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Looking for Physical Invariants in the Mechanical Response of a Tactually Scanned Braille Dot

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***Abstract*— One human finger explored plastic Braille dots using a variety of velocity and force profiles. The fingertip friction forces were measured. Characteristics of the interaction were studied to explore the manifestation of the amplitude/duration interdependence of signals across velocity, normal force and dot height. Both amplitude, defined here as maximum tangential force, and duration, were seen to vary with velocity and normal force, however the integral of the tangential force over time was found to not have a strong dependence on either variable. When three consecutive dots of varying height were examined, the tangential force integral was not constant, but increased in proportion to height. We propose that the nervous system may use the tangential force integral as an invariant to recognise the same spatial asperity explored under different velocity and force conditions.**

I. INTRODUCTION

A tactual texture is never explored in exactly the same mechanical conditions. In addition, the frictional interactions of a fingertip with surfaces frequently exhibit chaotic characteristics. This complexity can clearly be attributed to multi-scale, nonlinear physics that are at play during sliding [1]. Physiological and environmental factors such as fingertip hydration, applied pressure, contaminants, and exploration velocity are also constantly fluctuating during sliding and influence the frictional mechanics [2]. The fingertip itself is a bi-phasic, multi-material, multilayer composite structure which has different dynamic behaviors at the different length and time scales involved in frictional interactions.

Yet, the perceptual quantity of a texture is experienced similarly despite exploring it in a variety of ways [3], [4], [5], [6]. This independence to sensing conditions could appeal to a mechanism in the brain able to extract certain physical invariants. Since textures may be considered as a collection of asperities, the study of a single asperity, such as a Braille dot, may help clarify what these invariants might be.

The objective of the current study is to explore the physics underpinning the tactile perceptual invariant responsible for the constancy observed when a finger swipes over an asperity. Several groups studied skin deformation over small asperities [7], [8] but only quasi-statically. Among the considerable number of perceptual studies employing surfaces made of isolated asperities, Lamb found that subjects could correctly distinguish 75% of surfaces in which the period of the dots differed by only 2 percent [9]. Performance was virtually independent of the method of movement used, despite large differences in the velocity profiles. Conversely, Dépeault et al. found that average dot spacing affected the perception of sliding speed [10]. These results support the notion that whether swiping over an asperity quickly or slowly, asperities are perceived similarly. We propose that this constancy takes its roots in a physical effect where the same asperity scanned at different speeds preserves the time integral of the friction force over the traversal of the asperity.

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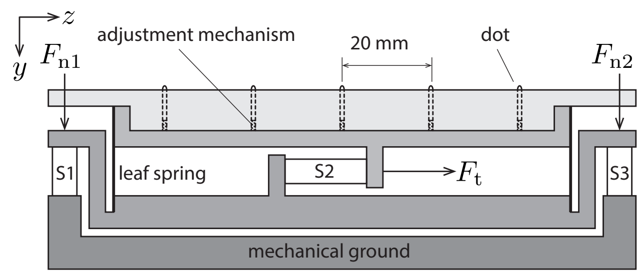

Fig. 1. The apparatus. The transducer measures the interaction forces of the finger exploring the Braille dot platform with dots of adjustable heights.

It was previously shown that in the tactile modality the perceived intensity of a stimulus tends to depend on the time of exposure to the stimulus [11], [12]. This was also shown in the case of a Gabor-windowed pink noise vibratory skin stimulus [13], which could model the sensory experience of a finger sliding over an asperity. Since the duration of a stimulus is determined by the scanning velocity, we hypothesized that a larger instantaneous mechanical effect for a faster scanning velocity of the same asperity could be equivalent to a slower velocity with a smaller mechanical effect. A purely elastic finger would preclude the occurrence of this dependency. We investigated this possibility by studying the friction mechanics of a finger exploring a Braille dot of different heights at different velocities and normal forces. The prediction power of these three variables (normal force, velocity and dot height) on the tangential force time integral of several braille dots was examined.

II. METHODS

A. The Experimental Set-up

The set-up comprised a friction force transducer as seen in Fig. 1, able to measure the normal force $F_n = F_{n1} + F_{n2}$ (Kistler 9313AA1) and tangential force F_t (Kistler 9217A) independently, described elsewhere [14]. A Braille dot exploration plate was tightly fixed to the set-up. Displacement

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Fig. 2. The Braille dot platform consisting of five consecutive dots mounted on an aluminium plate. The finger had no inclination to the platform.

