the displacement of a tactor placed on a 3 DoF, kinematic delta structure, providing both shear and normal stress on the skin.

rotated in the same direction and rate, simulating the weight perception. The authors showed that inducing various levels of shear stress on the fingerpad resulted in different perceived weights by the participants. The participants, who held the real objects in one hand, tuned the belt displacements for equivalent virtual weights (i.e., shear stress). From this experiment, they obtained a function that represented the relation between generated shear stress and the real object's weight. This function, an average gain factor for representing finger stiffness, was later used in follow-up experiments where they measured the reflexive response in grip force upon a sudden increase in real and simulated weights. The similar magnitude of the response in both conditions confirmed the suitability of the approach for weight rendering.

Building upon their initial findings, Minamizawa et al. [20] conducted experiments investigating the interaction between tactile and kinesthetic cues for weight rendering. They simulated object weight by displaying forces through a grounded kinesthetic device (Force Dimension, Omega 3), whose end effector was attached to the palm, wrist, or forearm via velcro straps. They placed urethane forms between the velcro straps and the skin to isolate the kinesthetic stimuli. They simultaneously deformed the fingerpad using their belt-based device placed on the fingertips. The first experiment aimed at measuring JNDs for reference stimuli between 50 g and 400 g using tactile cues alone or in combination with kinesthetic information applied at different locations, such as palm, wrist, and forearm. For stimuli below 200 g, the tactile-only condition provided JND values comparable to those of the combined condition. However, for heavier stimuli, the JND increased largely for the tactile condition, indicating a stimulus saturation or a limitation in fingerpad deformation. The location of the kinesthetic stimuli did not affect the JND values. A similar result was observed in their second experiment, where the weight discrimination ability for a simulated object using tactile, kinesthetic (applied on the forearm), and combined cues was compared to that of a real object. First, the weight discrimination ability of the participants was measured while holding a cubic object attached to a grounded force feedback device (real object condition). JNDs were measured for reference stimuli of 100, 200, 300, and 400 g. The experiment was then repeated while participants held the same object but the weight was simulated using tactile, kinesthetic, or combined cues. The JND values with the combined condition showed a similar trend to those measured with real objects, though the values were consistently slightly higher for all weights. The JND of the tactile condition was close to that of the combined condition for 100 g objects, while the kinesthetic condition resulted in a JND almost twice as large. As the reference weight increased, the JND for the tactile condition increased substantially, while the kinesthetic condition approached that of the combined condition, matching it for the 400 g reference stimulus. These results suggest that combining tactile and kinesthetic cues is particularly relevant for rendering lightweight objects.

Besides the discussed implementation, other belt-based devices in the literature include the hRing, developed by Pacchierotti et al. [72]. The device is worn on the proximal phalanges for compatibility with finger-tracking solutions. The authors demonstrated the device's capabilities for a pick-and-place task, obtaining overall lower interaction forces, completion time, and increased perceived effectiveness than in a visual-only condition. Other multi-cue devices featuring belt actuation have also been developed [73], [74]. However, these devices have yet to be evaluated within the context of weight rendering, particularly for those in which stimulation is relocated to the proximal phalanges.

3) Skin Stretch Through Tactors Actuated in Planar/ Tangential Movement: The devices in this category generate skin deformations by displacing one or multiple small, high-friction tactile units (tactors) tangentially to the fingerpad. In these devices, the user's fingerpad rests on the contact base of the touchable, graspable, or wearable device [75]. Most designs involve an aperture on the base, allowing the fingerpad to directly contact the tactor(s), which are mechanically actuated beneath the base. The aperture also prevents the fingertip from moving in unwanted directions, thus ensuring that tactor displacements solely induce skin stretch; see Fig. 3(c) for an example of a wearable design. Unlike belt-based solutions, most tactor-based devices allow the rendering of tangential forces in 2 DoF, potentially covering the whole plane tangential to the fingerpad, which helps generate directional cues. The skin deformations due to the weight of objects can be simulated by controlling the displacement amplitude and speed of the tactor towards the direction of gravity (Fig. 3(c)).

