

A Device and Method for Multimodal Haptic Rendering of Volumetric Stiffness

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Abstract. Vibrotactile signals are produced during haptic exploration of compressible objects through a variety of contact and bulk mechanical processes. Prior studies have found that vibrotactile feedback can influence stiffness perception, but the reason for this is unknown. Here, we investigated the role of vibration in stiffness perception during object squeezing. We propose a physically motivated explanatory model and rendering algorithm relating vibrotactile and force-displacement cues, then present a novel haptic interface that was designed to accurately reproduce these cues. Finally, we present the results of an experiment on the perceptual integration of vibrotactile and force-displacement cues during one- and two-finger stiffness perception. The results indicate that vibration feedback can increase perceived object softness during interaction with one finger, but preclude a similar conclusion for two-finger grasping. We argue that the results support the proposed model once innate differences in one- and two-finger exploration are accounted for.

1 Introduction

Mechanical vibrations are produced through a diverse array of contact and bulk mechanical interactions, including sliding friction, transient contact between objects, or the inelastic deformation of inhomogeneous media (e.g., a bag of coffee beans). The vibrotactile sense is capable of assisting the brain in discriminating touched surfaces or felt objects, in extracting properties such as roughness or surface regularity, and in identifying events, such as changes of contact conditions [1–3]. However, it has rarely been considered as a potential cue to softness, since soft or deformable objects or structures are rarely thought of as sources of such vibrations. Nonetheless, in many cases, such vibrations are often associated with macroscopic displacements of surface or bulk elements, leading to correlations between vibromechanical energy production in a bulk medium and macroscopic constitutive (force-displacement) behavior. Indeed, several prior studies have suggested that action-synchronized vibrotactile feedback can strongly influence haptic softness perception during object palpation [4–6]. However, the mechanism by which this occurs is uncertain.

The goal of our investigation was to measure empirically the role of vibromechanical sensory information in the perception of haptic object stiffness during grasping. We first propose an explanatory model and rendering algorithm relating vibrotactile and force-displacement cues. We then present a novel haptic interface capable of reproducing these cues during multi-finger squeezing, over a wider dynamic and frequency

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range than has been possible with previous devices. Finally, we present an experiment evaluating this effect, the results of which lend some support to the proposed model.

1.1 Vibrotactile Rendering of Volumetric Stiffness: A Mechanical Model

The compression of an object or mechanism can result in both macroscopic stress and strain signals and higher frequency vibrations generated through inelastic contact or bulk mechanical processes. We can examine a prototypical physical model encompassing such effects in order to derive a relation between vibrotactile and force-displacement stimuli. Here, we consider an elementary model for inelastic processes in a compressed bulk medium (Fig. 1).

Action phase dependence The linear viscoelastic part of the strain response of a compressed medium $x(t)$ due to an applied force $F(t)$ can be modeled as a mechanical impedance Z with $F(s) = Z_c(s)v(s)$, where s is the Laplace transform variable and $v(t)$ is the compression rate. If we also assume that there is a linear dynamical dependence between an increment $dx(t) = v(t)dt$ of compression and an increment $r(t)dt$ of inelastically produced vibration noise, then we obtain an action-phase dependence of the form $r(s) = Z_n(s)v(s)$, where $r(t)$ is the amplitude of vibration noise, and the *vibration production impedance* $Z_n(s)$ is introduced to encode stress in the sliding medium and other properties of the compressed material that affect noise generation.

Rendering the spectrum of mechanical vibrations To model vibration noise delivered to the finger during shear inelastic or frictional deformation, we refer to prior studies of force fluctuations in the frictional sliding of a finger on a surface [7], the compression of disordered media [8], and many other physical systems, all of which are observed to elicit random forces $\delta F(t)$ with fluctuation power spectra having characteristic $1/f$ dependences on frequency f . Such fluctuations can be modeled as pink noise $p(t)$, i.e., a random process with power spectrum density $S(f) \sim 1/f$.

