Discriminating tactile speed in absence of raised texture elements: Role of deformation and vibratory cues

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Abstract

Motion encoding in touch relies on multiple cues, such as displacements of traceable texture elements, friction-induced vibrations, and gross fingertip deformations by shear force. We evaluated the role of deformation and vibration cues in tactile speed discrimination. To this end, we tested the discrimination of speed of a moving smooth glass plate, and compared the precision of the responses when the same task was performed with a plate having a fine texture. Participants performed the task with and without masking vibrations. Speed discrimination was nearly as precise among the two surface types, as assessed by the steep slope of the psychometric function. Consistent with our previous work, high-frequency vibrations impaired the ability of the participants in discriminating surface speed. Results of the current study showed that it is possible to discriminate motion speed even in absence of a raised texture.

Keywords: Speed Discrimination, Slip Motion, Glass, Masking Vibrations

1 Highlights

- 2 • On a smooth surface, humans are able to discriminate the speed of a
- 3 moving surface by frictional motion cues
- 4 • The precision of speed discrimination is nearly the same with smooth
- 5 and fine-textured surface types

- 6 • High frequency vibrations impair the ability to discriminate speed of
7 moving surfaces

8 **Introduction**

9 It has been argued that motion is as important to touch as light is to
10 vision [1]. Tactile motion plays a central role in perceptual and motor tasks.
11 It provides feedback for the manipulation of handheld objects [2], and for
12 guiding hand reaching towards a target goal while touching a surface [3,
13 4]. During grasping tasks, our sensorimotor system rapidly adjusts the grip
14 force based on the small slips between the object and the skin, revealed as
15 vibrations [5].

16 Different cues contribute to the perception of motion in touch, includ-
17 ing the spatiotemporal pattern of skin indentation, as for example the one
18 generated by the tip of a pencil moving across the skin, high-frequency vi-
19 brations caused by frictional slips, and the gross deformation of the skin
20 and subcutaneous tissues, such as the stretch generated by a shear force
21 applied to the fingertip [6, 7, 8, 9, 10]. The role of the first two motion
22 cues, local indentation and vibrations, was investigated in several studies
23 [11, 12, 13, 14, 15, 16, 17, 18]. Here, we investigated the discrimination of
24 speed of a smooth movable surface (i.e., a glass plate for microscope slide).
25 Because of the lack of fine and coarse texture, shear deformation cues may
26 play an important role for this type of stimuli. Before introducing our study,
27 we will summarize recent findings about different cues in tactile motion per-
28 ception.

29 The indentation produced by traceable surface elements, like raised ridges
30 of the tip of a pen, provide a salient motion cue in touch [6, 11, 13]. For
31 instance, the perceived speed of a ridged surface depends on the distance
32 between its ridges, such as the closer the texture elements, the faster is
33 the perceived speed [12, 19]. In accordance with behavioral studies, a model
34 based on the spatiotemporal pattern of skin deformation, as the one produced
35 by a coarse texture, accurately reproduced tactile afferent signals [20]. In
36 addition, the somatosensory system uses heuristic cues arising from frictional
37 skin vibrations that are generated by sliding across or tapping against the
38 surface of an object [21, 14, 16]. Frictional vibrations play an important
39 role in motion detection, speed discrimination, and roughness discrimination
40 [6, 22, 17, 18]. Their importance as a motion cue has been demonstrated
41 mostly during slip motion on fine texture surfaces, lacking traceable elements,

while their role is likely to be less relevant on surface with coarse textures [6, 17]. A third type of motion cues are referred to as gross deformation cues, such as the tangential stretch of the skin caused by shear force and the transition from stick to slip between the skin and a surface [6, 10, 23]. A smooth glass plate, lacking fine and gross texture elements, has been used to investigate deformation cues [6, 10]. For light touch, i.e., for a normal force equal to 0.2 N, the slip of a smooth glass plate is indistinguishable from simple skin stretch [6]. Instead, it is possible to detect slip and partial slip of a glass surface at higher values of normal force, ranging from 2 to 5 N [10]. These behavioral results complement electrophysiological recordings of the afferent fibers. A moving glass plate elicits only a weak response in fast adapting fibers during light touch [6], whereas, for a normal force up to 4 N, nearly all afferents respond to tangential strain, and their response is broadly tuned to a preferred direction of force [24].

