Mind the spatiotemporal gap: Skin viscoelasticity limits our perception of discontinuous motion

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Abstract— **Our ability to perceive dynamic simulations on our skin is essential for interacting with our environment. The sense of touch, like vision and audition, is not a perfect sensor and exhibits perceptual thresholds that limit the resolution of both spatially distributed events, also known as the two-point threshold, and temporally distinct events, known as the gap-detection threshold. In the present study, we are interested in how these limits impact the perception of discrete moving stimuli that evolves both through time and space. We found that the spatiotemporal gap of stimulation can be masked and the preliminary results match with the prediction of a viscoelastic model of the skin, hinting at the potential role of skin mechanics in the filtering process.**

I. Introduction

Two visual stimuli sparsely spaced in space and time give us a persuasive impression of motion because the visual system blurs discrete images as a continuous moving scene [1]. The present study is interested in understanding whether similar behavior in touch is caused by the viscoelastic behavior of the skin that applies a spatiotemporal filter to the mechanical signal on the surface.

Touch is subject to finite spatial and temporal acuity. The spatial acuity depends on body location: two points threshold experiments report that two indentations of the skin spaced lower than 2 mm in the fingertip and 20 mm in the forearm can be felt as one [2]. Similarly, in time two successive stimulation can be felt as one if they are less than 30 ms apart, it is called the gap-detection threshold [3].

One hypothesis is that the mechanoreceptors buried several millimeters deep in the tissues, receive a degraded image of the mechanical interaction that happens at the surface. This degradation is caused by the viscoelastic properties of the skin that diffuse and delay stimulation, therefore acting as a mechanical filter to surface pressure.

Considering this spatiotemporal filtering, Kitagawa et al. [4] have already proved that the illusion of continuity exists in the vibrotactile domain. Moreover Cholewiak et al. [5] showed that the feeling of continuous motion depends on two parameters, the burst duration and the interburst interval.

II. Viscoelastic model of the skin

The skin can be modeled as a viscoelastic semi-infinite half plane. In this context, the spatiotemporal stimulation at the surface $p(x,t)$ is filtered spatially by continuum mechanics which will diffuse stresses $\sigma(x,t)$ deeper in the soft tissues, where the mechanoreceptors are located. These stresses change consequently the local strains, following a linear first-order viscoelastic relaxation, which will result in a temporal filtering of the original stimulation (Fig. 1a, b).

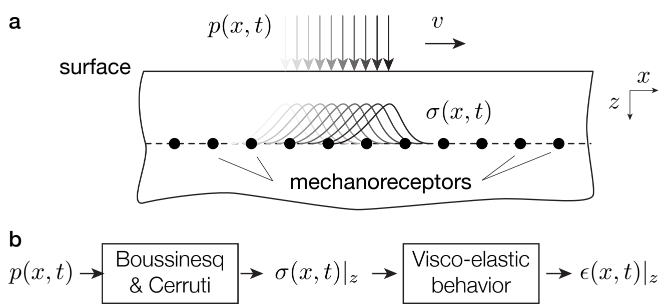

Fig. 1. **a**. Infinite half-plane model of the skin. The stress deep in the skin is a filtered version of the stimulus applied on the surface. **b**. Computation steps of the strains deep in the skin

To compute the strain to which the mechanoreceptors are sensitive to [6], the model first calculates the stress using Boussinesq and Cerruti equation [7]. This model considers that the skin is a semi-infinite homogeneous elastic medium on which a localized normal pressure $p = \delta(x)$ is applied. The equation (1) leads to the shear and compressive stresses as a function of their position x and depth z as follows:

$$\sigma_x = -\frac{2\,p}{\pi}\frac{x^2 z}{(x^2+z^2)^2} \quad \text{and} \quad \sigma_z = -\frac{2\,p}{\pi}\frac{z^3}{(x^2+z^2)^2} \quad (1)$$

These equations result in a blur of the pressure profile on the surface which diffuses the stresses on a larger area and removes the high spatial frequency content of the stimulation [8]. The stresses induce a deformation of the body which follows the viscoelastic Hooke's law. The compressive and shear strains ϵ can be expressed, in the Laplace domain, as a function of the local stresses:

$$\begin{bmatrix}\mathcal{L}(\epsilon_x)\\ \mathcal{L}(\epsilon_z)\end{bmatrix} = \frac{1}{E*}\begin{bmatrix}1-\nu^2 & -\nu(1+\nu)\\ -\nu(1+\nu) & 1-\nu^2\end{bmatrix}\begin{bmatrix}\mathcal{L}(\sigma_x)\\ \mathcal{L}(\sigma_z)\end{bmatrix} \quad (2)$$

where $\mathcal{L}$ is the Laplace transform, ν is the Poisson's coefficient and $E* = E + s\eta$ is the complex Young modulus of the skin layers, with $E = 1.1$ MPa the elastic modulus and η is the viscosity of the skin and s the Laplace operator. Time variation of the strain is computed numerically using a 4^{th}-order Runge-Kutta solver. The viscoelastic behavior leads to a low-pass filtering of the surface pressure with a cut-off frequency set to E/η = 100 Hz.