The earliest skin stretch devices that leveraged tactor actuation in planar/tangential movement were designed to provide directional cues on touchable device configuration [76], [77], [78]. The studies proposing these designs reported average direction discrimination thresholds between 11° [76] and 19° [77] depending on the shear displacement amplitude and velocity, movement direction, and number of moving tactile units. Gleeson et al. [78] showed that four orthogonal directions (distal, proximal, medial, and lateral) could be discriminated with high accuracy for displacements as small as 0.2–0.5 mm and velocities of 1 $\mathrm{mm/s}$ generated by one moving tactor. They also found that higher moving speeds and larger displacements caused greater accuracy in direction discrimination. Later, they showed the feasibility of using this rendering technique in a compact, fingertip-mounted design [79]. The results from these studies confirmed that moving small-sized tactile units could be exploited for rendering shear forces, like those occurring due to the weight of an object, in different directions on the fingerpad.

Furthermore, Gleeson et al. [80] proposed guidelines for designing skin stretch devices through tactor motion by testing tactors in two different textures and three sizes combined with apertures in three sizes in a direction discrimination study. They advised using rough-textured tactors to reduce slip and enhance direction identification accuracy. They found that the size of the tactor was insignificant for direction discrimination accuracy, suggesting that their size could be adaptable based on the application at hand and the finger size. Nevertheless, they recommended using a minimum tactor diameter of 7 mm based on the reported user discomfort with smaller tactors. With regards to the aperture size, small sizes resulted in low direction discrimination accuracy, probably associated with the lack of stimulation of the skin surrounding the contact point.

Following the design guidelines and results of Gleeson et al. [78], [80], further studies continued to explore the provision of directional cues with more compact devices [81]. More prominently, some studies [82], [83] aimed to render object stiffness using tactors actuated in tangential movement. These exemplary works used a graspable (i.e., stylus-like) skin stretch device with a tactor design following the guidelines from [80]. They showed that their design could provide perceivable levels of stiffness comparable to grounded kinesthetic devices [82] and augment the overall perceived stiffness when used in combination [83]. These studies converted the desired rendering forces into tactor displacements by applying a predefined gain factor, similar to the belt-based devices described in the previous section. However, Quek et al. [83] found that different gain factors resulted in different perceived stiffness levels with large intersubject variability. This variability was attributed to large differences in skin properties across participants, along with neural and cognitive factors.

Despite their high shear force rendering capability, devices utilizing tactors actuated in planar/tangential movement have not been used for weight rendering applications until the design of the HapTip device [67]. HapTip features tactor actuation in the tangential plane of the fingertip in a wearable configuration (similar to the illustration in Fig. 3(c)), and it can render forces by projecting a weighted sum of gravity and inertial accelerations. The authors showed that HapTip could convey basic directions (up, right, down, and left) and orientations (horizontal, vertical, and two diagonals). They also evaluated the weight rendering capabilities of the device by embedding two HapTip devices to the two sides of a cube surface to provide tactile feedback (i.e., shear forces due to tactor displacement) on the thumb and index finger when the cube was held. In a virtual reality environment, they asked participants to sort virtual cubes based on their weight by picking and shaking each object. The weights of the virtual objects were arbitrary, had no real equivalents, and were adjusted based on the amplitude of the tactor displacements, such that their proportions were 1/3, 1, 3, and 9. The results showed that the most typical sorting error comprised the mistaking of the two heaviest cubes, attributed to the saturated actuation of the device. However, the overall positive results, with an average sorting error of 2.2 over 20, where 0 was the perfect ordering, supported the system's weight rendering suitability.

4) Skin Stretch Through Tactors Actuated in 3 DoF Translational Movement: These devices create skin deformation through a tactor actuated via a 3 DoF (translational) kinematic mechanism, such as a delta structure [25]; see Fig. 3(d) for an illustration. This actuation allows the control of the tactor placed on a platform in all translational directions and, thus, can induce normal and tangential skin deformations. These devices have been designed in wearable or graspable configurations and broadly studied for various applications, such as rendering object curvature [84], stiffness [85], and weight. It should be noted that, despite their 3 DoF design, only the tactor motion towards gravity (shear force) is controlled for weight simulation. While this situation makes their rendering capability similar to the skin stretch through planar tactor motion, it also enables simulating contact and grasping forces when the user touches virtual objects.