Here, we aimed to further investigate the role of deformation and vibration cues for motion encoding in touch. To this end, we tested the discrimination of tactile speed on a smooth glass plate. From the precision of the response, it is possible to estimate to which extent participants were able to discriminate surface speed in absence of raised texture elements. For comparison with previous studies, the task was replicated using a surface with a homogeneous texture similar to the one used by [17, 25]. In both surface conditions, high-frequency vibrations were delivered synchronously with surface motion in half of the trials. This was to investigate the possible interplay between deformation and vibration cues. If these two cues were processed in separate channels, and speed discrimination on a smooth plate depended on deformation cues only, masking vibrations should affect the precision of the response on the textured but not on the smooth plate. Otherwise, this would speak in favor of an interplay between vibration and deformation cues, which may occur at a mechanical or at a neural level. The role of contact force in this task was investigated systematically in a second experiment.

1. Experiment 1: Speed discrimination on smooth and textured surfaces

In the first experiment, we investigated the speed discrimination on a movable smooth surface (microscope glass plate) and compared these results against the speed discrimination on a fine textured surface (3D-printed

77 Polylactic Acid plate). The effect of masking vibrations in the two surface
78 conditions was also assessed.

79 *Methods*

80 *Participants.* Fifteen naïve, right-handed participants took part in the exper-
81 iment (10/15 females, age ranging from 20 to 36 years; 13 naïve participants
82 plus author AM and CPR). The testing procedures were approved by the
83 ethics committee of the Santa Lucia Foundation, in accordance with the
84 guidelines of the Declaration of Helsinki for research involving human sub-
85 jects. Informed written consent was obtained from all participants involved
86 in the study.

87 *Apparatus.* A motion device displaced the contact surface up and down at
88 the required speed (Figure 1A-B). The motion device consisted of two rollers
89 with a rigid plane in between, rotating a plastic belt (270 mm length x 30
90 mm width). The two rollers were vertically aligned and the downward roller
91 was connected with a metal shaft to a Faulhaber motion control system.
92 This included a DC-Micromotor (Faulhaber 3242G024CR combined with 7:1
93 Gearheads 32A), a high-resolution encoder (Faulhaber IE3-512), and a po-
94 sition and speed controller (Faulhaber MCDC3006SRS). A rigid plastic box
95 having a cuboid shape (75 x 20 x 20 mm) was attached to the belt. This
96 way, the rotation of the motor produced a vertical displacement of the box.
97 We assembled two boxes having a contact surface of different materials, glass
98 and plastic. The base of each box was interlocking with a basement firmly
99 attached to the belt, so that they could be easily changed between two exper-
100 imental blocks. The contact surface was either a smooth glass plate (75 x 25
101 x 1.5 mm) or a plastic plate (75 x 20 x 1.5 mm). The glass plate was the one
102 used for microscope slides and had no detectable features on its surface. The
103 plastic plate was printed in Polylactic Acid (PLA) using a 0.4 mm diameter
104 nozzle, which produced a fine homogeneous texture on its surface. To detect
105 contact, a force resistive sensor was placed between the box and the contact
106 surface (Interlink 402 force resistive sensor connected to a Arduino UNO mi-
107 crocontroller). Prior to the experiment, the contact sensor was calibrated by
108 means of a set of calibration weights, ranging from 0.98 to 4.9 N. For a more
109 accurate measurement of contact force, the FSR was replaced with a Load
110 Cell in Exp. 2 (Fig. 1B). A vibromotor (Haptuator Mark II by TactileLabs,
111 connected to MAX9744 audio amplifier by Adafruit) was placed in a small
112 niche inside the box to generate masking vibrations. Vibration stimuli were

113 generated by a standard PC audiocard (HDA Intel PCH). Masking vibra-
 114 tions were recorded with an accelerometer attached to the contact plate to
 115 measure the amplitude and frequency of the signal (Fig. 2). A custom-made
 116 Matlab code controlled the vibration and the motion stimuli. A one degree
 117 of freedom finger holder was attached to the frame of the setup, supporting
 the participant's finger.