Mechanically, the finger acts as a damper above 100 Hz, obeying a constitutive law $F_{\text{skin}}(t) = -B\dot{x}_{\text{skin}}(t)$, where B is a damping coefficient, implying $p(t) = -B\dot{x}_{\text{skin}}(t)$. Now, most haptic devices can be approximated by an inertia m , which is much greater than that of the finger pad. Thus, if we command a current $I(t)$ yielding a force $F(t) = \gamma I(t)$, where γ is a motor gain factor, we have

$$F(t) = \gamma I(t) = m\ddot{x}_{\text{device}}(t) = m\ddot{x}_{\text{skin}}(t)$$

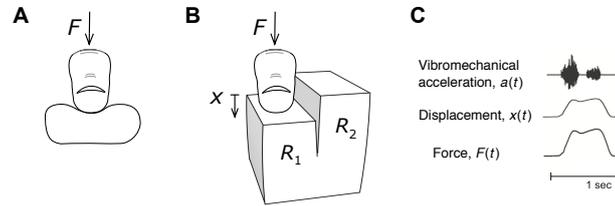


Fig. 1. Compressing an object can involve both viscoelastic deformation (**A**), and the release of vibromechanical energy (**B**, **C**) through a variety of processes, including shear sliding.

In the case of interest, we aim to impose a displacement on the finger pad equal to that excited by force fluctuations modeled as pink noise. From the foregoing, we can write $\dot{x}_{\text{skin}}(t) = -p(t)/B$, which yields

$$F(t) = m\ddot{x}_{\text{skin}}(t) = \frac{-m}{B}\dot{p}(t) \Rightarrow \boxed{\delta F_{\text{skin}}(t) = \frac{-m}{B}\dot{p}(t)} \quad (1)$$

That is, the commanded force fluctuation should be proportional to the derivative of the pink noise process. We use this result to render vibromechanical stimuli for the skin that possess the vibration spectrum characteristic of the inelastic process of interest (e.g., frictional compression). In our implementation, we synthesize pink noise in discrete time by applying a 3 dB/octave lowpass filter $H(s)$ to gaussian white noise $n(s)$, so that $p(s) = H(s)n(s)$, then apply a differentiator filter $D(s) \approx s$ to the result. $D(s)$ is band limited to limit gain and prevent aliasing, and is implemented in discrete time as a FIR filter of order 128. The resulting commanded surface noise force signal is $\delta F(t) = D(s)H(s)n(s)$.

Multimodal rendering For the integrated rendering of haptic force-displacement stimuli and vibrotactile feedback, we model the former as a mechanical impedance $Z_c(s)$ describing the mean bulk constitutive (force-displacement) behavior $\bar{F}(s) = Z_c(s)v(s)$, and the latter via an impedance model $Z_n(s)$ for the rate $r(t)$ of vibromechanical energy production vs. compression rate, with $r(s) = Z_n(s)v(s)$. The fluctuating force is non-zero only during loading, when it is given by

$$\delta F(t) = A\gamma r(t)\dot{p}(t), \quad r(t) = \mathcal{L}^{-1}\{Z_n(s)v(s)\} \quad (2)$$

where γ is the actuator gain and \mathcal{L}^{-1} denotes the inverse Laplace transform, see Fig. 2.

Due to the correlations between stiffness and vibration response embodied in this model, it is plausible that the latter provide a perceptual cue to stiffness. We conducted stiffness experiments for one- and two-digit grasps, to assess this hypothesis.

2 The effect of vibration feedback on stiffness perception

We designed experiments to assess the relative contribution, if any, of the putative vibration and stiffness cues described above to the perceived softness of squeezed (virtual) objects. In them, participants were presented with stimuli that varied in stiffness and vibrotactile feedback amplitude. Participants performed perceptual judgements as to the

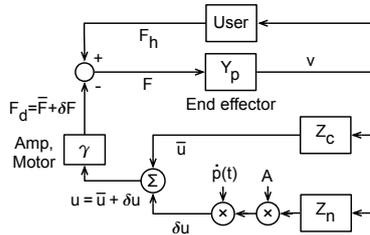


Fig. 2. A model for the haptic rendering of multimodal stiffness stimuli, incorporating both kinesthetic and vibrotactile cues.

stiffness of the felt stimuli, from which we were able to infer the extent of contribution of vibration to stiffness perception. During stimulus exploration, participants used either two-digit precision grip or one finger pressing with the forearm supported.

2.1 Apparatus: The UGrip Haptic Display

We present a new haptic interface that we have designed for the present investigation. We refer to it as the UGrip display. It is a force feedback device permitting its users to squeeze virtual objects in a haptic simulation (Fig. 3). The device presents its user with a pair of manipulanda that can accurately display specified force-displacement relations as well as high frequency vibromechanical feedback.

