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Fingertip Skin As a Linear Medium for Wave Propagation

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Abstract— **The skin is the medium that conveys tactile information arising from mechanical interaction with the environment. Several prior studies have demonstrated that mechanical waves propagating from the region of contact carry significant tactile information far away from the region of contact. It is therefore important to determine whether it is appropriate to consider the skin to be a linear wave propagation medium for since linearity would considerably simplify any analysis related to this phenomenon. For example, linearity would enable the application of the superposition principle, of the reciprocity principle, and others, even if the skin is considered to be anisotropic. The linearity assumption is important for the scientist interested in the physics of the tactile perception and it can also be surmised to be taken into account by the neural circuits processing tactile information. Such property would be important even if much of the other tactile physics, such as friction, are predominantly nonlinear. We found that indeed, the human fingertip skin could be considered to be a linear propagation medium, except in irregular regions such as the folds near the joints where linearity breaks down.**

I. INTRODUCTION

It was observed in previous studies that mechanical information arising from the dynamic contact of a finger with an object travels in the skin with amplitudes sufficiently large to excite mechanoreceptors populations far away from the region of interaction [1]. In fact, vibration propagation in finger has already been taken advantage in virtual reality applications [2], [3]. At the behavioural level, the impact of wave propagation in the skin for roughness discrimination was unambiguously demonstrated [4] and tt was further determined that vibratory signals in regions as distant as the forearm were tightly correlated with fingertip excitatio n signals during tactile scanning in natural conditions [5]. A recent study characterised the wave propagation patterns in the whole-hand when interacting and manipulating ojects [6].

Taken together, these results suggest that highly informative tactile signals are mediated by waves propagating in the skin and other tissues. This observation begs the question of which models and which assumptions are applicable to manner in which this type of tactile information is made available to the brain. It is well-known that the skin is a complex medium anatomically and histologically. It is multi-layered, non homogeneous, poroelastic solid with complicated support with respect to the surrounding structures such as the pulp and the skeleton [7], it exhibit complex material properties [8], [9] and is clearly anisotropic with several relaxation time constants [10]. At low strain rates, a quasi-linear model can successfully predict the behaviour of skin under indentation [11] but it was found pressure distribution data could not be fitted with the data using a Hertz contact model corrected with linear viscoelasticity [12]. In a distributed system setting, the waves at the surface of the body and of the fingertip seem to be well explained by linear viscoelastic models [13], [14]. As a lumped parameter system, the skin-covered finger exhibits a nonlinear response to tangential indentation, with relaxation hysteresis [15], it was however possible to successfully fit a second order linear impedance model to the behaviour of the fingertip under dynamic excitation [16]. Despite the skin inhomogeneous structure, anisotropic properties, and complex material properties, it appears that linear behaviour could be an acceptable assumption for the propagation of waves in the fingertip.

II. DATA COLLECTION

The data used were recorded by Louise R. Manfredi using the same procedure as that described in [1]. A mini shaker transducer (Model 4810, Brüel & Kjær, Skodsborvey, Denmark) impinged on the fingertip skin. The excitation signal was monitored using an accelerometer attached to the probe. The displacement of the skin was measured at different distances from the region of excitation, namely 1 mm, 8 mm and 16 mm, using a laser Dopler vibrometer (Model OFV-3001 with OFV-311 sensor head, Polytec, Inc., Irvine, CA). The excitation signal was a complex signal that was band-limited for different windows in the range from 50 Hz to 800 Hz. The amplitudes were between 0.005 mm and 0.1 mm. Measurements were made with five participants. For each participant, there were fifteen trials in total comprising three amplitudes repeated five times each .

III. RESULTS

Results are exemplified in Fig. 1 which shows the Fourier transform of the input signal for a 200–600 Hz window. The 95% confidence interval was plotted for each response curve as a shaded area. It is visible in this example only in the last plot, when the skin vibration was measured 16 mm away from the point of excitation. Otherwise, it was frequently too small to be visible graphically.

