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Multisensory Softness

Perceived Compliance from Multiple Sources of Information

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Chapter 3
Vibrotactile Sensation and Softness Perception

Yon Visell and Shogo Okamoto

3.1 Introduction

This chapter describes how mechanical vibrations can affect the perception of several material and surface properties, with an emphasis on the perception of compliance. Vibrations are fluctuations of force or displacement. They are generated by interactions with objects and as such they are produced during numerous human activities. They accompany, for example, frictional sliding of surfaces, tapping, rolling movements, displacement and compression of granular and aggregate materials, fracturing and breakage processes.

Prior research has demonstrated that the haptic channel is sensitive to vibrations, known as the *vibrotactile* sense, and can be used to discriminate touched surfaces of objects to extract properties such as roughness or surface regularity, and to identify events, such as contact onset and contact slip. Despite its importance, the vibrotactile sense has received little attention to date as a potential cue for compliance perception, especially when compared to other haptic perceptual channels or cues, such as cutaneous contact area, proprioception, and kinesthesia. One reason can be traced to the contact mechanical origin of vibromechanical signals which consist of high-frequency fluctuations in force or displacement. In many of the mechanical interactions listed above, vibration energy is produced through impacts between the surfaces of objects at a macroscopic scale or through interaction between surface microgeometry (asperities) as it happens during sliding friction (Akay 2002). In such cases, materials with high stiffness yield wide frequency bandwidth transient or sustained signal elements. In contrast, for compliant objects the effective stiffness

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of the impacting structures is low and the material may also be more damped. These properties yields only low energy at high frequencies during interaction.

Nevertheless, several studies have suggested that vibromechanical signals can influence perception during object palpation for a wide range of object compliances (Giordano et al. 2012; Kobayashi et al. 2008; Ben Porquis et al. 2011; Takahiro et al. 2010; Okamoto 2010; Ikeda et al. 2013; Rust et al. 1994; Okamura et al. 2001; Kuchenbecker et al. 2006; Kildal 2010, 2012; Visell et al. 2011). It is well established that high-frequency mechanical vibrations generated during manually tapping, scraping with a probe, or scanning with a finger can influence the perception of properties such as hardness (as reviewed below) and roughness (Klatzky and Lederman 1999; Hollins and Risner 2000; Bensmaia and Hollins 2003, 2005; Klatzky et al. 2003; Okamura et al. 1998). For example, amplifying vibrations generated during manual surface scanning, or imposing sinusoidal vibrations, increases perceived surface roughness (Hollins et al. 2000). Thus, it is reasonable to ask whether there exist high-frequency cues that are capable of influencing compliance judgements.

3.1.1 Vibrotactile Sensory Information

Vibromechanical stimulation of the skin affects both cutaneous receptors and receptors embedded in deep tissues, including muscles and tendons (Ribot-Ciscar et al. 1989; Freeman and Johnson 1982; Johnson 2001; Vedel and Roll 1982). The former stimulation include fast-adapting (FA) mechanoreceptors sensitive to phasic signals, in the form of Meissner and Pacinian corpuscles. These mechanoreceptive channels respond to transient or high-frequency mechanical stimuli. Also present are slower adapting (SA) mechanoreceptors that respond primarily to tonic signals produced by sustained or slowly-varying mechanical stimuli. In previous studies, the vibrotactile sense has been particularly associated with FA receptors. Mechanoreceptive afferents, which communicate the neural result of mechanical stimuli to the central nervous system, have been associated with receptive fields near to receptors that they terminate on. The size of the respective receptive fields for FA or SA mechanoreceptive afferents can range from a few square millimeters to several square centimeters, depending on the receptor type, innervation density, and biomechanical factors. Among physiologically identified FA receptors, Meissner corpuscles have small receptive fields, while Pacinian corpuscles lie deeper in the skin and possess larger receptive fields. The skin is sensitive to vibrotactile stimuli over a broad range of frequencies, up to nearly 1,000 Hz. Meissner corpuscles respond preferentially to vibrotactile signals in the range from 10 to 100 Hz, while Pacinian corpuscles respond to higher frequencies, but neither type exhibits narrow frequency-selective tuning like that present in the auditory system. In glabrous skin, which is found on the volar surface of the hand and feet, FA afferents comprise about 70 % of the cutaneous population. Vibrotactile sensitivity, measured in terms of the absolute or difference threshold for detection, varies as a function of body location and stimulus properties including contact conditions and frequency. Surveys of tactile sensitivity

at different body locations and for different stimulus parameters, including frequency and amplitude of stimulation, can be found in the following reviews (Morioka et al. 2008; Morioka and Griffin 2002; Verrillo 1966).