One of the earliest examples of this type of device used for rendering object properties was designed by Quek et al. [86]. The device was based on a delta mechanism; its end effector was connected to a rectangular tool having one tactor within one aperture on each of its four sides. The users grasped the tool with their thumb, index, and middle finger, hence each tactor stimulated a different finger. This configuration rendered forces on the fingerpads in both lateral and normal directions by moving the end effector, consequently tactors, in horizontal and vertical directions. They attached their tactile display to the end effector of a widely used kinesthetic haptic device (Force Dimension, Omega 3). Later, Suchoski et al. [87] used this device to render the mass of a virtual object when participants held the device by their thumb and index fingers in a pinch grasp. They compared the human perception of virtual masses rendered via their tactile display and the kinesthetic display. They measured the JND for the reference masses of 35, 70, 105, and 140 g. The participant's task was to adjust the mass of one block in a virtual environment in increments of 1 g, until it was equal to a reference block also being rendered. For the tactile display, the virtual masses were rendered by moving the tactors in the tangential direction based on a predefined gain factor ($0.2\ \mathrm{mm/N}$) found by [86]. They obtained Weber Fractions of 0.35 with the skin stretch device and 0.11 with the kinesthetic device, which the authors attributed to a more "natural" perception of the kinesthetic stimulation. It should be highlighted that although the device could render forces in 3 DoF translational movements, the weights were only rendered by 1 DoF (tangential) movement.

Recently, Schorr et al. [25], [68] designed a compact, wearable device providing skin stretch through 3 DOF tactor motion (see Fig. 3(d)) and evaluated its weight rendering capability. They rendered virtual weights by converting the interaction forces in the virtual environment into tangential tactor displacements considering a predefined gain factor obtained from Nakazawa et al. [88], and thus, regardless of the fingerpad stiffness variability among users. They conducted a weight magnitude estimation experiment using virtual objects of different sizes and weights. The results showed that participants could perceive differences in virtual object weight and that they applied increasing grasp forces when lifting virtual objects as rendered mass was increased. The same device was also used in a later study by Suchoski et al. [27] to evaluate the influence of scaling inertial forces on the perceived weight of a virtual object. The authors proposed using a scaling factor that multiplies the object's mass and divides the value of the gravitational acceleration in the virtual environment. By doing so, the overall weight of the object was preserved while the mass was increased, as did the inertial forces. They evaluated the effect of the scaling factor on weight perception in a discrimination experiment where participants were asked to pick and place two virtual objects: one reference object with 200 g mass without scaling and one comparison object ranging between 50 and 350 g with scaling factors of 2 and 3. They found that for a reference object of 200 g, the average PSEs for the objects with scaling factors 2 and 3 were 171.0 g and 150.5 g, respectively. These results show that the proposed method could amplify the perception of the weight of virtual objects without increasing the force output of the device.

The work of Leonardis et al. [89], who used a parallel mechanism device with articulated legs connecting actuators to a platform, is relevant for its approach to dealing with varying finger properties. The authors performed per-participant fingerpad stiffness characterization with the device to ensure individualized conversion of the interaction forces into platform displacement, thus minimizing intersubject variability. They tested their device and approach for pick-and-place object manipulation. The results showed that participants reduced their grasping forces when using the device compared to visual information only, indicative of a better estimation of the object's weight. A significant difference in grip forces between light and heavy objects demonstrated the system's suitability for rendering different weight levels. Another experiment involving the lift-and-hold of an object restrained by a virtual prismatic constraint showed a similar pattern. The grasping and reaction forces generated by the prismatic constraint were significantly smaller when using the device than the visual condition.

Finally, a study of particular importance in this category is done by Trinitatova and Tetserukou [90]. The authors proposed a palmar device with an inverted delta mechanism that actuated a tactor in contact with the skin. While the device featured 3DoF motion, thus capable of lateral skin stretch, the authors conducted their study on the rendering of weight in the normal direction to the skin. In the experiment, participants had to identify virtual objects of three different weights while holding them in the palm of their hand. Recognition rates between 80% and 97% were obtained. The study introduced the novelty of tactile stimulation of the palm to render weight and demonstrated the possibility of rendering weight solely by applying normal forces to the skin.

IV. Comparison of Tactile Weight Rendering Approaches

A. Comparison Criteria

We compared the five different tactile weight rendering approaches—i.e., asymmetric vibrations and skin stretch through the motion of a flat surface, belt, or tactors actuated in planar/tangential or 3 DoF translational movements—to guide the decision-making process for using them. To carry out the comparison, we established different criteria following the insights from the literature in the field and other properties listed in reviews on haptic devices and weight rendering, e.g., [26], [92], [93].

