No Strings Attached: Force and Vibrotactile Feedback in a Guitar Simulation

NO STRINGS ATTACHED: FORCE AND VIBROTACTILE FEEDBACK IN A GUITAR SIMULATION

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ABSTRACT

In this paper we propose a multisensory simulation of plucking guitar strings in virtual reality. The auditory feedback is generated by a physics-based simulation of guitar strings, and haptic feedback is provided by a combination of high fidelity vibrotactile actuators and a Phantom Omni haptic device. Moreover, we present a user study (n=29) exploring the perceived realism of the simulation and the relative importance of force and vibrotactile feedback for creating a realistic experience of plucking virtual strings. The study compares four conditions: no haptic feedback, vibrotactile feedback, force feedback, and a combination of force and vibrotactile feedback. The results indicate that the combination of vibrotactile and force feedback elicits the most realistic experience, and during this condition, the participants were less likely to inadvertently hit strings after the intended string had been plucked. Notably, no statistically significant differences were found between the conditions involving either vibrotactile or force feedback, which points towards an indication that haptic feedback is important but does not need to be high fidelity in order to enhance the quality of the experience.

1. INTRODUCTION

In recent years, the availability of relatively low cost virtual reality (VR) hardware devices has seen applications also in the music industry. Several VR musical instruments have been developed both in the academic and commercial world. An overview of design guidelines and applications of VR musical instruments can be found in [1].

In the computer music community, the sounds of stringed instrument have been simulated for decades, starting with the work of Hiller and Ruiz [2], followed a decade later by the simulations proposed by Karplus and Strong [3]. Moreover, physics-based simulation of such instruments has been an active areas of research within the community (see e.g. [4, 5]). However, this research has predominantly focused on simulating the sounds generated during interaction with strings, and visual and haptic feedback remain relatively unexplored (for a recent exception see [6]).

In this paper we propose a novel multisensory simulation of a guitar, which uses efficient yet accurate physics-based synthesis techniques to reproduce the auditory and haptic feedback accompanying the act of plucking guitar strings. In the current paper, we use the term *haptic* in a broad sense to encompass all somatosensory capabilities; that is, sensations that qualify as cutaneous (related to interactions at the level of the skin), kinesthetic (related to movements of one's body and limbs), and proprioceptive (related to the position of limbs and the static attitude of the musculature) [7, 8].

We first describe the system, which simulates the sensation of plucking guitar strings through a combination of visual, auditory, force and vibrotactile feedback. Subsequently, we present a user study evaluating users' experience of plucking virtual strings. The aim of the study was twofold: (1) It was meant to determine the degree of perceived realism of the system; that is the degree to which the system was able to replicate the sensation of plucking a real guitar string. (2) The aim was to explore the relative importance of force and vibrotactile feedback as elements for the creation of a realistic experience of plucking virtual strings. Specifically, it was considered relevant to determine if a realistic experience can be elicited when the simulation is devoid of force feedback and only involves vibrotactile feedback.

2. RELATED WORK

In the last two decades, haptic feedback has received increasing interest from the sound and music computing community, due to the strong correlation between auditory and haptic musical signals. In fact, both signals share highly similar and simultaneous temporal analogies, with a higher sampling rate for the audio channel. For a recent overview refer to the work of Papetti and Saitis [9]. Avanzini and colleagues [6,10] describe a multimodal architecture, which integrates physically-based audio and haptic models with visual rendering. Experiments with stiffness perception showed how auditory feedback can modulate tactile perception of stiffness. In her PhD dissertation investigating the role of haptic feedback in digital musical instruments, O'Modhrain [11] pioneered research on multisensory audio-haptic simulations in a musical context. As an example, she discovered that the playability of touch-free instruments, such as the Theremin, is significantly increased when haptic feedback is provided. Custom made devices to provide haptic feedback in a musical context have been developed together with physics-based audio-visual simulations in the work of Florens and colleagues [12]. More recently, Leonard and Cadoz [13] introduced a system, based on mass-interaction physical modelling, that supports real-time interaction with multisensory virtual music instruments. The combination of physically simulated strings and haptic feedback has also been rather extensively explored by Berdahl [14]. In this context, the applications have been mostly pedagogical and artistic, rather than targeted towards perceptual evaluations of auditory-haptic interactions. Berdahl proposes novel fader-based controllers where the plucking action can be felt while interacting with a virtual string [15]. The tight multisensory coupling between hearing and touch has also been explored in the simulations proposed by Liu and Ando [16].