3.2 Contact Mechanics and Softness Cues

Haptic compliance perception involves discerning the deformability of objects touched with the hand or foot, or even objects felt using a tool. As discussed in Chap. 1, compliance $C = 1/k$ can be quantified in terms of mechanical stiffness k, which in turn depends on the Young's modulus and geometry of the material. In the simplest case, the deformation x of a material can be described via a linear, quasi-static relation between force $F = -kx$ and displacement x, or between continuum mechanical quantities of stress $\sigma = -E\varepsilon$ and strain ε.

The problem of softness perception consists of using haptic sensations to perceptually recover the compliance or material elasticity of an object. Thus, the notion of softness involves the extraction of object properties from stresses and strains, or forces and displacements, that are felt during exploration. Most prior research has investigated compliance perception via manual touch (Harper and Stevens 1964; Scott-Blair and Coppen 1940; Freyberger and Färber 2006; Tan et al. 1995; Srinivasan and LaMotte 1995; LaMotte 2000; Friedman et al. 2008; Bergmann Tiest and Kappers 2009). However, the haptic perceptual system is able to discriminate objects of different compliance in a multitude of ways, including touching with a tool (LaMotte 2000) or with the hand or foot (Giordano et al. 2012; Kobayashi et al. 2008).

The perceptual system is capable of judging softness in different ways depending on the information that is available. The contributions from different sources depend upon the actions, tasks, or exploratory procedures being performed, the properties of the objects (their material composition, geometry, and microgeometry), and the contact mechanical setting involved. Their integration thus must account for such sources of variability and should proceed accordingly (see Chap. 5 for a model). The same can be said about what kind of vibrations are available during different types of interactions and thus how vibrotactual information could be used for softness perception.

It is useful to consider four basic interaction patterns, which are represented in Fig. 3.1. They consist of *direct skin contact* with a compressed elastic object, *indirect skin contact* with such an object, *transient contact* with a touched object, and *frictional sliding*. Through these, it is possible to gain some insight into potential roles of vibrotaction in softness perception. In the next four sections we will analyse the vibrotactile information available in each of these interactions and what experimental results are available about the perception of softness.

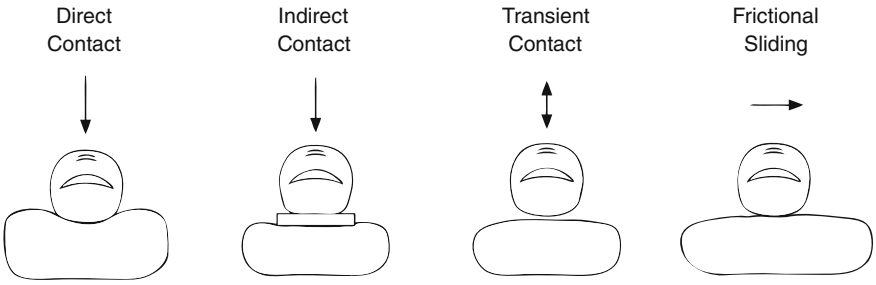

Fig. 3.1 Four prototypical scenarios where vibrotactile information is available and can potentially specify object softness: **a** Compressing a soft object with direct finger contact; **b** Compressing such an object via a rigid intermediary; **c** Producing a short, ransient contact through tapping; **d** Sliding the finger across the object surface

3.2.1 Direct Skin Contact

The first interaction type we consider involves direct contact between the skin and an elastic, compressed object, as shown in Figure 3.1a. This setting can be modelled using the Hertzian theory of non-adhesive linear elastic contact between two compressible bodies (Johnson 1995). One body consists of the skin and pulp of the finger, and the other constitutes the touched object. As the total normal force applied by the finger increases, the area of contact between the bodies grows. Simultaneously, the skin and underlying tissues deform, as can be quantified by an increase in strain energy density near the contact region. This gives rise to at least two potential perceptual cues (Bicchi et al. 2000; Scilingo et al. 2010) (see Chap. 11):

1. The rate of increase of contact area between finger and object surface with the normal force between finger and object surface
2. The rate of increase in strain energy in the volume of the finger near the contact region with normal force