$x_1 = (yF_{\mathrm{n}2}+zF_{\mathrm{t}})/F_{\mathrm{n}}$ was computed using the force sensors to determine the displacement of the centre of pressure, which we considered to represent the position of the finger.

B. Task

The aluminum plate (1.6×3×20 cm) held equally-spaced plastic Braille dots contributed by Metec Ingenieur AG, see Fig. 2. Before the dots were secured, the aluminum surface was polished using fine sanding paper ensuring a smooth background. An adjustment mechanism allowed control of the Braille dot height around 0.48 mm, as recommended by the Braille Authority [15]. The space between the Braille dots was set at 2 cm to ensure that the finger was exploring one dot at a time. The platform allowed us to make measurements for dots of different heights with similar exploratory conditions.

The participant (female, 22 years old) slid her finger (with no inclination) over the platform at different speeds (79 to 555 mm/s) and normal forces (0.4 to 1 N), see Table I. The participant was instructed to try different speeds but in practice trials tended to be grouped into slow and fast. She presented no history of skin pathology or motor disorders. Only one finger was used in the study owing to very large individual differences in finger mechanics. Futhermore, since such physical invariants are fundamental consequences of the mechanics of touch, the existence of such a quantity for a single participant featuring otherwise uniform properties such as skin condition may suggest that this quantity could have an important role in tactile perception. The finger used in the study had an approximate normalized hydration of 0.6. Generalization to populations of individuals is left for future studies.

C. Data Analysis

The tangential force F_{t} was analysed for each dot. To determine the velocity of exploration for each Braille dot, the position data was fitted to a 2$^{\mathrm{nd}}$-order polynomial with appropriate boundary values and differentiated to give a linear fit estimate. The velocity was then sampled at the center of each dot for analysis.

The data was filtered using a 5–50 Hz band-pass 1$^{\mathrm{st}}$-order Butterworth filter applied bidirectionally, thus preserving the shape and phase of the signal while removing the offset and fast oscillations.[1] The five Braille dots were segmented in each recording by zero-crossing analysis. To avoid any effect of the initial skin compression, only the last three dots were analyzed. They also showed a greater range of normal force and velocity. The three dots had increasing physical heights: 0.42, 0.48 and 0.61 mm respectively.

[1]Hereafter F_t shall refer to the filtered tangential force.

Dot 3	Min.	Median	Max.
Velocity (mm/s)	80	151	529
Normal force (N)	0.4	0.57	0.98
Dot 4	Min.	Median	Max.
Velocity (mm/s)	80	166	542
Normal force (N)	0.43	0.6	0.97
Dot 5	Min.	Median	Max.
Velocity (mm/s)	79	180	555
Normal force (N)	0.4	0.59	1

TABLE I

THE RANGE OF NORMAL FORCE AND VELOCITIES OF EXPLORATION FOR DOTS 3, 4 AND 5.

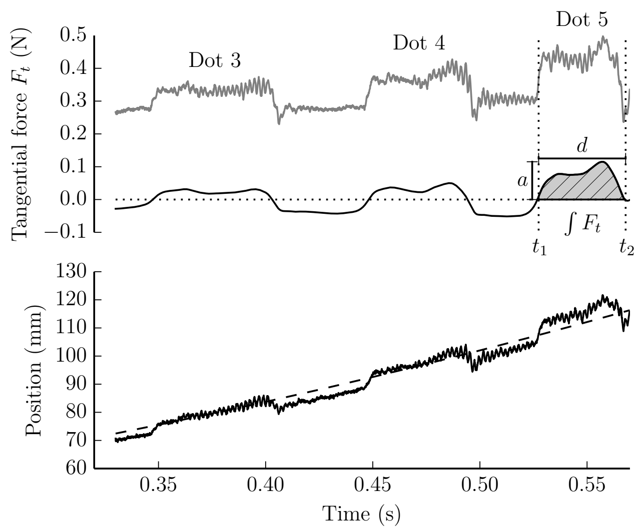

Fig. 3. Recording of a finger exploring three consecutive Braille dots. The duration d and amplitude a, defined as $\max_{t_1 \ldots t_2} F_t$, of the interaction as well as the filtering to measure the friction force integral are shown.