The first two selected criteria are size and mass, which relate to the physical properties of the devices used for tactile weight rendering. These characteristics can be essential when developing devices that benefit from a small form factor and low mass, such as hand-held or wearable devices.

We also included criteria related to the mechanical characteristics of these devices, namely the number of actuated DoFs, maximum rendering force, and actuation workspace. The number of DoFs indicates the number of dimensions in which a device can provide stimuli, i.e., forces. Therefore, devices

TABLE II
COMPARISON TABLE OF THE FIVE PRESENTED TACTILE WEIGHT RENDERING APPROACHES ACROSS THE SELECTED CRITERIA

Criterion	Asymmetric vibrations	Flat surface motion	Belt motion	Tactor motion planar/tangential	Tactor motion 3 DoF translational
Size (mm)	7.5 × 35.0 × 5.0 [61] 10.0 × 10.0 × 35.0 [53] 56.0 × 175.0 × 27.0 [22]	Undetermined	31.0 × 28.0 × 12.0 [72]	20.4 × 35.0 × 34.1 [67] 45.9 × 67.7 × 18.5 [81] 100.0 × 32.0 × 28.0 [83]	21.5 × 48.8 × 40.2 [25] 18.0 × 32.0 × 32.0 [89]
Mass (g)	5.1 [61] 8.15 [53]	210 [66]	15.3 [72]	22.43 [67]	31.6 [25] 16.31 [89] 260 [86]
DoF	1 DoF [23], [53], [63]	1 DoF [66]	2 DoF [24], [72]	2 DoF [67], [79], [83]	3 DoF [25], [89]
Maximum rendering force (N)	†0.292 [61] †0.294 [23] 0.43 [55] †0.196 [64]	Undetermined	†3.92 [24]	3.4 [67]	2.0 × 2.0 × 7.5 [25] 2.72 × 2.73 × 4.16 [89]
Workspace (mm)	Not applicable	Undetermined	Unlimited	±2.0 [67] ±2.5 [81] ±2.3 [83]	5.0 × 10.0 × 10.0 [25] ±7.5 × 10.0 × 15.0 [89] 5.0 × 5.0 × 5.0 [86]
WDT	Undetermined	Undetermined	†0.1–0.25 [20] (ref. 50–300 g)	Undetermined	†0.147 & 0.154 [27] (ref. 150.5 & 171.0 g) 0.35 [87] (ref. 35–140 g)
DDT	71 % 8-direction accuracy [91] ‡9°–25° SD [59]	Not applicable	Not applicable	†84.7% 4-direction accuracy [67] 12.9°–15.6° [76] 23°–25° [77]	69% 8-direction accuracy [89]

Approaches for which a criterion does not apply have been categorized as "Not applicable." Approaches for which no study has been found reporting a specific criterion have been labeled as "Undetermined". Abbreviations: Degrees of Freedom (DoF), Weight Discrimination Threshold (WDT), Direction Discrimination Threshold (DDT), Standard Deviation (SD). †Value converted to selected metric. ‡Value with no conversion to chosen metric.

with more degrees of freedom allow weight rendering in a broader range of hand or finger orientations and the possibility of simultaneously rendering grip and load forces. The maximum rendering force is used as a guideline for the largest weight that can be rendered. As previously explained, skin stretch devices render weight by stretching the skin a certain amount [24]. Due to this relation between force and displacement, the maximum rendering force of skin stretch devices, i.e., the maximum weight the device can render, is also conditioned by the maximum skin stretch that the device can induce. The actuation workspace can limit the device's motion, and so the amount of skin stretch and rendered weight.

The discrimination threshold for weight and directions constitutes another set of comparison criteria regarding the perceptual features of the devices. Approaches yielding lower discrimination thresholds indicate more naturalistic and coherent interactions upon different weights and grasp configurations.