The rate of increase in normal force can often be assumed to be slow, and the accompanying dynamics to be damped, due to the highly viscoelastic nature of the materials involved. Often the mechanics can be modelled as quasi-static. In such cases, transient mechanical signals can be presumed to be insignificant. Commensurate with this assumption, it could be hypothesized that, at a physiological level, the neural input from slowly-adapting (SA) afferents from the finger provide most sensory information, while inputs from fast-adapting (FA) afferent channels are less important. One could argue that vibromechanical cues contribute to softness perception by simulating transient strain patterns over the skin like those produced when touching an object, but there is little evidence to suggest that such cues contribute significantly to softness perception during direct skin contact, perhaps because contact area itself is so highly weighted, when available: As noted in Chaps. 1, 2, and 5, physiological and psychophysical studies have shown that haptic perceptual sensitivity to softness is highest when there is direct skin contact with a deformable surface.

An alternative possibility, discussed further in Sect. 3.3, is that vibration feedback could bias estimates of applied force during object compression.

3.2.2 Indirect Skin Contact

When touch is mediated by a rigid link, such as a handheld stylus or rigid mechanism, the cutaneous perceptual cues (1,2) noted above do not provide information about compliance, since contact area and skin strain reflect the force between the finger and a rigid surface but do not independently evidence the displacement of the surface. Adding a rigid link to the interaction with an object having deformable surfaces makes the interaction equivalent to the one obtained with an object with rigid surfaces. In such cases where cutaneous information is not directly informative about compliance, discrimination performance is significantly reduced (Srinivasan and LaMotte 1995). With rigid surfaces compliance estimation requires the combination of force and displacement information (see Chaps. 1 and 5). To estimate object compliance during indirect touch, cutaneous force cues could be combined with displacement information obtained from visual and proprioceptive sense data (see Chaps. 1, 2, and 5 for more information).

Several studies have demonstrated that individuals are able to estimate compliance under such settings (for example, estimating the compliance of a spring-loaded mechanism) (Srinivasan and LaMotte 1995; Tan et al. 1995; Bergmann Tiest and Kappers 2009; Jones and Hunter 1990). The results generally demonstrate reduced sensitivity when compared to the case of direct skin contact with a deformable object is available.

What does this suggest about possible roles of vibrotactile sensation in compliance estimation via indirect touch? It could be hypothesized that in such a setting, vibration could affect compliance estimates in one of two ways: by either biasing estimated displacements Δx or estimated forces ΔF (Fig. 3.2). As noted in Chap. 5, both types of bias are possible.

As vibrations are normally produced during object deformation, amplifying these vibrations could lead to a change in perceived compliance. This is partly supported in the literature (Visell et al. 2011; Kildal 2012, 2010).

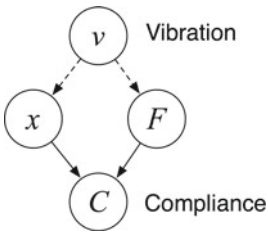

Fig. 3.2 Vibration stimuli may bias compliance estimates by altering perceived force F or displacement x

3.2.3 Transient Contact

So far we have discussed potential increases in perceived compliance due to vibration. In principle, however, vibrotactile cues could have the opposite effect namely they could decrease perceived compliance. Tapping on a hard surface elicits characteristic vibrations, in the form of transient mechanical signals, with broad frequency content, due to the rapid changes in contact forces. During such an interaction, a stiffer object may yield a more perceptually prominent vibrotactile signal. A model of the forces involved can be given by the Hertz theory of viscoelastic contact. A simplified version of the Hertz model that is suitable for the analysis of transient contact forces during impact with a viscoelastic object is due to Hunt and Crossley (1975), and can be written as

$$f_{impact} = K(z) - D(z)\dot{z}, \tag{3.1}$$

where z represents the depth of penetration beyond the undeformed surface of the object, K models the growth rate of contact surfaces, and D captures the dissipation. The tapping force excites vibrations in the object that can often be described by a source-filter model, consisting of an impulse response $h(t)$ equal to the response to an impulsive force, so that the net displacement is given by $y(t) = z(t) * h(t)$, where $*$ denotes convolution in time. For a stiff object this response combines contributions of broadly distributed frequency content arising from the contact force and contributions of high-frequency resonant modal frequencies. Either source may lie within the range of frequencies humans are sensible to, hence they could provide a potential perceptual cue to contact and to object compliance. Indeed, the notion that tapping on a surface is a suitable action for exploring surface hardness is familiar from everyday experience, and has further been explored experimentally (Lederman and Klatzky 1987).

