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# Design and Evaluation of a Multi-Modal Haptic Skin Stimulation Apparatus

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*Abstract*— **Human grasping and manipulation are facilitated by cutaneous mechanoreceptors that provide information about contact location, pressure, and events such as making and breaking contact. A challenge in designing haptic feedback devices for the wearer of a prosthetic hand is simultaneous display of multiple types of haptic information. We present the preliminary design and evaluation of an apparatus for relaying multi-modal haptic information. The apparatus moves a set of contact points tangentially over the skin at a controlled speed, with controlled normal force. We apply this stimulus to an artificial skin instrumented with an embedded accelerometer, and characterize the resulting signals. Vibration frequency increases with applied normal force and tangential speed, whereas vibration amplitude increases with normal force and depends on skin properties. The results indicate that different forces and speeds can, under some conditions, be discriminated using vibration signals alone. Accurate identification of speeds is provided by series of vibration events that depend on the spatial distribution of contact points. This study motivates future work to perform human perception studies and create a wearable haptic display for prosthetics based on this concept.**

## I. INTRODUCTION

Human grasping and manipulation is enabled by a sensorimotor system that is able to access multi-modal haptic information in the human hand [1]. Dexterous manipulation tasks, such as slippage control and active exploration, in which the contact conditions between the hand and an object change, are expressed in complex spatial cues and forces acting on the skin. Pressure, stretch, and vibrations on the skin result from changing contact conditions, and elicit responses from various skin mechanoreceptors [2]. People wearing hand prostheses are deprived of contact/location cues and forces during object manipulation. They have to rely to a high extent on visual feedback, leading to fatigue and frustration [3].

Relaying spatial cues and forces through a haptic device could enable the prosthesis wearer to access rich, useful information about the changing state of contact between the artificial hand and a grasped or manipulated object. Such feedback may help the prosthesis wearer grasp, manipulate, and identify objects. As a result, grasp stability and dexterous manipulation can be achieved, while releasing some of the attention to vision currently needed.

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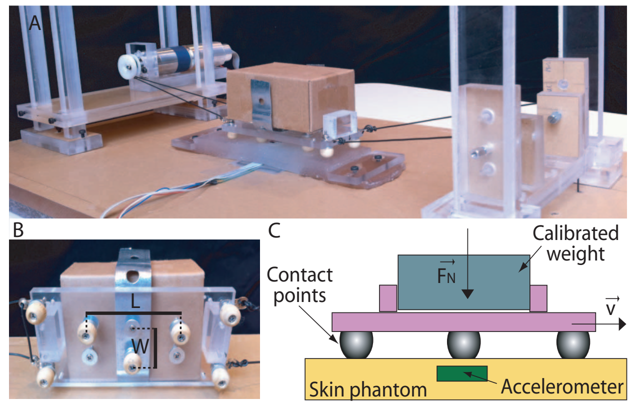


Fig. 1. Experimental apparatus. A. Haptic device and artificial skin. B. Detail of the bead structure. C. Schematic of the experimental apparatus. A speed $v$ and a normal force $F_N$ are applied at three contact points.

In prosthetics research, haptic feedback has been used mostly to convey force during stable grasp. Vibrations have been extensively used as a means to display information about grasp force, e.g., [4], [5]. Force feedback has also been transmitted through mechanisms that push on the skin, e.g., [6], [7]. Conventional grasp force displays lack contact motion cues, but vibration signals elicited from force exertion can convey significant information about changing contact conditions and spatial distribution of surface features. This has been previously exploited in virtual environments and teleoperators, e.g., [8], [9]. Haptic devices that render contact location, slip, and shear have been developed to display changing contact conditions [10], but existing devices are impractical for prosthesis wearers.

As a preliminary step toward designing a wearable haptic device that relays information about contact conditions, we present an apparatus able to generate spatial and force cues through moving contacts applied to the skin. The control parameters of the apparatus are the speed of a set of discrete contact points moving tangentially over the skin and a force applied orthogonally to the skin. The choice of the control parameters is motivated by human studies showing that grip forces are regulated by load forces [11], and tangential resistive forces convey texture information [12]. Recent work [13] found evidence that relaying information about slippage speed to prostheses users improved their ability to grasp a slipping object. In this paper, we describe the features of the signals generated by a multi-modal haptic apparatus and acquired by an instrumented artificial skin.