In the context of VR, although research has primarily focused on providing realistic auditory and visual feedback, haptic feedback has also been investigated. However, the focus has to a large extent been on cumbersome and expensive force feedback devices [17].

Kinesthetic and proprioceptive information is central to perception of solid objects, but so is cutaneous information derived from vibrations. The vibrations generated when an object moves across a surfaces encodes roughness [18] and the vibrations generated during tapping encodes hardness [19]. For these reasons, much research has focused on increasing the realism of virtual interaction using vibrations [20]. For example, it has been shown that the addition of vibrotactile feedback can enhance low-fidelity kinesthetic devices [19], vibrotactile feedback affect perceived hardness during tapping of one physical object on another [21], and vibrotactile feedback can be used to elicit an illusion of compliance when pressing a stylus against a rigid surface [22].

Figure 1. A user interacting with the system. On the top right a zoomed figure of the Phantom Omni device with attached the vibrotactile actuator. The actuator is inserted into a 3D printed plectrum.

3. MULTISENSORY SIMULATION OF PLUCKING GUITAR STRINGS

The system proposed in the current paper is created with the intention of eliciting a realistic sensation of plucking the strings of a virtual guitar. The system consists of three separate stimuli elements: haptic, auditory and visual. Figure 2 shows a diagram visualizing how the elements have been connected, and Figure 1 shows a user interacting with the system.

Specifically, the haptic feedback is provided by a Sensable Phantom Omni haptic device mounting a 3D printed plectrum on its arm tip. The plectrum is embedded with a Haptuator Mark II vibrotactile actuator manufactured by Tactile Labs. Visual feedback is delivered using an Oculus Rift CV1 head mounted display. Finally, auditory feedback is provided through a Vox HC30 guitar amplifier.

The signal driving the vibrotactile actuator is produced by an impact model run by the Sound Design Toolkit for Max/MSP [23]. Specifically, the contact force depends on the velocity and displacement of the objects in contact according to the following relationship:

$$f(x(t), v(t)) = kx(t)^{\alpha} + \lambda x(t)^{\alpha} v(t)$$

for $x \geq 0$, and 0 otherwise, where the compression x at the contact point is defined as the differences between the

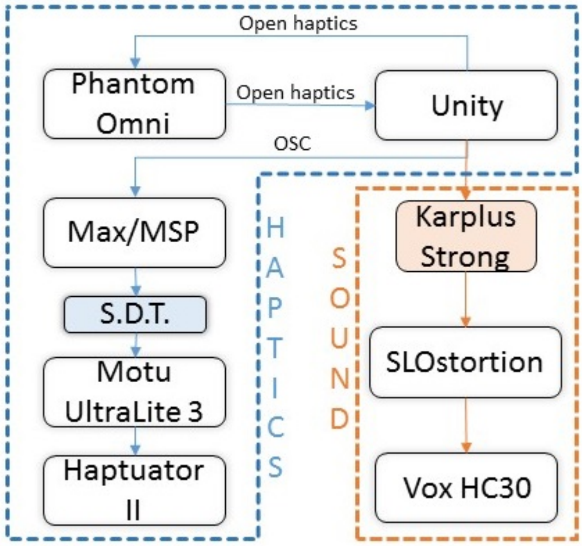

Figure 2. Diagram visualizing the software and hardware integration.

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displacements of the two bodies, and $v(t)$ is the compression velocity. The parameter k is the force stiffness and is a function of the mechanical properties of the two bodies, while λ is the force damping weight, and α is a parameter whose value depends on the geometry of the contact [6].

The parameters of the impact model were chosen by having two guitar players empirically experiment with different settings and choosing the parameters that felt closest to a guitar pluck. For the force feedback, the Phantom Omni haptic device is driven by a collision algorithm developed in the haptic plugin for Unity [24]. This plugin uses the Open Haptics toolkit [25] to render the contact force between the pen of the Phantom Omni and the virtual string.