The transient forces that are generated during tapping can yield vibromechanical signals that can be readily reproduced via a haptic interface using sufficiently wide bandwidth motors or actuators. Among the earliest work exploring the use of contact-generated vibration cues to communicate information about touched objects are robotic teleoperation studies in which a human operator of a master robot uses a slave robot to manipulate objects in a remote environment. The operator is provided with vibrotactile feedback that reproduces accelerations measured near the end effector of the slave device (Massimino and Sheridan 1993; Kontarinis and Howe 1995). The goal of such an arrangement, which can be described as a form of sensory substitution (Visell 2009), is to reproduce transient accelerations experienced at the end effector, simulating a setting in which the master and slave device were coupled via a rigid link capable of transmitting high-frequency vibrations, in the frequency range of several hundred Hz. The research investigated the extent to which feedback of this type could improve operator performance on basic tasks, such as peg insertion, but the results were mixed.

Later, researchers sought to enhance force or contact information in computer simulated virtual environments with vibrations that were designed to mimic the

physical response of real objects, either by means of a physical model (for example, the Hunt-Crossley impact model mentioned above) or based on the measured response of tapped materials (Kontarinis and Howe 1995; Okamura et al. 2001; Kuchenbecker et al. 2006). Studies have shown that by superimposing transient vibrations on contact forces, perceived surface hardness can be increased and material identity can be modified or enhanced (Kuchenbecker et al. 2006). Similar results have been observed with transient audio feedback, in the form of tapping sounds (see Chap. 4 for a comprehensive review). In general these methods of rendering, which employ a signal delivered through the auditory, visual, or tactile sense modalities which are triggered by the movement of the participant, have collectively been given the name of "event-based haptics".

3.2.4 Frictional Sliding

Friction involves tangential forces produced during the sliding of objects. Texture refers to small-scale modifications of mechanical interaction responses during sliding or during indentation. The forces involved comprise both slowly-varying nominal or constitutive responses and fluctuating components generated by surface or material imperfections. The latter signal components relate relative displacement of the objects concerned to high-frequency frictional force components (Ibrahim 1994; Akay 2002), whose frequency bandwidth can overlap that of the vibrotactile sense. In principle, perceptual information about interaction parameters, such as applied force or displacement, and material properties, such as surface hardness, are available through such signals. In everyday terms, even for objects with very soft surfaces, such as textiles like velvet or silk, texture-like force components can provide information about material properties. Additionally, as demonstrated in the well-known parchment skin illusion (Jousmäki and Hari 1998), amplifying the sound of frictional rubbing can create a perceptual experience that the sliding surface is dryer, rougher, or harder than is nominally the case.

In contrast to softness sensations elicited by pressing on a surface, softness cues produced by stroking with the finger are more difficult to interpret, since it is more challenging to analyze the physical interactions between the finger (or a probe) and the surface, and thus to relate softness perception to surface parameters. Nonetheless, it is plausible that individuals may use information acquired by stroking or scanning with a finger in order to estimate object compliance. First, because the sliding dynamics may directly depend on bulk material properties such as elasticity. Second, because surface properties may elicit prior expectations for object softness.

Textile softness is often perceived via rubbing with the fingers, as has been extensively studied in areas of the literature on applied perception and ergonomics (Pense-Lheritier et al. 2006; Chen et al. 2009). In order to obtain objective measures of fabric softness, several researchers have investigated the relation between reported textile softness and vibromechanical cues. Rust et al. (1994) were able to predict textile softness ratings using vibromechanical measurements obtained from a novel engineering instrument. Lang and Andrews (2011) observed a connection between the

object rigidity and sliding-produced vibrations in a probe . These studies were motivated by the idea that stroking a harder material can lead to a larger microscopic movements of a rigid probe as it comes in contact with the microscale defects of the surface upon which it slides. The magnitude and frequency of the vibrations caused by these contacts depend on the surface hardness—i.e., the microscale defects of the surface of a compliant materials would deform rather than making the probe. When the probe is mechanically coupled with a hard surface, their collective rigidity relatively increases, which leads to a larger resonance frequency and vibratory accelerations. When the probe is coupled with a soft surface, their comprehensive rigidity decreases, which leads to a smaller resonance frequency and significant damping ratio. Hence, the mean acceleration values depending on contact forces approximately reflect the compliance of surfaces. What is still unclear is whether humans can judge softness based on the cues generated by stroking alone as it is the case instead of perceived softness by tapping.