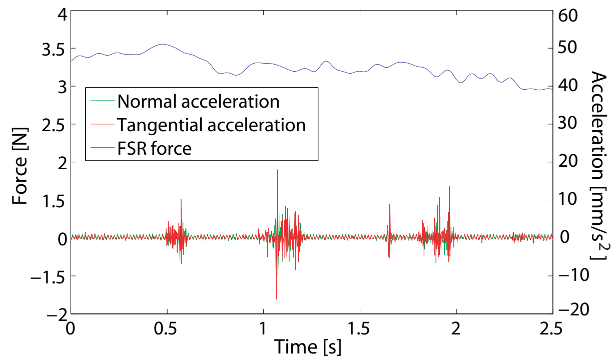


Fig. 2. Raw signals recorded by the artificial skin. Force and acceleration on tangential and normal directions when contact points move at a speed of 18mm/s and carry a weight of 3N along the skin. The series of three vibrations correspond to three contact points distributed on a moving bar.

## II. Experimental apparatus and procedure

### A. Experimental apparatus

*1) Haptic apparatus:* The haptic apparatus, depicted in Fig. 1A, controls tangential speed and normal force applied to an artificial skin. An acrylic bar moves horizontally along the surface of the artificial skin and carries calibrated weights on top. Underneath the bar, wooden beads are mounted (Fig. 1B); the three beads in the center of this structure contact the artificial skin, and the others (of lower height) are placed at the corners of the structure for stability purposes. The three contact points are arranged in a zig-zag pattern, with $L = 48$mm and $W = 15$mm, in order to maintain stability and equal distance to the center line of the artificial skin. Calibrated weights can be placed on top of the bar. A DC motor (Faulhaber DC-Micromotor 2642), driven by a speed controller (Atmel ATmega328P AVR microcontroller), drags the bar along the artificial skin at a constant speed. At its other end, the bar is connected to two counter-weights through non-deformable wires laid over two pulleys.

*2) Artificial Skin:* An artificial skin is used in this study as a surrogate for human skin. The skin (150x50x15mm) was built from plastisol (M-F Manufacturing), and equipped with two sensors: an accelerometer (Freescale MMA7361L 3-Axis Accelerometer 1.5/6g, 400Hz (XY) and 300Hz (Z) bandwidth) and a force sensitive resistor (FSR) (40x40mm, Interlink Electronics). The accelerometer was placed 2mm beneath the surface of the skin, whereas the FSR was placed under the skin. The force and acceleration recorded by the two sensors are shown in Fig. 2.

### B. Experimental procedure

The haptic apparatus controls two parameters: the speed of the contact points moving on the skin and the normal force applied to the skin through the calibrated weights. The contact points move at one of five possible speeds: 9, 12, 15, 18 and 21mm/s. Calibrated weights of 1, 3, 4 and 5N were used to apply normal force. At the beginning of an experiment, a speed command was sent to the microcontroller and a weight was manually placed on top of the bar. This paper focuses on the vibrations measured by the accelerometer; the FSR sensor was used to monitor the normal force applied through the weights. Data from the two sensors was collected at a sampling rate of 600Hz by a PC acquisition card (PC-Card-DAS16/16, Measurement Computing). A discrete vibration event occurs each time a contact point passes over the accelerometer. Both individual vibrations (associated with one contact point) and series of three vibrations (corresponding to three contact points) were analyzed. In order to characterize individual vibration frequency, weights of 1, 3 and 5N were used for applying normal force, whereas the contact points were moving at all experimental speeds. Individual vibration amplitude was measured under same speed conditions, while normal force was applied by weights of 3, 4 and 5N. Series of vibration events was analyzed in experiments in which weights of 3, 4 and 5N and all speeds were applied. The Euclidean norm of accelerations in the normal and tangential directions was used in subsequent analysis of the vibration signals. The peak frequencies of the individual vibration signal were extracted using the Welch power spectral estimation with an underlying Hamming window of 128 samples. The peak-to-peak amplitude was measured after smoothening the vibration signal with a Savitzky-Golay filter and applying a bandpass filter of 60 to 290Hz. The period between vibration events was determined by squaring the acceleration signals, applying a 2Hz FIR low filter and Fast Fourier function. Seven trials per speed per weight (140 trials) were conducted.

## III. Results

*1) Individual vibrations:* Vibration frequency was computed for each vibration event in each trial, and is plotted with respect to tangential speed of the contact points (Fig. 3A) and normal force applied to the skin (Fig. 3B). The results show that the vibration frequency increases monotonically and linearly with the tangential speed and normal force. For each speed, there was a significant difference in vibration frequency for normal forces of 1, 3 and 5N, as shown in Table IA. Single factor analysis of variance (ANOVA) with three levels, corresponding to the three forces, yielded $p < 0.01$ for each condition shown in Table IA. Tukey post hoc method indicated that significant differences appear between forces of 1 and 5N for each speed. ANOVA revealed a difference in vibration frequency for the tangential speeds of 9, 15 and 21mm/s at normal forces of 1, 3 and 5N. Each of the conditions yielded $p < 0.01$ and are shown in Table IB. Tukey post hoc method found that significant differences appear between speeds of 9 and 21mm/s.