Mechanical structure and sensing The interface consists of a pair of anodized aluminum plates with rubberized surfaces that are squeezed in opposition by the index finger and thumb. Each of the plates is able to displace up to 4 cm, so that up to 8 cm of compression of a virtual object can be simulated. The plates are coupled to low noise linear guides, ensuring translation with low friction and, statically, high torsional stiffness. Both actuators and sensors in the device are contactless. This results in good control in the direction of motion and stiff coupling to actuators. By design, the device has trivial kinematics, simplifying control implementation and ensuring that the frequency bandwidth extends to nearly 1 kHz. The displacement of each plate is sensed with a non-contact magnetic encoder (LM13, RENISHAW INC., ILLINOIS, USA) with a linear resolution of 1 μm .

Force display and calibration The apparatus is designed to reproduce forces that can statically resist displacements of the fingers during pinch grasping, and concurrently to present force- or displacement-dependent vibromechanical stimuli to one or two digits.

The linear voice coil actuators (MODEL NCC15-24-050-1R, H2W TECHNOLOGIES, SANTA CLARITA, CA) are each able to reproduce high forces, i.e. more than 37 N of static or 100 N of peak force. They generate a force proportional to the driving current I , the number n of coil loops, the field strength constant B of the permanent magnet, and a geometry factor $\Gamma(x)$ equal to the proportion of permanent magnetic flux passing through the coils for a given configuration (displacement) x , so that $F(x) = nBI\Gamma(x)$. In

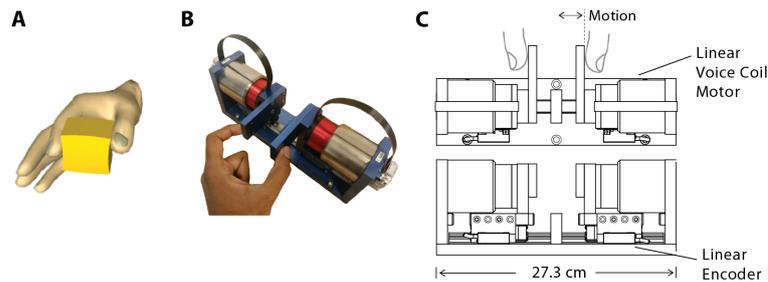


Fig. 3. The UGrip display device, presented here for the first time, is designed to enable its users to squeeze virtual objects (A). The device (B, C) consists of a pair of electromechanically controlled plates driven by high-power voice coil motors, yielding a display system capable of reflecting the full range of forces and frequencies that the fingers are sensitive to.

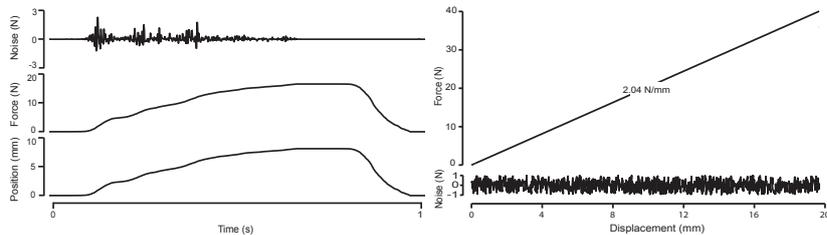


Fig. 4. Left: Time-domain stimulus components during a typical squeezing motion with the apparatus. Right: The rendered force-displacement profile is linear, and is accompanied by vibration noise. The amplitude of the latter is constant when the rate of loading is constant.

this device, actuators are driven by voltage-to-current mode amplifiers (H2W TECHNOLOGIES, SANTA CLARITA, CA) sufficient to produce the forces listed above. Forces measurement and calibration was performed by instrumenting the end effectors with precision miniature load cells (MODEL LLB130, FUTEK, IRVINE, CA).

Force feedback control was effected using the controller shown in Fig. 3. It was implemented using a two-axis motion controller (DMC-4123, GALIL MOTION CONTROL, ROCKLIN, CA). The programmable controller executes custom software implementing hard real time control loop with sampling frequency 8 kHz, ensuring artifact-free force reproduction. Program parameters are modified at runtime using ethernet communication from a personal computer executing the experiment software.