3.3 Effects of Low-Frequency Vibration on Softness

Prior literature has indicated that low-frequency vibrotactile stimuli, in the frequency range from 3 to 5 Hz, can evoke the perceptual sense of material softness (Ben Porquis et al. 2011; Takahiro et al. 2010). The softness experience that is evoked by such stimuli grows slowly, with a percept of vaguely defined onset. This slow but still noticeable softness sensation could be of practical interest, because it holds the potential to provide any handheld or grounded devices having vibrotactile channels with added value, namely the distinctive ability to produce artificial softness sensations.

3.3.1 Prospective Mechanism

Skin-mediated softness percepts are produced by the spatial distribution of pressure on the skin. Intensive pressure on a small area results in an experience of the contact with hard object, whereas widely extensive pressure is perceived as that with soft material, as shown in Fig. 3.3. According to the Hertzian contact theory (Johnson 1995), the radius a of a circular contact area made by two spherical bodies, here representing the finger pad and a soft object, is

$$a = \left(\frac{3w}{4}\frac{R}{E}\right)^{1/3}, \tag{3.2}$$

where w, R, and E are the contact force, composite radius and Young's modulus of the two bodies. The composite variables are

$$\frac{1}{R} = \frac{1}{R_f} + \frac{1}{R_s} \tag{3.3}$$

and

$$\frac{1}{E} = \frac{1 - \nu_f^2}{E_f} + \frac{1 - \nu_s^2}{E_s}, \tag{3.4}$$

where R_i, E_i, and ν_i are the radius, Young's modulus, and Poisson ratio of body i. The suffixes f and s describe the finger and surface to be touched by the finger, respectively. The values of R_f, E_f, and ν_f are assumed to be known. This can be justified by the assumption that a human observer should be roughly familiar with their own finger pad's size and softness. In case the soft object is a flat surface, $R_s = \infty$ and $R \approx R_1$. In this case, the two softness parameters ν_s and E_s may be estimated from a and w. Note that the value range of Poisson ratio is narrow and typically near 0.3. The effect of ν_s^2 can therefore be viewed as insignificant compared to E_s. The cutaneous and kinesthetic receptors of the human finger are capable of estimating both contact area and applied force. Humans can make use of slowly adapting type I (SA I) mechanoreceptive units and pressure-sensitive nocireceptors distributed beneath skin to estimate the pressure distribution and applied force caused by contact with soft surfaces. Receptors in the muscles and tendons of the finger and wrist are also sensitive to forces applied to finger pad.

At least three different engineering interfaces have been designed around the aforementioned principles, albeit by means of very different devices (see Chap. 14). Bicchi et al. (2000) and Scilingo et al. (2010) fabricated a finger pad contactor consisting of several concentric actuated cylinders with different radii. This device made it possible to control the pressure and contact area between a finger pad for testing the hypothesis that contact area plays a key role in softness percepts. In contrast, Fujita and Ohmori (2001) and Kimura et al. (2010) used balloon and sheet-based tactile displays, respectively, to elucidate and demonstrate the effects of contact area on softness percepts. The results of these studies affirmed the primary contribution of contact area to softness perception, although the explanatory hypotheses that each proposed have not been completely unanimous. Nonetheless, changes in the contact area can be said to effectively influence softness perception.

It is evident that the pressure distribution in the contact area has a strong connection with softness perception whereas its specific role leaves room for discussion. As described above, SA I units and some nociceptors are sensitive to pressure or sustained indentation. There is a distinct possibility that the activation of SA I units by vibrotactile stimuli induces softness percepts. For the low-frequency band or static mechanical stimuli, SA I units have the lowest thresholds, i.e., they are more sensitive than other units.

As described in the following section, larger low-frequency vibratory amplitudes are associated with softer percepts. The changes in the indentation can result in changes in deformed skin area, as shown in Fig. 3.3. With large skin indentation, large populations of SA I units are expected to be activated. Additionally, the size of