The guitar sound is synthesized by an efficient extended Karplus-Stong algorithm [26], originally developed by Kevin Karplus and Alex Strong in 1983 [3]. The algorithm simulates a string in the form of a feedback digital delay whose length represents the length of the string. Propagation losses are simulated using a low-pass filter. Jaffe and Smith [26] proposed improvements towards a realistic guitar sound. Although this simulation is a simplification compared to accurate physical simulations, it is efficient enough to run in real time with minimum CPU load. This fact is especially important in VR applications. In order to fully simulate the sound of an electric guitar the output of the Karplus-Stong algorithm was passed through a Wampler SLOstortion high gain drive pedal before being played back through a VOX HC-30 guitar combo amplifier. The pedal was set on overdrive mode with parameters matching the sound of the real guitar present in the training session, that was connected to the same amplifier, but on a different channel.

The visual stimuli presented an electric guitar which was created using the Unity 3D and displayed using an Oculus Rift CV1 head mounted display.

4. METHOD AND MATERIALS

As suggested, the aim of the study was to (1) evaluate the perceived realism of the proposed system and (2) to explore the relative importance of force and vibrotactile feedback as elements for the creation of a realistic experience of plucking strings while interacting with a virtual guitar. To meet this aim, we performed a within-subjects study comparing four conditions that varied in terms of the haptic feedback provided when users plucked virtual strings: no haptic feedback (N), vibrotactile feedback (V), force feedback (F), and a combination of force and vibrotactile feedback (FV).

4.1 Participants

A total of 29 participants (26 male, 3 female) aged between 19-44 years (M=28.2 years, SD=7.0) took part to the study. All participants were faculty or students at Aalborg University Copenhagen. On average, the participants had 8.2 years (SD=8.3) of regular, weekly practice playing a music instrument, they played 2.4 hours (SD=2.6) each week, and 21 participants reported being able to play one or more string instruments. All participants gave written informed consent prior to participation.

4.2 Procedure and Task

Initially the participants completed a questionnaire covering demographic information (i.e., age, gender, occupation, and musical experience). They were then introduced to the setup and task. They were informed that the study was exploring the perceived realism of virtual strings and were instructed to pay particular attention to the haptic sensations experienced during each condition. No information was provided about the variations in feedback across conditions).

Because the aim of the study was to explore changes in realism across the four conditions, the participants were asked to pluck the strings of a real guitar before exposure to the first condition. They were instructed to pluck all six strings and were allowed to do so for no more than three minutes. It was made explicit to the participants that this task was meant as a baseline for comparison during the four conditions, and that they should pay attention to the sensation of touching the real strings, including sense of stiffness (i.e., the strings resistance to deformation).

During each condition, the participants were required to pluck each of the six strings twice in randomized order. The string the participants should pluck was visually highlighted. Subsequently, the participants were asked to freely interact with the virtual strings and they were encouraged to both pluck individual strings and perform strumming interactions. After exposure to each condition the participants were required to fill out a questionnaire related to their experience (see Section 4.3).

The participants were exposed to the four conditions in randomized order, and the study lasted for approximately 20 minutes in total.

4.3 Measures

Because the primary aim of the study was to determine how realistic the participants found the four conditions, we primarily relied on self-reported measures. Specifically, after exposure to each condition the participants were asked to fill out a questionnaire including eight items related to their experience of interacting with the virtual strings. The eight items can broadly be divided into four categories:

- *Perceptual similarity:* Two items required the participants to explicitly compare the real and virtual strings in terms of (a) overall similarity and (b) stiffness.
- *Perceived realism:* Three items asked the participants to evaluate (c) the overall experience of realism, (d) the sensation of touching physical strings, and (e) the sensation of hearing physical strings.
- *Perceived thickness:* Two items asked the participants evaluate (f) the connection between the thickness of the virtual strings and the sensation of touching them, and (g) the connection between the thickness of the virtual strings and sounds they generated.

Table 1. The eight questionnaire items and corresponding anchors of the 7-point (1-7) rating scales.