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This spatiotemporal model embodies two main characteristics of skin mechanics that could explain perceptual confounds. First, the spatial filtering provides a lower limit on the resolution of individual tactile stimulation, which could be the cause of the two-points threshold [6]. Second, the temporal filtering is also likely to impede discrimination between two successive impulses at the same location.

In realistic conditions, such as an object moving on the surface of the skin, the stimulus evolves spatially and temporally. If the velocity of the moving stimulus is constant then, a discontinuity will induce impulsive pressure on the surface which are both separated in space and time. The resulting strain in the soft tissues, 2 mm deep in the skin will be a filtered version similar to figure 2.

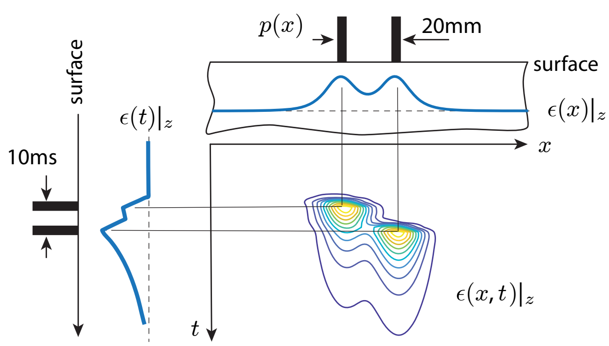

Fig. 2. Spatiotemporal representation of the normal and tangential strains applied on the surface (black bars) and 2 mm deep in the skin (blue lines and contour plots)

III. Materials and Methods

1) Stimuli: Discrete spatiotemporal stimulations was provided via a wheel rolling without slippage on the skin (Fig. 3a). The wheels were imprinted with a square-wave pattern which duty cycle (ratio between the size of the tooth and the spatial period) could be changed. The wheels were driven by a servo-controlled DC-motor (Faulhaber 2657W012CXR-275) on a linear rail and maintained at a constant normal force via a low-stiffness suspension. Participants were presented with six 50 mm-diameter wheels with a fixed tooth length and variable gap. The duty cycles of these wheels vary from 50% to 90% based on preliminary investigations, which corresponds to a range of spatial periods between 11.8 mm and 22.3 mm.

2) Psychophysical study: A 2-Alternative Forced Choice procedure was chosen. A random series of paired stimuli (one patterned and one smooth wheel) was presented to the participant's forearm. In each trial, subjects had to report which wheel was the smooth one and his/her answers were saved. Three different linear speeds were tested for each wheel: 5 cm/s, 10 cm/s and 20 cm/s.

IV. Results

The results of one participant are presented in figure 3b, c. The percentage of correct identification of the smooth wheel decreases with increasing duty cycles, for all three speeds. At the lowest duty cycle, the subject made no mistake and at the highest duty cycle, the subject made correct identification in 60% of cases. According to the method of constant stimuli, this study suggests that the limit of the spatiotemporal acuity could be located around 80% of duty cycle for the slowest speed, which translate to a gap of 2.7 mm. This first result does not allow us to conclude for the higher speed.

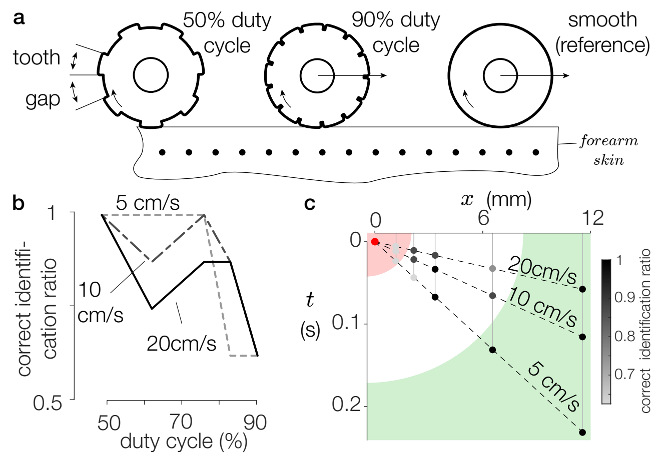

Fig. 3. **a** Schematics of the presented stimuli. Trajectories follow a no-slip condition. **b** Psychometric curve on one subject **c** Correct identifications ratio in the space-time domain with respect to the initial contact (red dot). In the red zone, the ratio is under 60% and in the green zone, the subject was always correct

V. Discussion and Conclusion

The pilot study conducted extends the notion of two points threshold to discontinuous mechanical events that evolve both in time and space. Preliminary results are consistent with the hypothesis that the viscoelastic behavior of the skin acts as a filter that blurs the mechanical stimulation on the surface. However a wide range of subject is needed to validate it. While this study focused on square-wave signals, the approach can be extended to richer spatiotemporal signals.

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