Figure 1: Experimental setup. A) The setup including the actuated box, the vibromotor and the force sensor. Two boxes having a glass or a plastic contact plate were used in two experimental blocks. B) Exploded drawing of the device (modified version used in Exp. 2). C) Motion, vibration and force profile in a single trial. In the upper panel, positive values of velocity correspond to downward motion and negative values to upward motion. Measured and target values are represented in black and in red, respectively. To prevent using motion duration as a cue, path length was randomized across trials. Middle panel: In half of the trials, high-frequency vibrations were presented while the participant contacted the plate (vibration condition). Vibration amplitude was set to zero in the other half of the trials (control condition, not shown in the figure). Vibration onset and offset was synchronized with the initiation and the cessation of contact. The lower panel shows the contact force. Raw and filtered data are represented in red and in black, respectively

118

Figure 2: Masking vibrations: x, y, and z acceleration component. Vibrations were recorded with an accelerometer (ADXL337 connected with an Arduino UNO microcontroller, sampling rate 360 Hz) attached to the contact plate, and processed with Fast Fourier Transform.

119 *Stimuli and Procedure.* Participants sat on an office chair in front of the ap-
 120 paratus, resting their right index finger on the finger holder. A black curtain
 121 hid the device from the participants' sight. Throughout each experimen-
 122 tal session, participants wore earplugs and headphones playing pink noise
 123 in order to mask external sounds. Participants performed a forced-choice,
 124 speed discrimination task. The advantage of using a discrimination task is
 125 that, differently from a yes/no detection task, the response is less bias-prone,
 126 i.e., it does not depend on the decision criterion. Each experimental session
 127 consisted of 240 trials divided into two blocks. In each block, participants
 128 performed the experiment either with the smooth glass plate or with the tex-
 129 tured plastic plate. The order of the two blocks was counterbalanced across
 130 participants.

131 The experimental procedure was based on the method of constant stimuli.
 132 The sequence of the stimuli in a trial is illustrated in Fig. 3 and Fig. ??.
 133 Each trial included a reference and a comparison stimulus. The order of the
 134 two was counterbalanced across trials. We instructed participants to push
 135 on the contact surface with their index finger to start the tactile stimulus.
 136 The servomotor and the vibromotor were actuated when the normal force
 137 (averaged across the last 20 ms) exceeded the threshold value of 1.5 N. The
 138 surface moved either upward or downward, with the motion direction of the
 139 second stimulus always being the opposite of first one. The motion speed was
 140 equal to 3.43 cm sec^{-1} in the reference stimulus, and it was pseudo-randomly
 141 chosen between five values ranging from 0.63 cm sec^{-1} and 6.24 cm sec^{-1} in
 142 the comparison. After each trial, participants reported whether the surface
 143 moved faster in the first or in the second stimulus interval. To prevent using
 144 motion duration as a cue, the path length of stimulus was pseudo-randomly
 145 chosen within a range of 10-14 mm. In half of the trials, masking vibrations
 146 consisting of a 100 Hz sinusoidal wave were delivered synchronously with the
 147 motion stimulus (Fig. 3).

148 *Analysis.* We analyzed categorical responses by means of Generalized Linear
 149 Mixed Models (GLMM) [26], separately for each surface type, glass and plas-
 150 tic. We included the motion speed (S) and the presence/absence of vibration
 151 ($V = 0$ without vibration and $V = 1$ otherwise) as fixed-effect predictors.

$$\Phi^{-1}[P(Y = 1)] = \beta_0 + \beta_1 S + \beta_2 V + \beta_3 SV + \vec{u}, \quad (1)$$

152 where $P(Y = 1)$ was the probability of reporting that the comparison was
 153 faster than the reference. Fixed-effect parameters were denoted with Greek

Figure 3: Experimental procedure. A) Control condition B) Masking vibration condition

letter $\eta_{1,\dots,4}$ and random-effect parameter vector with the lowercase letter $\vec{u}$. The parameter β_1 (referred to as the model slope) estimates the reliability of the response in the control condition (without vibrations). With vibrations, the model slope was equal to $\beta_1 + \beta_3$. For comparison with previous studies, we computed the Just Noticeable Difference ($\text{JND} = 0.625/\beta_1$), the Weber Fraction ($\text{WF} = \text{JND}/3.43$, which is the value of the reference speed), and the related 95% Confidence Interval (CI) by means of the bootstrap method explained in [26]. Next, we applied the following model to compare the response between the two surface types:

$$\Phi^{-1}[P(Y = 1)] = \eta_0 + \eta_1 S + \eta_2 V + \eta_3 G + \eta_4 SV + \eta_5 SG + \vec{u}, \quad (2)$$

This corresponds to a 2x2 factorial design (2 surface types x 2 vibration conditions). Model (1) and (2) were selected among a pool of nested models based on the Akaike Information Criterion (AIC) and likelihood ratio test (LR test). The R packages *lme4* and *MixedPsy* were used to fit the GLMMs [27, 26].