For each Braille dot recording (40 swipes in total = 120 dots), features were extracted as shown in Fig. 3. We analyzed both the duration and the amplitude of the swipe, where the amplitude is defined as the maximal tangential force, $\max_{t_1 \ldots t_2} F_t$, over the time interval of the dot. Since the finger is almost purely dissipative, the force samples collected over the course of the contact with a dot is related to the work exchanged with the finger as follows: the work exchanged between the finger and the scanned dot is $W_{\mathrm{e}} = \int_{t_1}^{t_2} \vec{F}(t) \cdot \mathrm{d}\vec{x}(t) = \int_{t_1}^{t_2} \vec{F}(t) \cdot \vec{v}(t)\mathrm{d}t$, where t_1 and t_2 are the times at which the finger meets the dot and leaves it, respectively, $\vec{F}$ is the force of interaction and $\vec{v}$ the average velocity of the particles in contact with the dot, which we approximate by the velocity of the point of action of the measured force on the plate. Because the force of interaction did no work in the direction perpendicular to the plate, $\vec{v}$ could be substituted by a constant, $\bar{v}$, during the traversal of a dot. Hence, the work exchanged by the finger was approximatively proportional to $\bar{v}\int_{t_1}^{t_2} F_t$ since the forces were sampled at regular time intervals. As a result, the summed measurements $\int_{t_1}^{t_2} F_t$ represent the work exchanged by the finger normalized by scanning velocity up to a constant. Thereafter, this value is described as tangential force integral.

Tangential force integral	The area of the tangential force signal, $\int F_t$, for the duration of the time interval of the dot exploration, as defined by *duration*, below. Estimated as $h\sum_{i=k_1}^{k_2} F_t[i]$, where $k_i = \lfloor t_i/h \rfloor$, h is the sampling period (10 kHz), and $F_t[i]$ is a discrete-time sampling of F_t.
Amplitude	The maximum tangential force over the time interval of the dot exploration, defined as $\max_{t_1 \ldots t_2} F_t$.
Duration	The time of the swipe over the braille dot, measured as $t_2 - t_1$, where t_i are identified as the zero-crossing times of F_t surrounding the peak of each finger–dot collision.
Height	The distance from the platform to the top of the Braille dot, as measured using a high-quality height gauge providing sub-millimeter precision.

TABLE II

FEATURES OF THE MECHANICAL RESPONSE TO SCANNING A DOT.

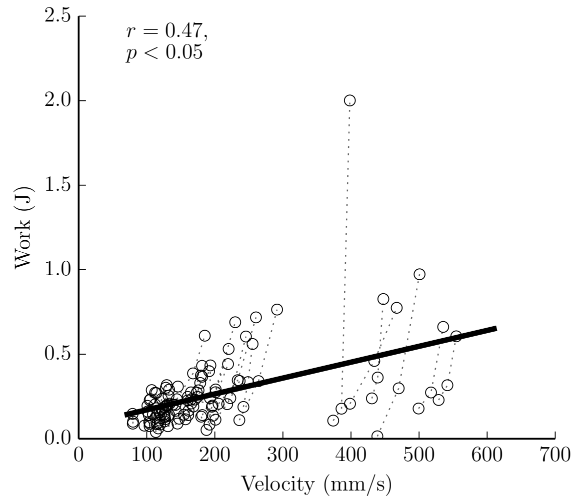

Fig. 4. Work exchanged between the finger and the Braille dot against velocity of exploration.

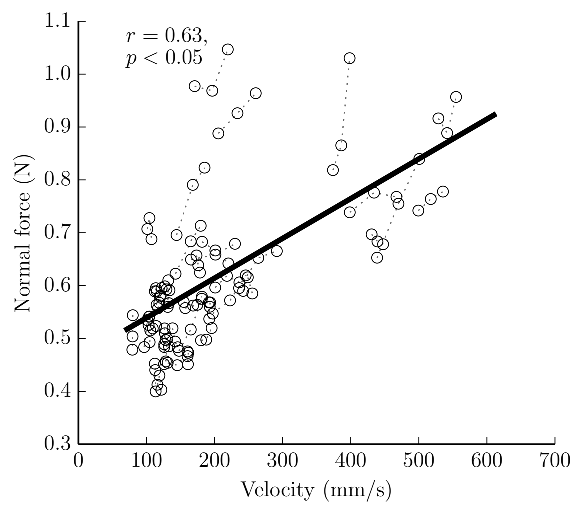

Fig. 5. The normal force increases with velocity during the exploration of different Braille dots.