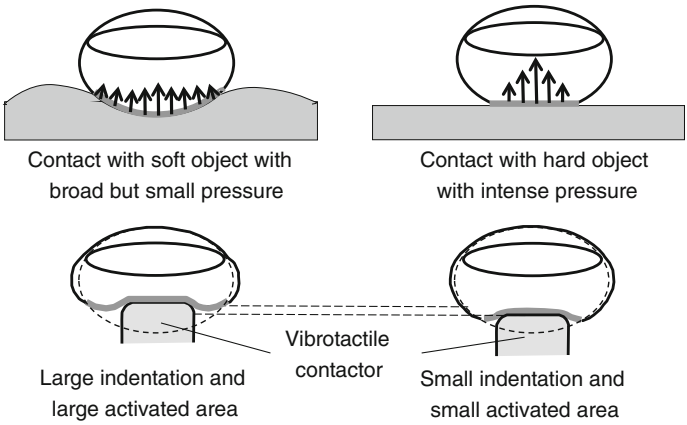

Fig. 3.3 *Top* Pressure distribution caused by contacts with objects. *Down* Finger pad deformation via vibrotactile indentation

population of activated SA I units is more predictive than the impulse rate of single unit about the area of the contact (Suzuki et al. 1999).

3.3.2 Low-Frequency Softness Rendering

Fig. 3.4 shows a schematic view of an experiment that evaluated effects of low-frequency on softness perception (Okamoto 2010; Takahiro et al. 2010). The experiment was based on the method of constant stimuli. In it, participants compared a low-frequency (5 Hz) vibrotactile stimulus and a physically soft sample and judged which stimulus was felt softer. Vibrations were generated using a voice coil

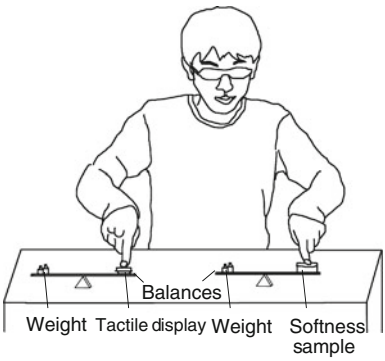

Fig. 3.4 Comparison between low-frequency vibrotactile stimuli and softness specimen

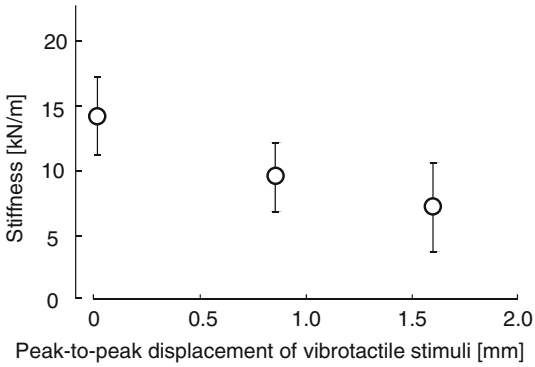

Fig. 3.5 Low-frequency vibrotactile stimuli versus softness of specimen

motor with a contactor consisting of a plastic plate. The vibrotactile amplitudes were 0–1.6 mm under a sustained load of 0.5 N. The physically soft specimens were cylindrical silicone rubber samples whose spring coefficient ranged 4.7–22.3 N/mm. Two balances were used to ensure equal loads were applied to the two stimuli. Fig. 3.5 shows the compliance of the silicone perceived to be matching the one of vibrating device. The perceived hardness decreased as a function of the vibration amplitude. In this experiment, the true contact area between the vibrotactile contactor and finger pad varied with stimulus amplitude in such a way larger amplitudes led to larger contact areas. In a subsequent investigation, the contact area was held constant, and the same effects of the amplitudes on the softness percepts were observed (Ben Porquis et al. 2011). Furthermore, there is evidence that low-pass-filtered white-noise vibrations can have a similar impact on softness percepts (Ikeda et al. 2013).

3.4 Volumetric Softness

During direct and indirect object contact (Fig. 3.1), vibration can accompany the compression when the displacement of the volume releases energy. Such vibration can be a potential cue to softness, but vibration can be released during a variety of other inelastic processes. It is thus not surprising that vibromechanical energy alone, when is not correlated with action, is unlikely to affect perceived softness. For example, when touching a washing machine, one is seldom left with the impression of owning a "soft" appliance.

A haptic interface that provides similar vibration feedback to what is felt during such situations might be expected to yield increased sensations of softness. A schematic illustration is shown in Fig. 3.6. Several published demonstrations and perceptual studies have provided evidence that vibrotactile feedback can modulate volumetric softness (Visell et al. 2011; Kildal 2010, 2012). Other perceptual

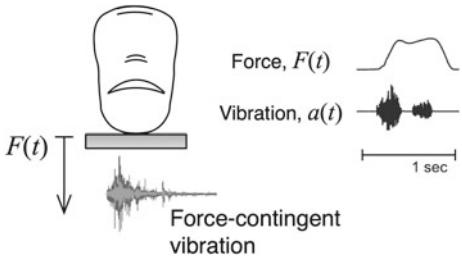

Fig. 3.6 The compression of a surface accompanied by suitable vibration feedback can yield increased sensations of volumetric softness, due to a straightforward sensorimotor contingency between the generation of internal vibromechanical energy during object compression

effects, including force-to-visual displacement gain modulation [or "pseudo-haptics" (Lecuyer et al. 2000)] are also known to affect volumetric softness perception.