Figure 4 shows vibration amplitude with respect to tangential speed and normal force. The plots reveal trends according to which vibration amplitude linearly depends on the normal force and has a nonlinear dependence on the tangential speed. A single-factor ANOVA with three levels, corresponding to normal forces of 3, 4 and 5N, yielded significant differences ($p < 0.01$) for tangential speeds of 12 and 21mm/s (Table IIA). Furthermore, Tukey post hoc

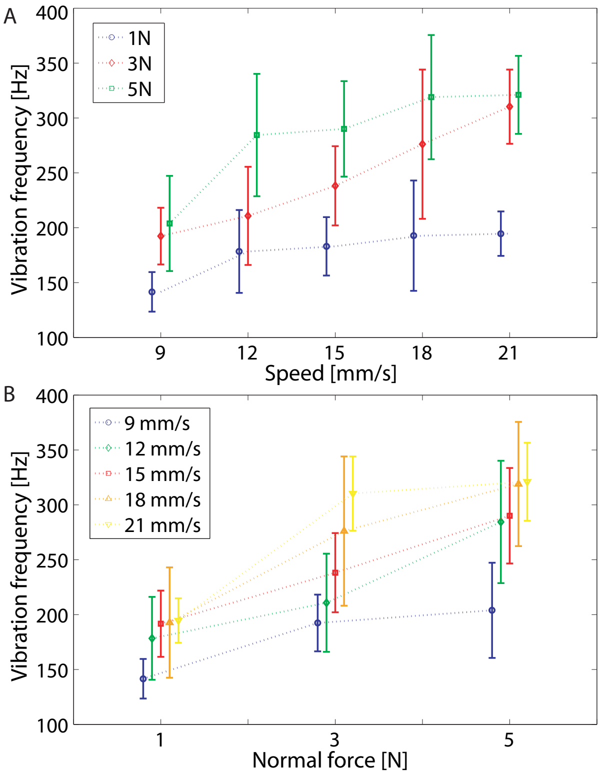


Fig. 3. Vibration frequency with respect to tangential speed (A) and normal force (B). The frequency of vibrations increases with both the tangential speed and normal force.

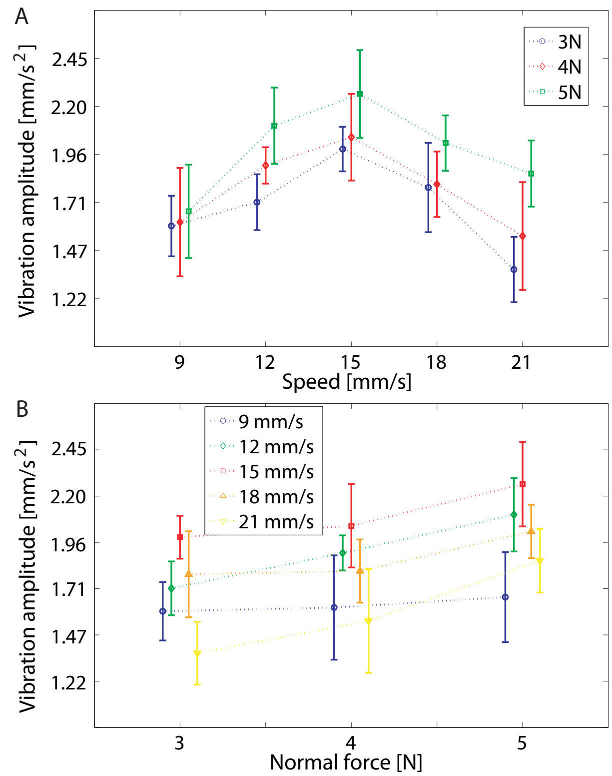


Fig. 4. Vibration amplitude with respect to tangential speed (A) and normal force (B). Vibration amplitude varies linearly with the normal force and is influenced by the elastic features of the artificial skin.

method revealed that normal forces of 3 and 5N can be distinguished for these two speeds. ANOVA with five levels, corresponding to all experimental speeds, showed that these speeds can be differentiated for normal forces of 3, 4 and 5N, according to $p < 0.01$ for each of the experimental conditions. Details are provided in Table IIB. Tukey post hoc test indicated that significant differences appear between speeds of 9 and 15mm/s, and between speeds of 15 and 21mm/s, for each normal force investigated.