III. RESULTS

In contrast with most studies, we investigated features of the data with the aim of identifying physical quantities that have *low* correlation with exploratory conditions, known as physical invariants. We found that W_{e} was somewhat correlated with velocity ($r = 0.47$, see Fig. 4) while $\int_{t_2}^{t_1} F_t$ (equivalent to $W_{\mathrm{e}}/\bar{v}$) remained independent ($r = -0.13$), Fig. 6a). The influences of the three variables (velocity, normal force and height) were plotted for each feature (tangential force integral, amplitude and duration, as defined in Table II). Dotted lines showed the recordings for dots within the same swipe, with the black line as the regression across dots. Pearson's correlation is given for each diagram with a p value indicating 95% confidence.

Both amplitude and duration were well predicted by velocity, despite the fact that velocity did not well-predict the tangential force integral, see Fig. 6. The increase in amplitude with velocity was in line with the hypothesis proposed in [13]; that amplitude and duration have a multiplicative relationship to perceived intensity. This is analogous to their product being approximately constant for the same asperity explored at different velocities. In other words, we expected the amplitude of the signal to increase with velocity v when exploring the same Braille dot of width w since the duration d of the measurement is shorter ($v = w/d$), which was confirmed in our analysis, see Fig. 6c.

For the normal force, the same relationship was seen, as shown in Fig. 7. The increase in amplitude with normal force could be logically explained by a stronger impact if the pressure is high. The increase in duration as the normal force increases resulted from the observation that during a faster swipe, the participant tended to press harder, see Fig. 5. These results showed that velocity and normal force don't predict the tangential force integral even though they influence the amplitude and the duration of the signals.

Examining the interaction of the finger with three dots of increasing physical height, we found that both the amplitude and the tangential force integral increased correspondingly, see Fig. 8. A dependent Student's t-test was used to determine whether distributions were significantly different. It was found that both friction force integral and amplitude scaled significantly with dot height, while the duration remained essentially constant: although a small significant difference was found for dots 4 and 5, the Pearson's correlation $r = 0.09$ was quite low for Fig. 8c. Indeed, the diameter of the dot studs was consistently 1.6 mm and the increase in height very minimally affected the trajectory of the finger.