In one study of effects of vibration feedback on volumetric compliance perception, Kildal demonstrated that a rigid box pressed with the finger or a stylus could feel as though it compressed in height (Kildal 2010, 2012). This sensation was evoked by vibration feedback that was coupled to applied force. The stimuli consisted of vibrations supplied by a resonant vibrotactile actuator driven by a voltage (amplitude) signal. The stimulus design was motivated by a mechanical model consisting of a spring loaded mechanism moving over a corrigated surface. A vibration transient was supplied whenever the normal force on the device changed by a quantity ΔF. Averaging over vibration transients yields a stimulus $s(t)$ with RMS amplitude given by

$$s_{\mathrm{rms}}(t) = S_0 \frac{dF}{dt} = S_0 k \frac{dx}{dt}, \tag{3.5}$$

where S_0 is a constant amplitude factor, F is normal force, t is time. The parameters k and x are the virtual stiffness and displacement of the simulated mechanical model responsible for producing the feedback.

Visell et al. (2011) investigated whether action-synchronized vibromechanical stimuli felt when pressing on a surface could yield influence the perceived compliance of a walking surface. The vibration feedback they presented to participants depended on the force that was applied to the walking surface. These signals were comparable to those experienced when stepping on a natural material that produces acoustic energy when compressed (e.g., snow, gravel, leaves, soil), or displacing a foot operated mechanism that generates friction noise (e.g., a pedal or slider). Vibromechanical results of stepping onto a walking surface have been found to be related for the identification of the type of material that natural and man-made walking surface are composed of (Giordano et al. 2012). The authors' investigation was based on a pair of experiments. The first sought to ascertain the dependence of perceived compliance on on the vibration stimulus waveform, and on the relation between applied force and feedback amplitude. The stimuli consisted of vibration feedback that varied in two respects: the driving waveform (sinusoidal, white noise, or poisson noise) or

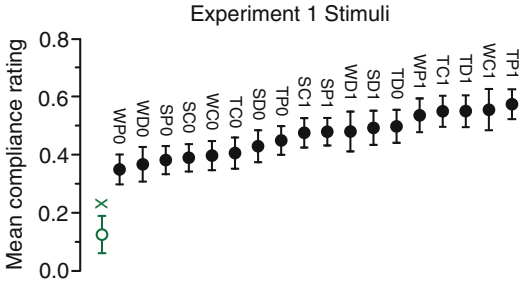

Fig. 3.7 In one experment, Visell et al. (2011) found that nine different types of vibration feedback were all able to elicit a significantly increased percept of compliance when compared with the "no vibration" case. Image from Visell et al. (2011)

and the temporal dependence on force (proportional, time-derivative, or constant). Results indicate that vibrotactile feedback could elicit an increase in perceived compliance and that the effect grew in proportion to the feedback amplitude (Fig. 3.7). In a second experiment, the authors manipulated the compliance of the walking surface that users stepped on, using a novel haptic interface (Fig. 3.8). The goal was to determine whether compliance and vibration are perceptually integrated in an organized way, and to calibrate the perceptual effect in physical units, yielding a quantity of change in physical compliance that could be achieved with a given vibrotactile feedback amplitude. Results point out that vibrotactile feedback provides a perceptual cue for compliance (Fig. 3.9). The vibration amplitudes required to produce an appreciable bias in perceived compliance were very low, near to the absolute threshold at which subjects could detect the vibrotactile stimuli when stepping. Thus, the