*A*

| *Tangential speed* | *p-value for comparison of 1, 3 & 5N* |
|---|---|
| $9mm/s$ | 0.006 |
| $12mm/s$ | 0.003 |
| $15mm/s$ | 0.0009 |
| $18mm/s$ | 0.005 |
| $21mm/s$ | $< 0.0001$ |

*B*

| *Normal force* | *p-value for comparison of 9, 15 & 21mm/s* |
|---|---|
| $1N$ | 0.001 |
| $3N$ | $< 0.0001$ |
| $5N$ | 0.0002 |

TABLE I

P-VALUES FROM ANOVA FOR THE VIBRATION FREQUENCY AS A FUNCTION OF TANGENTIAL SPEED (A) AND NORMAL FORCE (B).

*2) Vibration event series:* The series of vibration events provides spatial cues resulting from the distribution of contact points on the moving bar. An envelope applied to the raw signal featured low frequencies in the range of $0.3 - 1.0$Hz and was found to depend only on the tangential velocity (Fig. 5). Single-factor ANOVA with five levels, corresponding to all five speeds, yielded $p < 0.0001$ for each normal force. Tukey post hoc test found that significant differences occur between all tangential speeds. The ideal time between vibration events can theoretically be computed as the ratio of contact point distribution ($L/2 = 24$mm) to tangential speed. With respect to this ideal period, the normalized root mean squared deviation (NRMSD) for each speed is: 9% for 9mm/s, 9% for 12mm/s, 6% for 15mm/s, 10% for 18mm/s and 7% for 21mm/s.

## IV. Discussion and Conclusions

In this paper we presented a conceptual mechanical design and an objective experimental characterization of an apparatus proposed for relaying information about space/motion, forces and consequently vibrations acting on the skin. The experimental results suggest that vibrations elicited by a moving contact point on the skin are information carriers that integrate both force and spatial cues. The frequencies measured ranged from 125 to 375Hz, similar to the sensitive range of Pacinian corpuscles [14]. Analysis indicates that vi-

***A***

| *Tangential speed* | *p-value for comparison of 3, 4 & 5N* |
|---|---|
| $12mm/s$ | 0.001 |
| $21mm/s$ | 0.002 |

***B***

| *Normal force* | *p-value for comparison of 9, 12, 15, 18 & 21mm/s* |
|---|---|
| $3N$ | $< 0.0001$ |
| $4N$ | 0.002 |
| $5N$ | 0.0001 |

TABLE II

P-VALUES FROM ANOVA FOR THE VIBRATION AMPLITUDE AS A FUNCTION OF TANGENTIAL SPEED (A) AND NORMAL FORCE (B).

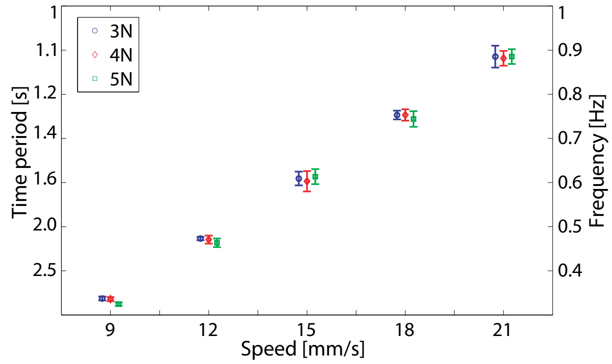


Fig. 5. Time period and frequency of vibrations events resulting from the spatial distribution of contact points. The time period varies linearly with the tangential speed and does not depends on the normal force. The plot shows an accurate discrimination of speeds.

bration frequency alone may enable discrimination between some speeds and between some normal forces. The results also show that vibration amplitude depends on the normal force. A cutaneous stimulation study [15] reported that the magnitude of perceived normal force increases as applied normal force increases from 1 to 5N. In our experiments, the vibration amplitude plotted with respect to speed was a parabola with a global maximum at 15mm/s. We surmise that this is a consequence of the resonant frequency of the artificial skin and may depend on various factors, e.g. material properties and thickness. The resonant frequency of the natural skin has been studied physiologically in [16] and its presence could be considered in the design of haptic devices. We found that vibration amplitude can be used to differentiate some speeds and normal forces. In addition, spatial cues resulting from series of vibration events display accurate information about the speed of contact points.

The characteristics of the haptic apparatus were obtained using an artificial skin instrumented with an embedded accelerometer. The artificial skin offers a degree of objectiveness in determining the signals generated by the apparatus. Further investigation will be carried out with human subjects to validate whether the obtained signals correspond to tactile afferent signals actually felt by the human skin.

The combination of multi-tactile variables, such as motion and normal forces, based on a set of contact points could play an important role in manipulation with prosthetic hands. Relevant tasks include controlling slippage by efficiently regulating grip forces and haptic exploration for object texture recognition. Our long-term goal is to build a haptic device for prostheses based on the proposed mechanism, and evaluate it in manipulation tasks.

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