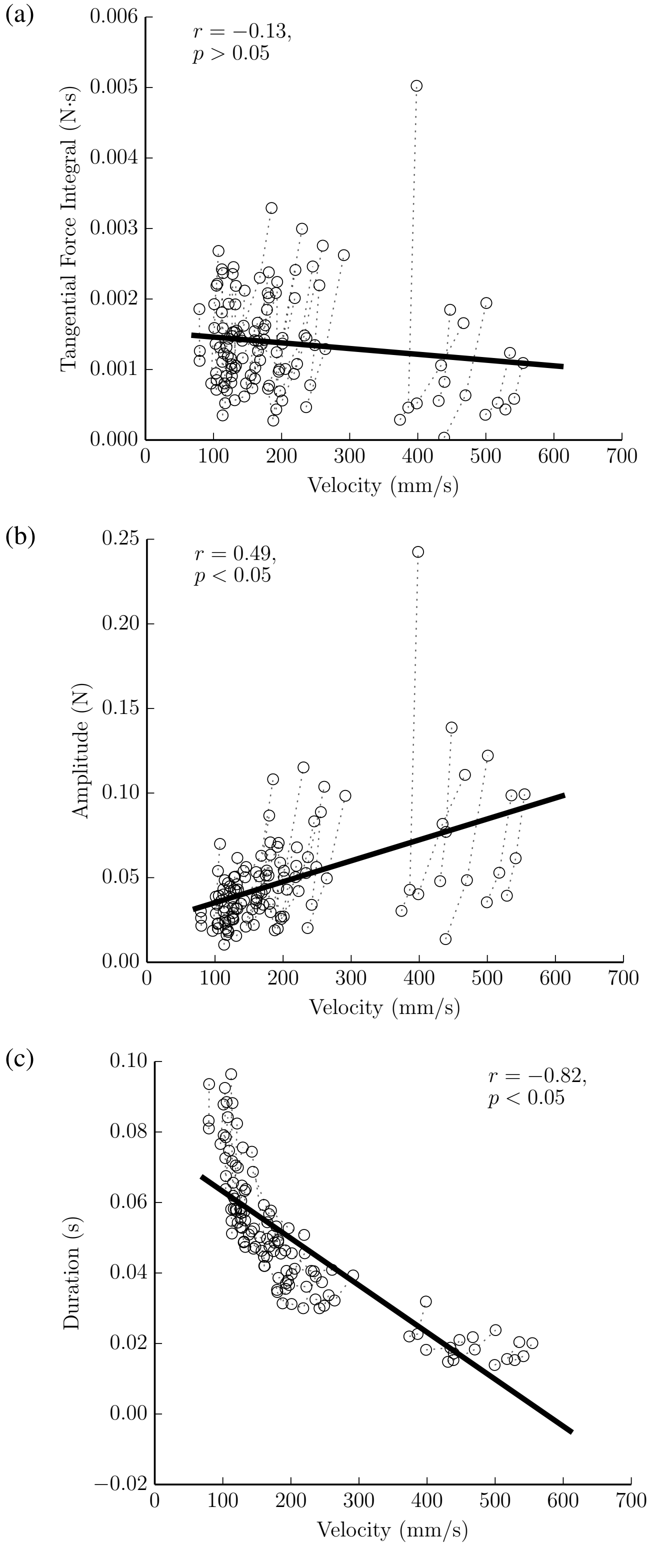

Fig. 6. Tangential force integral, amplitude and duration of the recording as a function of velocity for all three dots. The amplitude consistently increases with velocity, while the duration decreases. However, the friction force integral remains relatively constant, or invariant (low correlation).