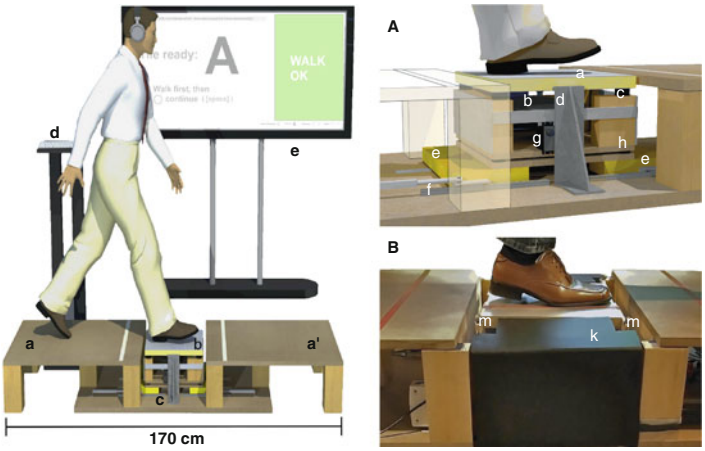

Fig. 3.8 Effects of vibration on volumetric softness. Image from Visell et al. (2011)

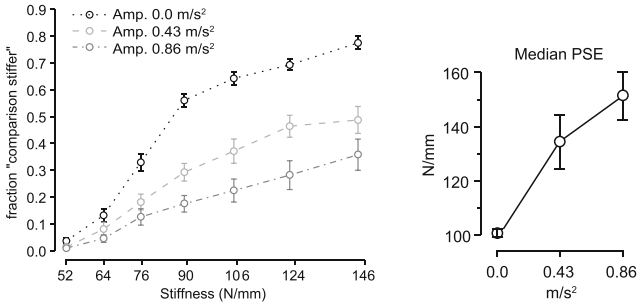

Fig. 3.9 Effects of vibration on volumetric softness

amplitudes used were considerably smaller than the ones experienced during normal walking on natural granular materials, such as gravel, as humans are well aware of the vibrations present there. It is not entirely clear why the stimuli were so effective in this experiment, which did not involve training and did not require awareness that vibration feedback was being provided. The compliance estimation task adopted in this study resembles prior experiments in which subjects used their hands to estimate the haptic compliance of spring mechanisms or other objects with non-deformable surfaces (LaMotte 2000; Tiest and Kappers 2009; Jones and Hunter 1990). Based on those results, and on considerations of contact mechanics, it was expected that subjects in the experiments described here required both force and displacement information in order to judge compliance. In this light, it appears that added vibration feedback results in a modification of force and/or displacement information that increases compliance estimates. Prior research has shown that localized vibration stimulation of the foot sole can increase perceived force at the same location (Kavounoudias et al. 1999, 1998), which could be thought to influence compliance judgments. However, an increase of force estimates would tend to reduce compliance estimates, whereas the aforementioned results reviewed show an opposite tendency. Thus, a more likely explanation, which is also consistent with the results of Kildal (2010, 2012), seems to be that vibration elicited an increased sensation of displacement, as if an object or material was compressed or displaced. If so, an observer could be presumed to infer an increase in compliance that grows linearly with the increased sensation of displacement. The results of (Visell et al. 2011) were consistent with relative increases in estimated displacement of 25.0 and 33.5 % in low- and high-amplitude vibration conditions (amplitude 0.43 and 0.86 m/s^2) as tested in the study, suggesting a monotonically increasing relation between vibration amplitude and compliance perception. The model proposed in Chap. 5 suggest that the increase in sensed displacement may be related to a biased detection of the unperturbed position of the object. The first contact with a vibrating object is obtained earlier than the resting state position. This should increase the amount of displacement sensed afterwards. But on this basis one could ask: Why indeed is the washing machine not perceived to be "soft"?

3.5 Conclusions

A wide variety of mechanical signals arise during haptic interaction with structured surfaces and objects. Among these, there are several sources of high-frequency mechanical vibration that might influence haptic softness perception. They range from transient vibrations induced during tapping on a surface, to subtle fluctuating forces during frictional sliding, to vibrations resulting from inelastic processes accompanying the compression of solid objects. The heterogeneous nature of the contact mechanical interactions involved precludes, to some extent, a unified explanation of all such effects. However, several studies reviewed above have provided evidence for such effects. Together, they indicate that vibrotactile cues can influence the perception of object compliance. This is notable because in standard accounts of haptic perception, such cues are not normally considered to be relevant to softness perception. Rather, compliance is often described as being primarily mediated via proprioceptors in the muscles and joints, and via cutaneous receptors for force or contact deformation.

In most cases, vibrotactile cues have a comparatively weaker influence on perceived softness than can be achieved by manipulating the material properties of the objects themselves or by manipulating force-displacement relations reproduced by a haptic interface. Nonetheless, the notion that a hard surface can be rendered more or less compliant through mechanical vibrations alone is powerful and compelling.

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