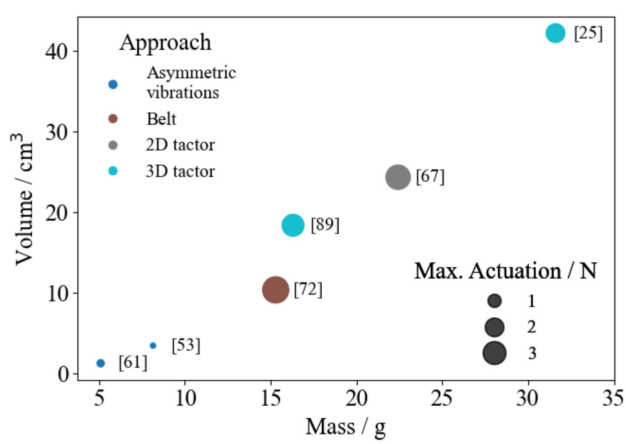

Fig. 4. Graphical comparison of the tactile weight rendering approaches based on the reported devices' size, mass, and maximum actuation. Here, the size is represented as the volume in cubic centimeters. The flat surface motion approach is not shown as relevant studies did not report these criteria.

B. Comparison

Table II summarizes values of the different comparison criteria across the five tactile weight rendering approaches reviewed. Fig. 4 shows the visual comparison of the different approaches based on size, weight, and maximum actuation. The reported values are extracted from the studies reviewed in Section III. By doing so, we aim to provide a more focused comparison of the weight-rendering devices in the literature through their specifications. Here, we report the results using a standard metric for each listed criterion, converting other reported metrics when possible. For the size and the mass, we report magnitudes as indicated by the authors of the device. For the number of DoFs, we considered the values reported by the authors and otherwise derived them from the actuation of the system and the kinematic model.

We computed the maximum rendering forces for asymmetric vibration devices as the maximum perceived force of the pulling illusion. Whenever the maximum rendering was reported by the authors as the rendered mass, we converted the value to force units.

The workspace, just like the size, is typically listed as the range in each actuated dimension. Since asymmetric vibration devices vibrate in place, producing small displacements to the device they are attached to, their effective workspace is negligible, so it was not evaluated. On the other hand, we indicated that belt-based devices provide an "unlimited" workspace in the actuated DoF. In the normal and ulnar-radial directions, the workspace limits of the device depend on the length of the actuated fabric belt and constraints of the finger deformation. Therefore, provided sufficient force by the actuators, the device can potentially deform skin up until its maximum deformation, which some articles have measured to be up to 5 mm in the shear direction [94] or until slippage occurs.

We present the weight discrimination threshold (WDT) as the Weber Fraction (WF) with the corresponding reference weights. Whenever the value was provided as the JND, we computed the WF by dividing the JND by the reference weight. We did not provide values for asymmetric vibrations and skin stretch through flat surface motion as those studies looking into weight rendering typically do not investigate discrimination thresholds but compare two or three weight levels or shifts in perceived weight [23], [63], [66]. While the results of these studies indicate the devices' rendering capability, the absence of an explicit metric for the WDT led us to define the value as unknown.

We did not consider belt and surface devices for the direction discrimination threshold (DDT) since they can only render tangential forces in a single direction. The direction detection accuracy and the JND are reported for the remaining approaches, depending on the experimental approach. One result worth elaborating on is the value provided for asymmetric vibrations, obtained from the study of [59]. In the experiment, participants were presented with a vibration and were allowed to freely indicate its direction. The reported values in the table correspond to the mean of the within-subject standard deviation when determining the direction of the vibrations.

V. Discussion

This review addresses the usage of tactile interfaces for rendering the weight of virtual objects. These devices can substitute and augment kinesthetic devices to provide a more coherent, accurate, and naturalistic sensation of weight. Doing so can potentially increase manipulation performance in teleoperation tasks or improve the efficacy of robot-assisted and VR simulators for training and learning motor tasks. We first classified the tactile weight rendering approaches in the literature within a proposed categorization. Then, we compared them across several criteria based on the insights of the retrieved studies to inform the selection of approaches based on developers' requirements.

A. Which Approaches Have Been Used to Render Weight Through Tactile Stimulation?

Two major groups of approaches have been determined according to the type of stimulus used to render weight: asymmetric vibrations and skin stretch. The asymmetric vibration approach can simulate weight by inducing a pulling sensation by actuating a vibration motor with an asymmetric output acceleration profile. The skin stretch approach is based on deforming the fingerpad to stimulate the skin mechanoreceptors and induce the sensation of weight. This approach can rely on the actuation of a flat surface, belt, or tactor in planar/tangential or 3 DoF translational movements. Multiple studies have presented and evaluated these approaches in grounded, hand-held, and wearable devices in the context of weight rendering.