A high degree of repeatability was indicative of linear behaviour, which justified further investigation. From these responses, linear regression was performed at each frequency, using the input and output acceleration amplitudes. Linearity

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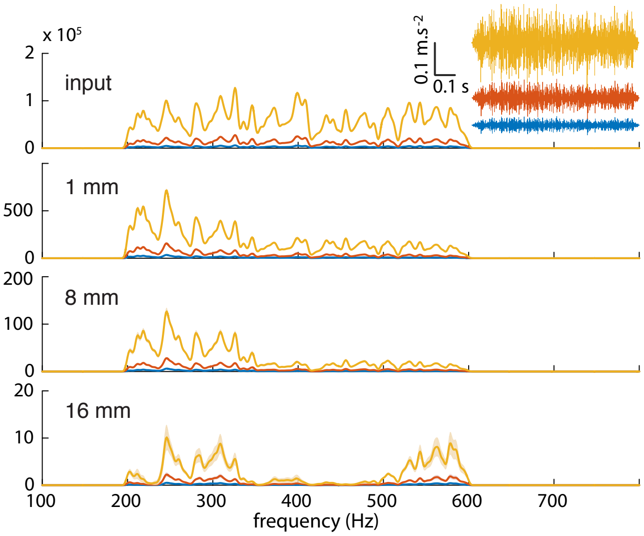

Fig. 1. Typical result. Input vibration (top) recorded from accelerometer. Responses at three diffrent distances. Colour correspond to input amplitudes.

was assessed using a measure of fit quality, namely the coefficient of determination.

Figures 2 and 3 shows the results for one participant. Figures 2 shows the best and the worse fit quality for specific frequencies and distances.

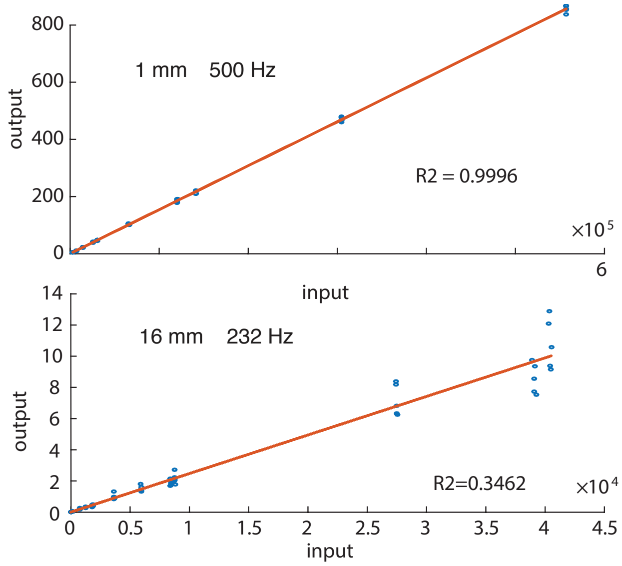

Fig. 2. Best and worst fit for ONE participant.

At all three distances, linearity was high overall, see Fig. 3, with averages of the coefficient of determination mostly above 0.8. At 1 mm away from the source the lowest value of the coefficient of determination was greater than 0.99. At 8 mm away from the source wave propagation the system can be still be consider to be linear in the whole range of frequencies tested, with imperfections at some frequencies. At 16 mm non-linear behaviour begins to manifest itself, also at some discrete frequencies.