Power Analysis. We performed the power calculation by using the R package *simr* [28]. We assumed a sample size equal to 15 participants, 60 trials each (corresponding to trial repetitions in each experimental condition), and effect size equal to 0.40 (slope of the model, or β_2). With these parameters, statistical power of the GLMM would be above 80%. This sample size is in accordance with the one reported in similar studies in the literature [17, 10, 29].

Results

The first aim of this study was to test whether participants were able to discriminate the motion speed of the smooth glass surface, with the fine plastic surface serving as control. As illustrated in Figure 4, participants were able to perform the task with either of the two types of surface. Without masking vibrations, the parameter of slope in Eq. (1) was significantly larger than zero with the smooth glass plate ($p < 0.001$; 0.65 ± 0.079 , $\beta_{1(\text{glass})} \pm \text{Std. Error}$) and with the homogeneous-textured plastic plate ($p < 0.001$; 0.75 ± 0.10 , $\beta_{1(\text{plastic})} \pm \text{Std. Error}$). This means that, differently from previous studies on the detection of slip motion, participants discriminated the motion speed of the smooth glass plate, well-above chance level.

Figure 4: Results. A) Psychometric functions in a representative participant, raw data and GLMM fit (glass surface). Control condition and masking vibrations condition are represented in light and dark grey, respectively. B) The bar plot shows the estimated slopes in the control (light grey) and masking vibration conditions (dark grey) in Exp. 1, separately for the glass and PLA surface (GLMM estimates to 15 participants). The error bar represents the 95% confidence interval estimated with the bootstrap method. C) The bar plot shows the estimated slopes in the control and masking vibration conditions in Exp. 2 (GLMM estimates to 6 participants).

186 With the glass plate, tactile speed discrimination was impaired by high-
 187 frequency vibrations. Accordingly, the slope was significantly smaller with
 188 masking vibrations compared to control ($p < 0.001$; -0.20 ± 0.048 , $\beta_{3(glass)} \pm$
 189 Std. Error). The same effect of masking vibrations was observed with the
 190 plastic surface ($p = 0.002$; -0.16 ± 0.05 , $\beta_{3(plastic)} \pm$ Std. Error). Results
 191 are illustrated in Figure 4A-B, in a representative participant, and in Figure
 192 4C for the whole population. We evaluated the difference between the two
 193 surface conditions by means of the GLMM in Eq. (2). The precision of
 194 the response, although higher with the plastic interface, was not significantly
 195 different between the two surfaces ($p = 0.06$; 0.057 ± 0.031 , $\eta_5 \pm$ Std. Error).¹
 196 For comparison with previous studies, the values of JND in the four ex-
 197 perimental conditions are reported in Table 1, along with the related 95%
 198 CI. With the fine plastic surface and in absence of vibrations, the value of
 199 Weber Fraction, $WF = JND/V_{ref}$, is equal to 0.26, which is close to the
 200 ones reported in previous studies where the skin was stimulated either with
 201 a sandblasted surface or with a brush [30, 25, 17].

Estimate	Inferior	Superior	Parameter	Vibration	Surface
1.03	0.82	1.33	JND	no	Glass
1.48	1.13	2.10	JND	yes	Glass
0.90	0.71	1.13	JND	no	Plastic
1.15	0.86	1.69	JND	yes	Plastic

Table 1: Experiment 1: Values of Just Noticeable Difference (JND) in the four experimental conditions. Estimates and 95% CI estimated with the bootstrap methods from the GLMM.

202 2. Experiment 2: Evaluating Contact Force

203 According to previous literature, tactile discrimination of motion may
 204 change depending on the level of normal force. For comparison with previous
 205 studies, we replicated the task (only on the glass plate) and replaced the force
 206 resistive sensor in the apparatus with Load Cell that provides a more accurate
 207 measurements of force.

¹The estimated values of η_5 is slightly smaller than the difference between $\beta_{1(glass)}$ and $\beta_{1(plastic)}$. This is due to the choice of the random-effect parameters in Eq. (2).

208 *Participants.* Six right-handed participants took part in the experiment (2/6
209 females, age ranging from 22 to 38 years; 4 naïve participants plus author
210 AM and CPR).