It should be noted that different categorizations of these approaches can also be performed. For example, Pacchierotti et al. classified haptic devices according to whether they were worn on the hand or the fingertip [92]. Hand devices were further separated by kinesthetic or vibrotactile feedback, while fingertip devices were divided according to the rendered sensation (e.g. normal indentation, lateral skin stretch). Lim et al. classified weight rendering devices according to the haptic cue used by the devices, namely forces, skin stretch, vibrations, weight shifting, and others [26]. Finally, Adilkhanov et al. classified the devices in their review based on the degree of wearability, further classified by their actuation principle [93].

The approaches presented in this review are classified similarly to the review by [26], limited to asymmetric vibrations and skin stretch, which act upon the tactile sense. The skin stretch approach, following a similar perspective to [93], has been further divided according to the actuation or stimulation mechanism of the available devices. Such a perspective was followed instead of a sensation-based classification, as in [92], because most of these devices can provide a combination of sensations, such as normal indentation and lateral skin stretch. Additionally, although some of the devices are inherently wearable, like the ones that rely on belt motion, others can be integrated into all sorts of solutions, like tactor devices, implemented in wearable [67] and grounded solutions [86]. Classification according to the actuation principle allows for a comparison of devices that can be used across all wearability scales, increasing the scope of application of the results.

B. What are the Main Advantages and Disadvantages of Each Approach?

Ideally, an experimental comparison of the available devices is needed to determine the best approach to each case using different experiments related to the application of interest. However, as far as we know, no such comparative studies for weight-rendering exist in the literature. Here, we have collected information from different studies on weight rendering and object manipulation to provide insights into their strengths and weaknesses. Some factors like wearability or cost primarily depend on the device design and specific use case. Thus, we have not included them as comparison criteria but will refer to them when they pertain.

The *asymmetric vibration* approach finds its main strength in the compact size and weight, making it easy to integrate into a wide range of devices, including wearable and handheld ones [23], [63], [95]. On the other hand, this comes with the cost of a reduced number of DoF and rendering forces, limiting the range of rendered weights and supported grasp configurations. Although numerous 2-DoF [91], [96], [97] and 3-DoF [98] devices using asymmetric vibrations were proposed, they are mainly used for navigation purposes and are yet to be evaluated for weight rendering. The use of such multi-DoF devices would increase the versatility of this rendering approach and allow exploiting the well-known capabilities for directional cues. Some proposed devices can achieve larger forces [22], [99] at the expense of heavier and larger designs. Alternatively, combining asymmetric vibrations with other rendering modalities, like pseudo-haptics [100], can help increase the maximum rendering weights.

It is important to acknowledge two further limitations of this approach. The first pertains to the noticeable vibration induced, which can have an impact on the immersion and naturalness of the interaction when rendering non-vibrating objects. The second refers to the ongoing research on the design of the waveforms to induce the pulling illusion. While several of the presented studies have pointed at the adequacy of 40 Hz signals for causing the illusion [23], [53], [57], other frequencies in the range of 10–100 Hz have been proposed based on the differences in the frequency response of the actuators. A comprehensive review of asymmetric vibration technologies would be a valuable tool for promoting this approach's use and further development.

Overall, asymmetric vibrations, due to the reduced magnitude of rendered forces, are a promising tool for rendering variations in the weight of an object, as done in [63], or to augment the perception of weight when combined with some of the other approaches.

Only one study has explored the induction of skin stretch through flat *surface motion* [66] for weight rendering. The main advantage of this approach is the possibility of deforming the entire fingerpad, thus potentially inducing a more naturalistic sensation. The main disadvantage relies on the absence of studies that can inform about the capabilities of the approach. A possible explanation is the difficulty of exclusively immobilizing the finger to induce skin stretch upon surface movement. Grounding the device at more proximal phalanxes [24], [68] could increase the usability of this approach. Alternatively, the use of articulated parallel structures, similar to [25], [89] and replacing the tactor in contact with the fingerpad with a flat surface, as proposed in [84], could also help to immobilize the finger. Further studies should be conducted to ascertain aspects of this approach, such as the accuracy of rendering different weights in various directions.