Questionnaire items:	Scale anchors:
Perceptual similarity:	
(a) The sensation of touching the virtual and real strings was:	Completely different / Identical
(b) Compared to the real strings, the stiffness of the virtual strings was:	Much lower / Much higher
Perceived realism:	
(c) I found the experience of interacting with the virtual guitar realistic.	Strongly disagree / Strongly agree
(d) It felt as if I was touching physical strings.	Strongly disagree / Strongly agree
(e) I felt like I was hearing physical strings.	Strongly disagree / Strongly agree
Perceived thickness:	
(f) It felt as if there was a connection between the thickness of the strings and how they felt.	Strongly disagree / Strongly agree
(g) It felt as if there was a connection between the thickness of the strings and the sounds.	Strongly disagree / Strongly agree
Perceived ease of use:	
(h) I found it easy to pluck the strings of the virtual guitar.	Strongly disagree / Strongly agree

- *Perceived ease of use:* Finally, one item (h) asked the participants to evaluate how easy they found it to interact with the virtual guitar.

All eight questions were answer using 7-point rating scales, ranging from 1 to 7. Table 1 presents the eight questions and the corresponding scale anchors.

In addition to the questionnaire administered after each four conditions, we also asked the participants to indicate which of the four the preferred once they had tried them all. Moreover, the participants were encouraged to explain their preference.

Finally, to determine whether the addition of more haptic feedback would positively affect the participants ability to pluck the virtual strings, we logged the number of erroneously plucked strings during the part of each trial where the participants had to pluck predefined strings. Impacts between the virtual plecturm and strings were considered errors, if they occurred after the correct string had been plucked and before a new string was highlighted. We deliberately ignored errors made prior to the participants plucking the correct string, as these errors were more likely to result from visual misperception. That is, errors occurring prior to initial contact with a highlighted string were likely the result of incorrect visuomotor coordination, rather than the sensation of the haptic stimuli itself. Conversely, errors occurring after a highlighted string had been plucked could be the result of an inability to perceive the haptic stimuli produced while plucking.

5. RESULTS

This section presents the results obtained from the self-reported measures pertaining to the participants' experience and the behavioral measure related to the number of errors performed during exposure to each condition.

5.1 Self-reported measures

The data obtained from the eight questionnaire items were treated as ordinal and analyzed using Friedman tests. When statistically significant differences were found pairwise comparisons using Dunn-Bonferroni tests were performed.

Perceptual similarity: A statistically significant difference was found in relation to *overall perceptual similarity* ($X^2(3) = 15.152, p = .002$) and the pairwise comparisons identified a statistically significant difference between N and F ($p = .031$), and between N and FV ($p = .004$). In both cases N yielded significantly lower scores (Figure 3a).

Similarly, a statistically significant difference was identified in regard to *stiffness relative to physical strings* ($X^2(3) = 17.831, p < .001$), and the pairwise comparisons found between N and F ($p = .003$), and between N and FV ($p = .007$). N yielded significantly lower scores (Figure 3b). Note that both F and FV had a median score of 4, suggesting that the two conditions may have provided the greatest resemblance with the physical string in terms of stiffness.

Perceived realism: A statistically significant difference was found between the scores related to *overall realism* ($X^2(3) = 11.757, p = .008$), and the pairwise comparisons indicated that the participants scored FV significantly higher than N ($p = .026$), as apparent from Figure 3c.

The statistical comparison also indicated that the scores differed significantly with respect to the participants' *sensation of touching physical strings* ($X^2(3) = 18.253, p = .005$), and the pairwise comparisons indicated significant differences between N and F ($p = .008$), and between N and FV ($p = .003$). Again, N yielded significantly lower scores than F and FV (Figure 3d). As indicated by Figure 3e, no significant difference was found in relation to the item pertaining to the participants' sensation of *hearing physical strings* ($X^2(3) = 1.159, p = .763$).

Perceived thickness: A statistically significant difference was found between the scores related to the *perceived connection between string thickness and touch* ($X^2(3) = 12.641, p = .005$), and the pairwise comparisons suggest that participants rated FV significantly higher than N ($p = .019$), as apparent from Figure 3f. No significant difference was found with respect to the item related to *perceived connection between the thickness and the produced sound* ($X^2(3) = 5.260, p = .154$).

Perceived ease of use: No signficant difference was found between the scores related to *percevieved ease of use* (($X^2(3) = 2.026, p = .567$)), which are summarized in Figure 3h.