Stimuli We rendered multimodal stiffness stimuli using the method presented above. Participants explored the stimuli by squeezing the manipulanda with a two finger precision grip or by pressing it with one finger with the forearm supported (Fig. 6). Output forces F_i , $i = 1, 2$ for each finger were computed as functions of measured positions x_i . The forces are given by an additive combination $F_i = \bar{F}_i + \delta F_i$, where \bar{F}_i is the constitutive component, which varies slowly, and δF_i is the fluctuating component. Due to the inelastic nature of the latter, we presented vibrations only during loading. Vibration stimuli were generated as shown in (Fig. 3). We model the noise generation impedance $Z_n(s)$ as equal, up to a constant factor, to the stiffness $Z_c(s) = k/s$ so that the vibration stimulus is given by $\delta F(t) = Ak\dot{p}(t)dx(t)$, where $dx(t)$ is the instantaneous increment of displacement, and A is a constant gain factor. A typical multimodal stiffness stimulus as presented in the experiment is shown in Fig. 4.

2.2 Procedure and Adaptive Staircase Method

The experiment was designed to measure stiffness perception in one of four conditions, obtained by combining the grasp type (one or two-digits) with the feedback type (with or without vibration). We fit psychometric functions for stiffness perception separately from responses in each condition. In each condition, the experiment utilized an adaptive staircase procedure based on a two interval forced choice task, which required participants to compare the comparison stimulus with variable stiffness k in the experimental condition concerned (i.e., with or without vibration feedback, one or two-digits) with a standard stimulus having a fixed reference value, k_0 of stiffness and zero vibration feedback. In the vibration condition, the amplitude was $A_0 = 3.4$. Participants felt

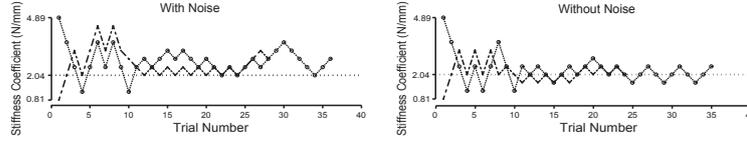


Fig. 5. Example staircase pairs during a single adaptive procedure from the experimental set. The conditions correspond to single-finger exploration. Left: With noise. Right: Without noise.

the comparison and standard stimuli in a two-alternative forced choice task in which the two stimuli were presented in sequential random order. Participants responded via keyboard entry indicating whether the first or second stimulus felt softer, or less stiff. During each staircase, the comparison stiffness k was controlled using a 1-up, 1-down adaptive procedure that converged toward the point of subjective equality (PSE), where the comparison stimulus with stiffness k felt equally stiff to the standard stimulus with stiffness k_0 . No vibration feedback was provided during standard stimulus presentation.

The value of k was manipulated during the experiment dependent on the responses of the participant (Fig. 5). The initial value of k was set to a “high” or “low”, randomly selected to lie between either $2k_0$ and $2.5k_0$ (“high” condition) or between $k_0/2.5$ and $k_0/2$ (“low” condition). When participants responded that the comparison felt stiffer (resp. less stiff), then the stiffness k was decreased (resp. increased) by one step unit. The step size was initially large (12 dB) and was reduced to a smaller level (3 dB) after five reversals in the direction of the threshold-tracking sequence. In each condition, two staircase procedures were performed at a time, one beginning at “high” initial stiffness, and one at “low” stiffness. The two were performed in interleaved fashion, with one of the two randomly selected for presentation on each trial. Each staircase was continued until 20 reversals were reached. A total of eight staircases (four interleaved pairs) were completed by each subject, one pair in each of the experimental conditions. Subjects were required to pause for 2 minutes between staircase pairs. The total experimental duration for each subject was approximately 50 minutes.

2.3 Analysis of Experimental Data

The results of the experiment in each condition consisted of binary response data indicating whether or not the standard stimulus (no vibrations, and stiffness 2 N/mm), was judged less stiff than a comparison that varied in stiffness, with the latter controlled by the adaptive procedure. Binary response data in each condition, i.e. at each vibration level ($A = 0, A_0$) and in each exploratory condition (one- or two-finger pressing) from each of the 8 subjects were fitted to a cumulative normal distribution using a probit regression model. A total of 32 probit regression fits were performed; a representative example is shown in Fig. 6. None of the fits failed to converge.