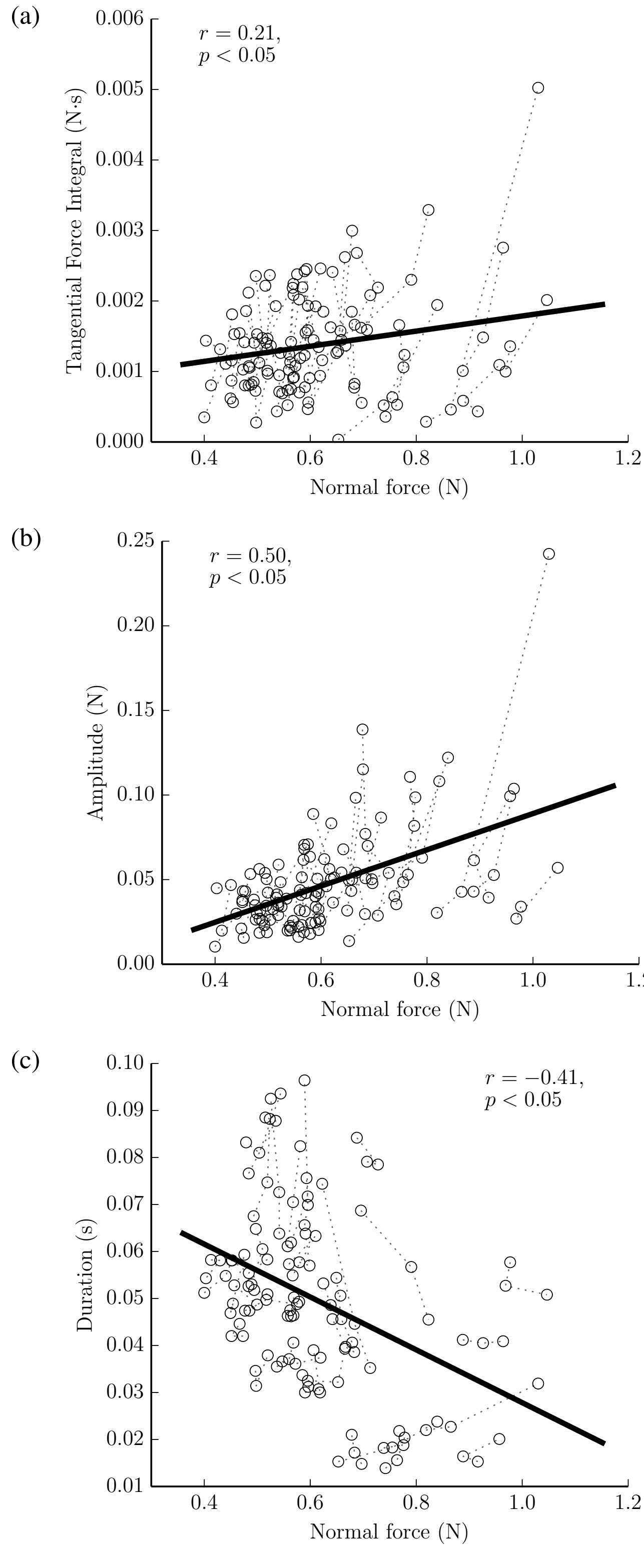

Fig. 7. Tangential force integral, amplitude and duration of the recording as a function of normal force for all three dots. The duration consistently decreases with normal force, while the amplitude increases. However, the friction force integral remains relatively constant, or invariant (low correlation).

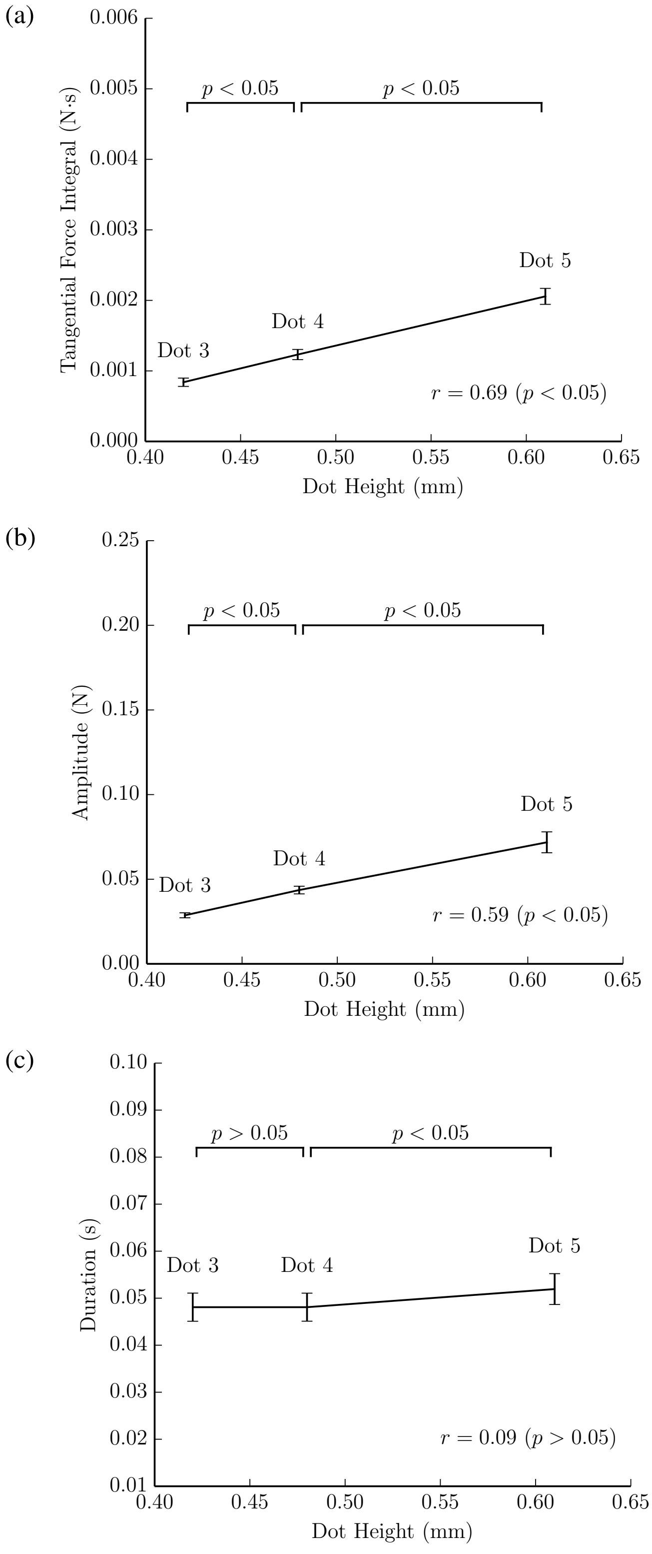

Fig. 8. Tangential force integral, amplitude and duration of the recordings as a function of dot height. Using 40 samples per dot, a dependent Student's t-test was computed to determine whether distributions were significantly different. It was found that both friction force integral and amplitude scaled with the physical height of the dot, while the duration remained essentially constant.