211 *Apparatus.* The apparatus was similar the one in Exp. 1. This time, a
212 load cell (LC, CZL616C Micro Load Cell by Phidgets Inc) combined with
213 LC amplifier (HX711 Load Cell amplifier, sampling frequency: 80 *Hz*) was
214 used to measure contact force (Fig. 1A-B). The specifics of the LC are the
215 following: repeatability error: 390 *mg*; maximum weight capacity: 780 *g*.
216 Force values were read by Arduino UNO by using the HX711 Arduino Library
217 to interface with the amplifier.

218 *Stimuli and Procedure.* The same procedure of Exp. 1 was used. This time,
219 only the smooth glass surface was tested.

220 *Analysis.* As for Exp. 1, the perceptual response of individual participants
221 and population were fitted with GLM and GLMM, respectively. As in our
222 previous study [31], force signals were filtered using a second order, Butter-
223 worth low-pass filter (cutoff frequency equal to 10 *Hz*). An example of raw
224 data and filtered data is illustrated in Fig. 1C. In each trial, we saved the
225 peak of the filtered signal for additional analyses.

226 *Results*

227 *Speed Discrimination.* Categorical responses were in agreement with the pre-
228 vious experiment. Participants were able to discriminate the velocity of
229 the glass plate; perceptual judgments were less accurate with masking vi-
230 brations. In the condition without vibration the slope of the GLMM was
231 0.96 ± 0.10 . The estimated value of the slope is significantly different from
232 zero ($p < 0.0001$). The slope in the condition without vibration is signifi-
233 cantly steeper from the slope in the condition with vibration, the difference
234 in slope being equal to 0.41 ± 0.01 ($p < 0.0001$). This is illustrated in Fig
235 4C showing the estimates of the slope of both conditions with and with-
236 out masking vibrations present. Consistently with Exp. 1, in conditions
237 involving masking vibrations, participants were less precise in discriminating
238 speed and so had a decreased slope. This is also showed in Table 2 where
239 we reported the estimated values of JND in the two conditions (bootstrap
240 estimates and 95% CI).

Estimate	Inferior	Superior	Par	Vibration	Surface
0.70	0.55	0.82	JND	no	Glass
1.32	1.06	1.61	JND	yes	Glass

Table 2: Experiment 2: Values of Just Noticeable Difference (JND) in the two experimental conditions. Estimates and 95% CI estimated with the bootstrap methods from the GLMM.

241 *Contact Force.* By means of the force sensor, we measured the force profile
 242 for each trial and in each participant. Fig. 1C shows the force profile of
 243 one trial in a representative participant. The two peaks of force represent
 244 the maximum force in the reference and comparison stimulus. Between the
 245 two stimuli, the force is zero because the participant was required to release
 246 contact from the plate.

247 For each participant and trial, we saved the peak of force profile for
 248 further analysis. Fig. 5 illustrates the distribution of force peak in the
 249 six participants. The median value of force peak ranged from 2.6 to 4.1
 250 N across participants (colored line in the figure). These values are within
 251 the range reported in previous studies investigating simulated and natural
 252 manipulations [5, 32, 10].

253 Discussion

254 We investigated the ability of human participants to discriminate the mo-
 255 tion speed of a smooth glass plate using touch. Participants were surprisingly
 256 good at this: Their responses were only 13% less precise when compared to
 257 a control condition, where the motion stimuli were delivered with a plastic
 258 plate having a fine texture (Exp. 1). This has important implication for
 259 models of motion encoding in touch, because it shows that rich perceptual
 260 information is provided even in absence of fine and coarse texture elements.
 261 Contact force as measured in Exp. 2 was within a range typical of grasp and
 262 manipulation tasks.

263 The current findings raise the question of which are the tactile cues that
 264 convey motion information in absence of detectable texture elements. A
 265 recent study suggested that the brain uses a deformation-based mechanism
 266 for slip detection on smooth surfaces [10]. Fingertip shearing caused by a
 267 stroking glass plate is related to surface displacement, as long as the finger
 268 is not fully slipping against the plate. Additionally, the skin in contact with
 269 the plate undergoes deformations due to partial slips. In [10], the authors

Figure 5: Distribution of the force peak across participants. Values from different participants are illustrated each with a different color. The solid colored lines are the median values.

270 hypothesized that shearing and partial slip may play a role in slip detection
 271 [10]. Likewise, speed discrimination on smooth surfaces may be partially
 272 based on deformation-rate cues, such as fingertip shearing rate and the onset
 273 of the stick-to-slip transition.