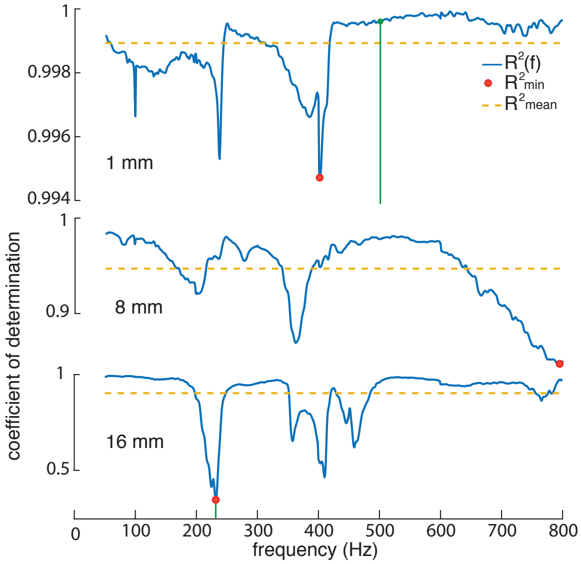

Fig. 3. Results for one participant. **(c)** Linearity measurement for the whole spectrum range at three distances

Looking at the overall results, see Fig. 4, a globally high value for the coefficient of determination was found for the five participants and for all distances from the source. Nonlinearity in the transmission of mechanical waves began to be significant only for certain participants and always for the greater distances. Occurrences of nonlinear behaviour at larger distances from the source was not systematic and some participants' fingers remained by-and-large linear throughout the whole range of distances. Others, however, started to exhibit noticeably nonlinear behaviour in some regions of the frequency spectrum, even at a distance of 8 mm, in some cases. Participant JWC, despite a high linearity at shorter ranges, was the only one to exhibit a behaviour corresponding to a value of coefficient of determination under 0.5 at 8 mm.

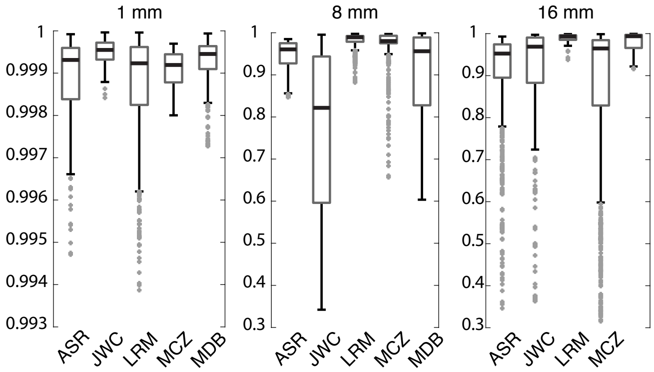

Fig. 4. Results across participants. Box plots give the median of the coefficient of determination over the whole spectrum, the quartiles and outliers (in grey). Each data set has 850 data points.

Nonlinearities can be related to a drop in signal amplitude throughout its propagation in the skin, as shown by Fig. 5. Overlapping the input and output curves shows that linearity deterioration corresponds to signal attenuation. This phenomenon is more prominent at a distance of 8 mm then at 16 mm for participant JWC. This case has the peculiarity of present very low linearity, even at a distance of 8 mm. This observation suggests that the origin of the phenomenon should a common origin both distances. Through the whole batch of data, a significant nonlinear behaviour systematically correlates with attenuation.

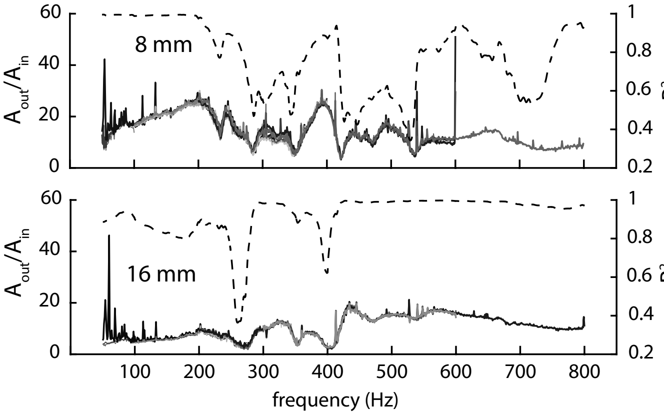

Fig. 5. The coefficient of determination (dashed line) correlates with signal attenuation (full lines).