IV. DISCUSSION

In this experiment the influence of velocity and normal force over the mechanical response of three dot heights was investigated. The aim was to find correspondences with a physical constant in the tactile modality, which we propose as a basis for perceptual constancy during asperity exploration.

Both amplitude and the tangential force integral scaled with dot height, see Fig 8a,b. However, the observation that the amplitude was well correlated with the dot height (Fig 8b) is misleading because the amplitude is also seen to increase with velocity, see Fig 6b, and therefore could not be considered an invariant. In fact, the tangential force integral improved on the predictive power of the amplitude ($r = 0.69$ vs. 0.59)[2], and it was not confounded with exploration parameters. That the tangential force integral appeared to be the best predictor agrees well with our previous observation that both the amplitude and the duration of the interaction contribute to the perceived intensity [11], [12], [13], since it is the product of both parameters.

The third variable, the physical height of the dots, also allowed us to show that even when the movement is complex and many variables are at play, the tangential force integral systematically scaled with the dot height. This reinforces the low predictive power of the velocity and normal force on the tangential force integral and proposes this value as the invariant used by the somato-sensory system. It also shows that the major source of variance within a single dot is probably contaminants or sweat, since it is minimal compared to the variation caused by height increase. The heights of the dots in this experiment varied by 0.2 mm, however the change in the tangential force integral was very significant (regression coefficient of 0.69, Fig. 8a). This leads us to wonder whether such changes in the tangential force integral can be seen in discrimination tasks at the nanometer scale [17]. Conversely, it questions whether the inability to discriminate asperity height could be predicted by the tangential force integral. On the other hand, such a discrimination difficulty might be explained by the Weber fraction: the ability to perceive intensity likely worsens as features decrease in size. We plan to consider such possibilities in future research.

We can surmise that the reason why the physical constancy was represented by the tangential force integral is because it best reflects the overall strain delivered to the finger. During lateral motion, a single bump on the surface can yield a skin stretch larger than 30% [7]. Since the finger may be compared to an elastic membrane filled with an incompressible fluid [8], we can imagine that at each impact, the skin deforms toward the bone. The same overall deformation occured for each dot, however the details of the deformation at a given time are probably different when the velocity or the normal force change. If the overall deformation is the same, how can we explain our use of different exploration techniques [18] to discriminate different objects?

These observations further suggest that regardless of the scanning kinematic and tonic characteristics, the same dot

[2]Correlations were significantly different with $p < 0.05$ [16]

is perceived, in line with what was observed perceptually [6], [19]. We have investigated the effect of two important exploration conditions, however there exist other parameters during a single swipe which influence the mechanics of the impact, which we have not accounted for in this work. For example, it is known that the occlusion mechanism (sweat accumulation between the ridges during sliding) affects the friction mechanics [20], [21]. We can infer that these variables will show a similarly poor relationship to the tangential force integral. We found however that a lot of these variables are inter-related, see Fig. 5, meaning they will most likely already be included in the bulk strain measurement.

V. CONCLUSION

Both amplitude and duration were well predicted by velocity and normal force, despite the fact that the various experimental conditions did not correlate with the tangential force integral over a single asperity. However, when studying the tangential force integral for the exploration of three consecutive dots of different heights, the integral increased with dot height. These findings showed that the integral is a good predictor of asperity characteristics since it remained constant regardless of exploration conditions, but varied with dot height.

VI. FUTURE WORK

The existence of a mechanical invariant quantity, the tangential force integral, which is robust to changes in velocity and pressing force when scanning Braille dots is the main contribution of the present article. We intend to expand the present study with a view to clarify whether this invariant is found in an intra-subject condition for several participants and whether it further correlates with psychophysical experiments on asperity discrimination.

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