274 Frictional vibrations provide a second class of motion cues in touch. These
 275 play an important role in motion detection and for the discrimination of stim-
 276 ulus features like speed, roughness, and texture [6, 22, 15, 17]. Recent findings
 277 showed that the responses of Pacinian fibers are strongly modulated by the
 278 speed of the moving surface, supporting the hypothesis that the vibration
 279 spectrum may provide an auxiliary cue to motion speed [18]. Additionally,

during tool use they allow us to discriminate the texture of a surface sensed with a probe, and the position on the probe where it impacts with an object [33, 34]. In a previous study we described a masking effect of vibrations by using either a fine (sandblasted billiard ball) or a coarse texture surface (raised ridges) to deliver the motion stimuli [17]. This masking effect was numerically larger on the fine texture. Likewise, masking electrovibrations impair sharpness perception on touch screen applications [35]. In the current study, we extended these results to speed discrimination on a smooth glass plate. Motion cues based on frictional vibrations and shear force are heuristics, because are not based on $\dot{x}_i$, where x_i is the position on the skin of a traceable surface element (e.g., a raised dot). We propose the term *frictional motion cues* to identify these heuristic cues in touch.

Perceptual impairment caused by masking vibrations may be explained either at a mechanical or at a neural level. The small slips between the surface and the skin revealed as skin vibration may provide auxiliary information on surface speed, and these would be masked by the high-frequency vibrations generated by the vibromotor. Masking vibrations may decrease the signal-to-noise ratio of fast adapting fibers, leading to a noisier perceptual response. At a central level, tactile motion and vibratory stimuli activates human middle temporal complex (hMT+) [36, 37]. In particular, vibratory stimuli activate the medial superior temporal area (MST), but not area MT itself [38].

The neural representation of motion in touch could be based on a within-fiber, intensity code [7, 8] and on a between-fiber spatiotemporal code [20]. The latter is defined as the sequential activation of neighboring afferent fibers in response to a traceable feature of the surface, moving across their receptive field [6, 20]. An example of spatiotemporal code is the sequential activation of fast adapting fibers (FA)-I following the motion of a surface with a single raised dot [6]. In the model proposed in [20], tactile motion arises from the responses of the fibers to a moving pattern of skin indentation, based on a spatiotemporal code. This model does not incorporate lateral sliding and the concomitant shear forces. Scanning is mimicked by moving an “image” of the indentation pattern across the skin. The brain may use an intensity code to represent surface motion from the high-frequency vibrations and the gross deformation of the skin [6, 17]. In accordance with the hypothesis of the intensity code, a brush moving across the skin at different velocities produces a modulation in mean firing rate within the single afferent fiber [7, 8]. An intensity code could also account for motion encoding on a smooth surface. Instead, in this case a spatiotemporal code is unlikely for the lack of traceable

318 elements.

319 These models postulating different motion cues and neural codes are not
320 mutually exclusive. Alike in vision, where an observer is able to perceive the
321 depth of a painting in absence of binocular cues, tactile system can encode
322 and process surface motion also when the stimulus lacks one of the redundant
323 motion cues. For instance, a moving pattern generated by a wave of vibrating
324 pins provide a vivid sensation of a moving surface, even in absence of a net
325 shear force [29, 39]. On the other hand, the results of the current study
326 suggest that vibration and deformation cues may provide rich information to
327 discriminate surface speed.

328 Conclusions

329 This and previous results showed that touch is more than an “imager”,
330 because it is possible to discriminate motion features, such as direction and
331 speed, even in absence of a texture. The different cues—spatiotemporal
332 cues, vibration, and deformation—provide redundant motion information;
333 therefore, they could be integrated for an optimal estimated of tactile motion.

334 Author Contribution

335 **Alessandro Moscatelli:** Conceptualization, Methodology, Visualiza-
336 tion, Software, Formal analysis, Writing - Original Draft, Writing - Reviewing
337 and Editing, Supervision. **Colleen P. Ryan:** Conceptualization, Investiga-
338 tion, Data curation, Writing - Original draft preparation, Writing - Review
339 and Editing. **Simone Ciotti:** Software, Methodology, Validation, Visu-
340 alization, Data curation. **Lucia Cosentino:** Software, Validation, Data
341 curation. **Marc O. Ernst:** Conceptualization, Writing - Reviewing and
342 Editing. **Francesco Lacquaniti:** Conceptualization, Supervision, Writing-
343 Reviewing and Editing.

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