Preference rating: When asked to select their preferred condition technique 41.4% (12 participants) chose FV, 37.9%

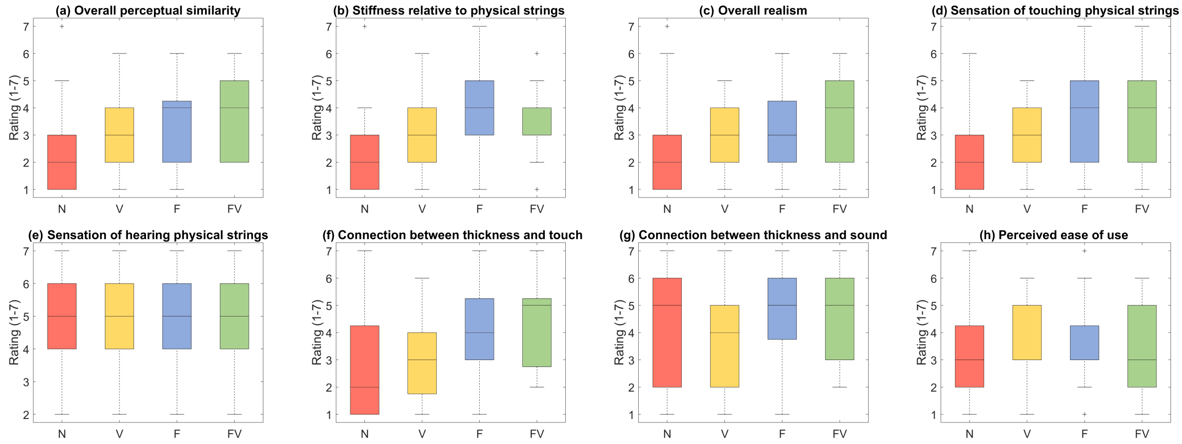

Figure 3. Boxplots visualizing the results related to the eight questionnaire items in terms of medians, interquartile ranges, minimum and maximum ratings, and outliers.

(11 participants) chose F, 10.3% (3 participants) chose V, 3.4% (1 participants) chose N, and 6.9% (2 participants) had no preference. A Cochrans Q test was run to determine if the percentages of participants who chose each condition differed. Sample size was adequate to use the χ^2-distribution approximation. The Cochrans Q test suggested that the difference was statistically significant ($\chi^2(4) = 19.103, p = .001$). Pairwise comparisons using Dunn-Bonferroni tests revealed significant differences between FV and N ($p = .012$), and between F and N ($p = .033$).

5.2 Number of Errors

One participant was excluded from this analysis because the data obtained during one of the four conditions was corrupted. The results of the behavioural measure of the number of erroneously plucked strings was treated as interval data. However, the data did not meet the assumption of normality, as assessed by Shapiro-Wilk test ($p > .05$), and significant outliers were identified, as apparent from the boxplot in Figure 4. Thus, the data was analyzsed using non-parametric methods.A Friedman test indicated that number of errors differed signficantly between conditions ($X^2(3) = 11.170, p = .011$) and pairwise comparisons using Dunn-Bonferroni tests indicated that FV yielded significantly fewer errors than N ($p = .047$).

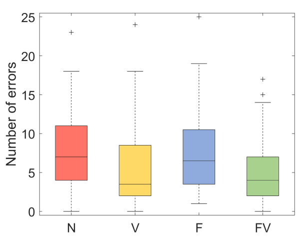

Figure 4. Boxplots visualizing the results related number of errors items in terms of medians, interquartile ranges, minimum and maximum ratings, and outliers.

6. DISCUSSION

The results related to *overall perceptual similarity* suggest that the sensation of plucking the virtual strings resembled its real world counterpart the most, when the simulation involved force feedback (i.e., both F and FV were significantly different from N). Based on the distribution of ratings (Figure 3a) it is apparent that some of the participants rated FV higher than F. However, no statistically significant difference between the two conditions was found. Moreover, the distributions of scores were relatively similar for F and V. It should be stressed that the median score for FV only was 4, suggesting that the participants did not experience a high degree of perceptual similarity. Future studies are necessary to determine if more elaborate string synthesis models yield more convincing results or if the scores can be attributed to limitations of the haptic rendering.

The conditions involving force feedback also provided the best match to the real guitar strings in terms of *stiffness relative to physical strings* (Figure 3b). That is, both F and FV had a median scores of 4, which indicates that the stiffness of the stings was not perceived as much higher or much lower than the stiffness of the real guitar strings.