IV. DISCUSSION

From the input and output amplitude relation in the frequency domain, the homogeneity property of the superposition principle is directly verified in our experiments. For all scalars α, there is a constant h such that

$$Y_f = hX_f = \mathscr{S}(X_f)$$
$$X'_f = \alpha X_f \Rightarrow \mathscr{S}(X'_f) = hX'_f = h\alpha X_f = \alpha\mathscr{S}(X_f)$$

Linearity observed throughout the frequency range confirms the additivity property of the superposition principle. Linearity was assessed with signals that contained multiple frequencies. Hence, the response studied at each individually frequency showed linearity since many type of nonlinear system cause the output to oscillate at frequencies that are not present at the input. In our measurements however, a band limited input signal produced an output in the same band as exemplified by Fig. 1.

The data also shows that the medium has little memory, meaning that the input-output relationship of the system under study depends on past inputs. Each signal presented to the skin for 1 second and throughout 135 trials remained linear and did not seem to undergo modifications in its response at least during the time scale that we have considered.

Lower coefficients of determination could be explained by the deterioration of the signal-to-noise ratio in the frequency regions where the output amplitude become low but not by nonlinear skin behaviour and be measurement artefacts. Figure 6 shows the average across participant of the signal amplitude decay of the signal through propagation at the two smaller distances. At a distance of 1 mm, the confidence interval (in grey) is narrow and tracks the curve but with increased distance the confidence interval diverges.

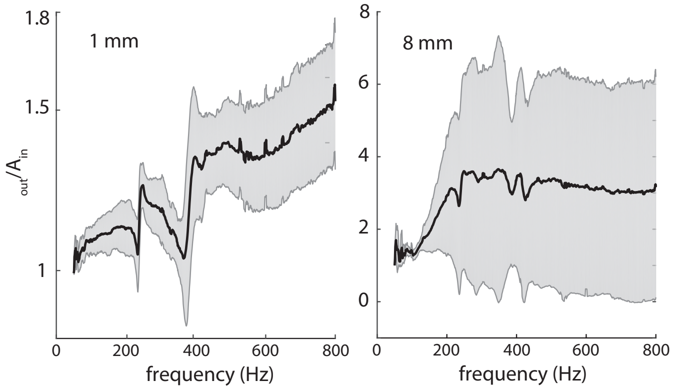

Fig. 6. Here are presented averages (black curve) and confidence intervals (grey area) of amplitude decay of the signal across participants, **(a)** for 1 *mm* and **(b)** for 8 *mm*.

This observation suggests that the shape of the finger, which is the domain inside which waves develop, and which depends on the anatomy of a person, gains increasing influence with distance from the source of excitation. At a distance of 1 mm it is a general occurence across participants that the skin may be considered to be a linear linear system. We could infer that for the participant for which linearity drops dramatically this occurence could ne linked to the proximity of a joint since a joint would modify preloading and supporting conditions of the skin. Our data also highlights one aspect of the mechanical response of the skin.

The study of the input-relationships aiming at understanding which aspects of the input vibrations are transmitted to various parts of the anatomy is greatly facilitated by our results. For example, modal or seismographic analyses can be thus performed to model the effect of propagation of waves in the finger by leveraging the reciprocity principle. The apparent linearity of skin, as a material, also simplifies the analysis of the information from environment and many features of linearity discussed above have implication in perception. For example, a key question in this area is discover the mechanisms by which the brain maintains perceptual constancy in the face of the variability of the mechanics of touch. This task would be greatly facilitated if the skin can be considered to be a linear propagation medium. This would imply that variability can be mostly ascribed to bio-tribology and not to tissue mechanics.

V. CONCLUSION

The literature and the present results points out linearity in the mechanical behaviour of the skin, despite its histological biomechanical complexity. This may explained by the simple fact that mechanical wave propagation allows for linear, small signal analysis, at least far away from the supporting boundaries of the domain considered (nails, articulations). As a part of a future work, it could be interesting to study, the limits linearity in order to characterise where it breaks down either because of the influence of anatomical structures of under large signal excitation.

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