We investigated influences of vibration on stiffness perception by analyzing the effect it had on the PSE, slope, and intercept of the psychometric functions during either one- or two-finger squeezing. The analysis used a repeated measures analysis of variance (ANOVA) test. In the one-finger conditions, vibration feedback significantly increased PSE vs the non-vibration condition (mean 2.34 vs. 2.02 N/mm, $p < 0.05, F(1, 7) > 5.3$), indicating that the stimulus felt softer when vibration was

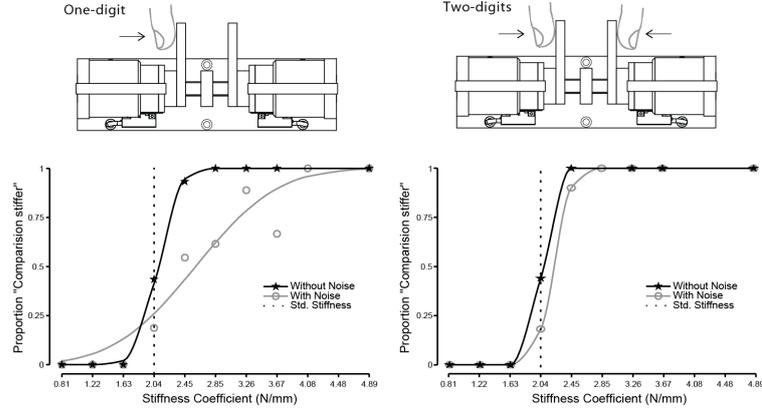


Fig. 6. Psychometric curve fits from one participant. Left: Single-finger exploration, with and without vibration. Here, vibration elicited a bias in the PSE, or a reduction perceived stiffness of the comparison stimulus, and a reduction in sensitivity (slope of the PSE). Right: Two-finger exploration in the same conditions showed no significant effect (see text).

present. Despite this, data from two of eight participants evidenced a small negative effect (in both cases less than one standard deviation in size). Slope was not significantly affected in the one-finger condition ($p > 0.16$, $F(1, 7) = 2.4$). However, the slope was largest in the no-noise condition for all but two of the participants (the same two as noted above). Thus, it appears possible that the lack of observed significance was due to outliers or small sample size. In the two-finger condition, there was no significant effect of vibration on stiffness PSE ($p > 0.3$, $F(1, 7) = 2.0$) or slope ($p > 0.75$, $F(1, 7) = 0.1$), indicating that two-finger stiffness perception was unaffected by the presence of vibration. The presence of vibration did not significantly affect intercept during interaction with one- ($p > 0.19$, $F(1, 7) > 2$) or two-fingers ($p > 0.8$, $F(1, 7) = 0.06$), indicating that subjects were not biased to indiscriminately answer “softer” when vibration was present. Absent vibration, there was no significant difference between the PSE for one and two finger squeezing ($p > 0.15$, $F(1, 7) > 2.3$), indicating a lack of effect of exploration type on stiffness judgements. However, participants were significantly more sensitive during two-finger squeezing, as evidenced by the higher slope (7.9 vs. 17.5, $p < 0.05$, $F(1, 7) > 5.8$).

3 Discussion and Conclusion: Rendering and Perception

In this paper, we presented a physically-motivated model for the perceptual integration of action-phase-dependent vibration cues in softness perception during the palpation of a soft object. This motivates the hypothesis that an increase in vibration feedback increases perceived softness, as has been observed in prior studies on pressing and walking cited in the introduction. We used this model to derive an algorithm for the multimodal rendering of stiffness cues. We also presented a new high-fidelity haptic interface designed to accurately reproduce both kinesthetic and vibrotactile cues during one- or two-finger squeezing. To our knowledge, this is the first haptic force feedback interface capable of reflecting nearly the entire dynamic range and frequency bandwidth of end-point forces that the haptic system is sensitive to.

We further employed this device to assess the perceptual integration of stiffness and vibration during one- and two-finger squeezing. The results support the notion that action-phase dependent feedback supplies a cue that increases perceived object softness during one finger squeezing. The experiment did not require training, and participants were supplied no information related to the cues being provided. We can conclude that vibration felt during single-finger pressing of a rigid surface is combined with the mechanical stiffness of the surface in the haptic perception of compliance. In the same condition, it appeared that vibration might impair stiffness sensitivity, but our results were inconclusive. There are a number of potential reasons this could be true, such as sensory adaptation or cognitive factors, so we do intend to investigate further.

The results appear to be consistent with the mechanical model we proposed. Additionally, prior studies observed that displacement perception is highly accurate during pinch grasping [9], and that stiffness perception by a single finger is poor when contact area cues are not available [10]. Indeed, we observed two-finger stiffness perception to be more accurate than one-finger squeezing. Further, based on our model, we predict that vibration affects stiffness perception by altering displacement estimates (since the incremental amplitude of vibration is proportional to the increment of displacement). Since two-finger size perception has been found to be highly accurate, one may expect the brain to rely on this source when estimating stiffness [11].

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