The scores pertaining to *overall realism* (Figure 3c) indicate that the participants found the experience to be the most realistic when exposed to FV (FV was the only condition that differed significantly from N). Moreover, when the participants were asked about the degree to which they had a *sensation of touching physical strings* (Figure 3d), both F and FV yielded the highest median scores (both differed significantly from N).

The four conditions yielded largely identical and relatively high scores in relation to the self-reported *sensation of hearing physical strings* (Figure 3e). We take this to mean that most participants felt that the auditory feedback sounded as if it was generated by a physical string rather than an algorithm. It is hardly surprising that no difference was found between the four conditions, because the same auditory feedback was used across all conditions.

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Based on the questionnaire item related to the perceived *connection between the thickness and touch* (Figure 3f), it would appear that the participants may have perceived the virtual strings as having different thicknesses when exposed to FV. Even though a significant difference only was found between FV and N, it is worth noting that FV is the only condition that yielded a median score higher than 4.

The results related to the *connection between thickness and sound* (Figure 3g), indicate that the participants to some extent experienced a connection between the thickness of the strings and the sound that was produced when they were plucked. However, no significant differences between conditions were found. Moreover, the spread of the scores was relatively large with respect to N and V. It is possible to offer at least two possible explanations for the large spread. That is, it is possible that the phrasing of the question prompted some participants to compare the sound to the visual appearance of the strings, while other may have compared the sound the haptic sensation of the strings. For that reason, we are reluctant to draw any conclusions from these results.

The finding that the simulations involving force feedback provided the most compelling experience is corroborated by the preference ratings and the associated qualitative feedback. That is, the majority (23/29) of the participants preferred the two conditions involving force feedback, but an almost equal number of participants preferred FV (12/29) and F (11/29). Notably, 4 out of the 11 participants who preferred F, explicitly stated that they chose F over FV because the vibration had been too strong. Of the 11 participants who preferred FV, 7 participants remarked that the vibration either made the haptic sensation of plucking the strings more realistic or added to the sense that the friction varied. Thus, the participants were somewhat conflicted about the contribution of the vibrotactile feedback, suggesting the need for future studies exploring variations in vibration intensity.

No differences were found in relation to *perceived ease of use* (Figure 3h). However, we did observe a significant difference with respect to the number of erroneously plugged strings after the correct string had been plucked (Figure 4); namely the participants plucked significantly fewer errors during FV compared to N. Moreover, even though no significant differences were found between V and the other conditions, it is worth noting that V appears to have yielded fewer errors than both N and F. In other words, the two conditions devoid of vibrotactile feedback resulted in the highest number of errors. It is possible that the added vibrations made the impact between the virtual plectrum and string more salient, and thus causing the participants to retract their hands more swiftly.

7. CONCLUSION

In this paper we proposed a system that allows users to pluck virtual guitar strings while receiving multisensory feedback in response to this interaction. The system was evaluated in a user study exploring the perceived realism of the simulation and the relative importance of force and vibrotactile feedback. The results indicate that the two conditions involving force feedback provide the highest degree of perceptual similiarlity to real guitar strings. While no significant differences were found between the two conditions, the condition including both force and vibrotactile feedback yielded scores indicating that it was the best at mimicking interaction with real guitar strings. The self-reported measures related to overall realism yielded similar indications. However, the participants scored the two approaches similarly when they were asked to what extent they felt that they touched real strings. The absence of significant differences between the three haptic conditions, makes it uncertain whether force or vibrotactile is the most important for a realistic experience. Nevertheless, judging by the distribution of scores and the preference ratings, force feedback appears to be central to the participants' experience of realism, and we suspect that the combination of force and vibrotactile feedback may serve as the best proxy for physical strings. It is encouraging that the vibrotactile condition generally scored higher than the condition devoid of any haptic feedback. However, future studies involving a wider range of vibrotactile feedback are necessary in order to determine if vibrotactile feedback will suffice in and of itself. Particularly, it is necessary to compare variations in the algorithm rather than just comparing the presence and absence of vibrotactile feedback. Finally, no differences were observed with respect to perceived ease of use, but the behavioral measure provides some indication that vibrotactile feedback may decrease the risk of accidentally hitting strings after the intended string has been plucked. Thus, even if vibrotactile feedback may be less important than force feedback with respect to perceived realism, it is possible that it can help reduce the number of incorrectly plucked strings.

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