Using *belt motions* to induce skin stretch for rendering weight finds its main advantage in the large forces that can be induced with a small size and weight without workspace limitations. Additionally, it yields comparable weight discrimination thresholds to physical objects in the presence or absence of kinesthetic information for low weights [20]. Additionally, the absence of rigid or bulky components at the fingerpads allows seamless interaction with physical objects. This property makes the approach appealing for rendering weight in virtual or augmented reality. Their main limitation is the single degree of actuation in the ulnar-radial direction, which prevents the rendering of weight and inertial forces in the proximal-distal direction of the fingerpad. Overall, the wearable and compact form factor of belt devices makes them well-suited for augmented and virtual reality applications that require free hand movements and relatively large weights to be rendered. However, the grasping motion of the object needs to be restrained to a lateral grasp for the feedback to be effective.

Using *tactors actuated in planar/tangential motion* can compensate for the lack of stimulation in the proximal-distal direction of the fingerpad in a similar size and weight as the approach on belt motions. As a result, the planar/tangential tactor approach finds its main advantage in the possibility of conveying cues (like weight) in multiple directions [76], [77], thus supporting a wider range of lifting configurations. Additionally, the aperture-based design allows its use in wearable [67], handheld [83], and grounded [76] devices without attaching the finger to the device. This aperture-based design, however, poses a limit to the amount of deformation that can be applied to the fingerpads and, with it, the maximum rendered weight. Additionally, the grounding of the outer part of the fingerpad can lead to reduced perceptual acuity and, potentially, a reduction in the naturalness of the interaction. Both limitations could be attributed to the local deformation of the skin in contact with the tactor relative to the surrounding skin, grounded on the aperture, as discussed in [87]. The lack of deformation of the surrounding skin prevents the corresponding mechanoreceptors from being stimulated. This observation is backed up by [80], who noticed a reduction in direction discrimination performance for smaller apertures, which constrained a larger skin area.

Skin stretch devices relying on *tactor actuation in 3 DoF translational movements* provide an additional level of rendering capabilities and good all-around performance across all comparison criteria. The three-DoF actuation of these devices represents the main advantage of this approach, enabling the rendering of weight in the tangential [27] and normal directions [90], as well as the simultaneous rendering of weight and grip forces in a lateral grasp. This flexibility is realized while achieving similar WDT to other approaches like belt actuation [20], [27]. All this comes at the cost of reduced tangential forces and increased size and weight, compared to belt and tactor actuation in planar/tangential movement. Compared to other studies, the more limited WDT reported by Suchoski et al. can be attributed to the aperture-based design of the device which, as previously discussed, can lead to reduced perceptual acuity [87]. Overall, the high versatility of this approach makes it an appealing option for demanding virtual reality applications where high-fidelity rendering and support for different grasp configurations are required.

In summary, each weight rendering approach offers distinct advantages alongside corresponding disadvantages, requiring careful consideration tailored to specific use cases and limitations.

C. Limitations of Current Approaches and Future Perspectives

Below, we propose future research directions on tactile weight rendering based on the limitations of current approaches found in the literature. Further research in these directions could ultimately increase the performance of these tactile weight rendering approaches, impacting user experience, immersion, and performance during training and teleoperation tasks.

1) There is a Need for Comparative Studies and Standardization: As mentioned earlier, providing the definitive best tactile weight rendering approach for specific applications is challenging due to the need for more comprehensive information on particular properties of the reported devices in the literature and comparative studies that experimentally evaluate and compare the existing devices. As it may not always be feasible to access these devices, one way to mitigate this problem is by standardizing the process, such as developing design and evaluation guidelines, open-source software and hardware for testing, and information-sharing platforms, with a joint effort of experts.

Many studies evaluate the weight rendering capabilities by asking users to distinguish between different rendered weights [23], [67], [90]. The different choices in the design of these comparative studies, stimuli selection, and accuracy metric, among others, make the results difficult to extrapolate, generalize, and compare to other solutions. Instead, experiments using standard psychophysical methods should be performed to obtain generally accepted metrics like the JND or the WF, as in [20], [27], [87]. This approach would allow a more direct comparison of the rendering fidelity. Additionally, experiments comparing the rendered weights against physical ones, in line with [20], [64], [66], should be performed. Doing so can validate the correspondence in magnitude between the two and how naturalistic the rendering is through metrics like the PSE, and subjective questionnaires, such as in [89].

2) Devices Should Account for Variability in Fingertip Properties: In the studies conducted with skin stretch devices, e.g., [66], [83], large intersubject variability was observed in the perceived properties of the virtual objects and task performance. One reason for this variability was the use of position control, which relied on a constant scaling factor or an average fingerpad stiffness to convert the virtual forces into displacements, disregarding differences in skin properties across participants. Several studies reported that such differences in finger mechanical properties and size could cause large variabilities in fingertip deformation [101] and resulting tactile perception [102], [103]. Therefore, these variabilities in skin properties should be considered for interface design. For skin-stretch devices, one idea to overcome this problem could be the development of force-controlled systems, as done by [104], [105], or per-participant estimations, as in the study of [89]. For asymmetric vibrations, such variabilities could be mitigated by designing the acceleration signal considering the differences in fingertip properties in the dynamic model of finger-actuator contact, as proposed by [56].

Other anatomical variables should also be considered to ensure accurate haptic rendering across individuals. Factors like differences in finger size are known to influence direction discrimination accuracy in tactor-based devices [80]. Differences in size and shape are particularly relevant for wearable and handheld devices, which tightly interact with the user's anatomy. Given the complexity of creating a one-size-fits-all design, adjustable or personalizable devices are promising solutions to improve the quality of the haptic sensations, as observed in a preliminary evaluation in [106].

3) Devices Should Allow More Diverse Grasp Configurations: Most of the reported devices in this review allow users to interact with virtual objects in a pinch grasp, with the index finger and the thumb in opposition. As the number of fingers used to lift an object influences the perceived weight [39], more research is needed on developing devices supporting and evaluating multi-finger grasp. Other grasp types involving the palm, like power grasps (where the object is gripped by pressing it with the fingers against the palm) and non-prehensile grasps (where the object is held with the open hand with the palm facing upwards) [107] are also possible. Therefore, studies should explore the combination of palmar and finger haptic devices, like those in [108], [109], to achieve a more naturalistic and versatile weight rendering. Additionally, during a non-prehensile grasp and certain orientations of pinch and power grasps, weight is applied in the normal direction to the skin. While numerous studies have explored weight rendering through lateral skin deformations, weight rendering through normal skin deformations has only been evaluated for palm feedback [90]. Determining whether a weight percept can also be induced using fingertip tactile devices could further inform about the rendering capabilities of the approaches.

4) There is a Need for Realistic Rendering of Object Properties: Most studies in this review evaluated tactile interfaces in terms of their capability to simulate perceivable weights—not necessarily counterparts of realistic objects. A closer resemblance between virtual and physical objects can increase immersion [110] or a better transference of learning in a virtual environment to the real world [111]. Hence, realistically rendering object properties, such as exact weight, friction, or texture, is another exciting future research direction. Devices can be benchmarked against physical counterparts to identify potential mismatches between the rendered and actual stimuli [66] and to ascertain the specific areas of improvement. As previously discussed, developing solutions that seamlessly adapt to the individual properties of the user can improve the perceived fidelity of the rendering [106].

Finally, multimodality haptic rendering is an exciting direction with great potential. As discussed in Section II, numerous factors influence the perceived weight of an object, such as surface roughness, shape, or temperature. Some examples of haptic devices based on the proposed approaches integrating multimodal cues have already been presented [73], [74], [90], [112]. Combining existing actuation and sensing methods into a single device could help achieve this objective. While challenging, further development of novel actuation methods, device designs [113] and miniaturization [114] promise exciting future research directions.

VI. Conclusion

This study provides an overview and comparison of weight rendering approaches through tactile stimulation as a potential approach to enhance rendering accuracy when used in conjunction with kinesthetic devices or to substitute kinesthetic stimulation when simulating small weights. We conducted an exhaustive literature search and proposed a categorization of the different approaches followed by a comparison across several criteria based on the insights of the retrieved studies. This search distinguished two main approaches: asymmetric vibrations and skin stretch, induced via the motion of a belt or flat surfaces or tactors actuated in planar/tangential or 3 DoF translational movements. Based on the comparison, the asymmetric vibration approach provides some limitations that indicate that its use for weight rendering is limited to applications involving tight size constraints and low-fidelity rendering. Although each skin stretch device has specific advantages, the large maximum rendering force and low weight discrimination threshold, among others, indicate increased suitability of belt and 3D tactor devices for weight rendering. The limitations of the solutions and gaps in the literature identified in this review indicate a need for further research to determine the optimal way of rendering weight via the tactile sense. This review aims to motivate and guide the development and usage of tactile displays for more accurate weight rendering, improving immersion in virtual reality and performance and learning in training and teleoperation applications.

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