Mechanical Impedance of the Hand Holding a Spherical Tool at Threshold and Suprathreshold Stimulation Levels

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Abstract

We report mechanical impedance of the hand for sinusoidal stimulation at the threshold and suprathreshold levels in the frequency range of 10-500 Hz delivered through a ball-shaped interface. The participants held the ball mounted on a minishaker in a way similar to that of holding a ball interface of a force-feedback device. A minishaker excited the ball in the vertical direction, resulting in vibrations on the skin of the hand in mostly the tangential direction. The position detection threshold curve was similar to that measured earlier using a stylus in the pen-hold posture, but the force detection threshold curve and the mechanical impedance was shifted upwards in the high frequency region. The mechanical impedance at the threshold and suprathreshold levels were essentially the same, indicating that skin characteristics do not change in the dynamic range of tactual perception for the same tool-holding posture.

1. Introduction

With the advances in haptics technology, many kinds of force-feedback haptic interfaces are now available. Most of them come with interface tools that can be grasped by a user's hand during the interactions with remote or virtual haptic objects. Common tool shapes include stylus, thimble, puck and ball, resulting in varying hand-holding postures and contact areas with the tool. We have been interested in examining the effect of tool shapes on the proximal stimuli received by the fingers of the hand (e.g., [1]). The present study considers the spherical tool (e.g., a ball or a puck), found in the Delta or Omega devices (ForceDimension, Switzerland) and magnetic levitation devices [2], that is typically held in the hand with multiple fingertips. Specifically, we report the following with regard to a spherical interface tool:

- Detection thresholds of vibrotactile stimuli transmitted through a rigid spherical tool, both in position and force, over a frequency range of 10 – 500 Hz;
- Mechanical impedance of the hand grasping the spherical tool measured at threshold and suprathreshold levels over the same frequency range.

Detection threshold is a basic psychophysical measure that is needed in estimating the perceived intensity (or sensation level) of physical stimulation, as demonstrated in some of our previous studies (e.g., [3-6]). Detection thresholds of vibrotactile stimuli depend on many experimental conditions, such as contact site, contact area, and the use or lack of a rigid surround (see [7-10]). However, detection thresholds transmitted through a tool held in the hand have not been studied extensively, despite the need for such data for the design of haptic interfaces and rendering algorithms. Brisben et al. reported the displacement detection thresholds for a cylindrical tool that was held in the palm of the hand in a power grip and vibrated in a direction tangential to the skin of the palm [9]. One of our previous studies published the displacement and force detection thresholds measured with a stylus held in a pen-holding posture [1]. In the present study, we investigated the detection thresholds for a spherical tool held with multiple fingers. These detection thresholds were subsequently used for estimating the mechanical impedance of the hand at both threshold and suprathreshold levels.

Mechanical impedance of the hand is an important biomechanical property instrumental in designing haptic interfaces and in understanding the effect of haptic rendering algorithms. Numerous previous studies have investigated the mechanical impedance of the human skin under different conditions [11-15]. In addition to using a new tool shape, the present study went further by measuring mechanical impedance at supra-threshold stimulation levels, as well as at threshold levels.

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Two experiments were carried out. In Exp. 1, we measured the detection thresholds using an adaptive procedure and estimated the mechanical impedance at threshold levels. In Exp. 2, the mechanical impedance at supra-threshold levels were estimated using the detection thresholds obtained in Exp. 1. We present the methods used in the experiments in Sec. 2, followed by the experimental results in Sec. 3. We discuss the results and conclude the article in Sec. 4.

2. Methods

The methods used in the present study are similar to those used in our previous study [1] that reported the detection thresholds and mechanical impedance of a pen-hold posture using a stylus tool. This section thus focuses on the differences in experimental design between the previous and present studies.

2.1. Apparatus

The apparatus consisted of a mini-shaker system that could deliver vibrations of any waveform with amplitudes below micrometer levels, and at the same time record both acceleration and force data (Fig. 1). The main component was a mini-shaker (Bruel & Kjaer, Model 4810) with a bandwidth of 18 kHz. A polycarbonate solid ball of 2-inch diameter was attached to the end of the vibrating shaft. Further details about data acquisition hardware, signal processing, and system calibration can be found in [1].

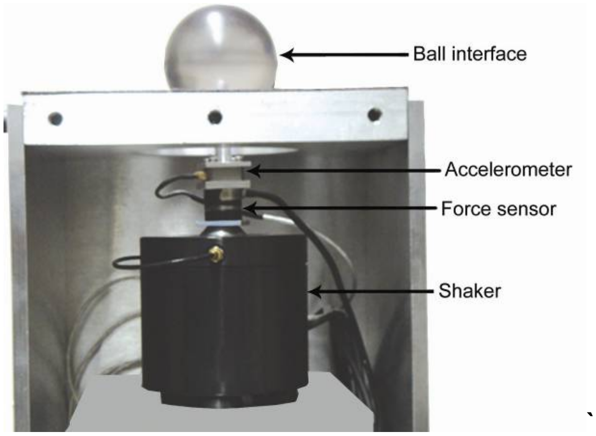

Fig. 1. Shaker assembly with one of the side panels removed

Fig. 2. Experimental Setup

2.2. Participants

Four males and six females (19−31 years old with an average of 24 years) participated in this study. Eight were right-handed and the other two were left-handed by self-report. Five participants were experienced users of vibrotactile haptic devices. The rest were considered to be inexperienced.

2.3. Procedure

The participant sat in front of a computer monitor with the right hand holding the ball interface (Fig. 2). The participant's elbow and forearm rested on an arm rest. The participant was instructed to hold the ball with all five fingers. In this posture, vibrations transmitted through the ball were mostly tangential to the skin in contact. The areas of the skin touching the ball are illustrated by shaded ovals in the inset of Fig. 2.

The stimuli consisted of 1-sec sinusoidal waveforms at seven frequencies (10, 20, 40, 80, 160, 320, and 500 Hz) equally spaced on a logarithmic scale (except for the highest frequency).

In Exp. 1, a three-interval, forced-choice, one-up three-down adaptive method was used. On each trial, the participant was presented with three stimulus intervals. One randomly selected interval contained the test stimulus and the other two contained no signal. The participant's task was to indicate during which interval the haptic stimulus was felt by pressing the key "1", "2" or "3". The resulting detection threshold corresponds to the 79.4-percentile point on the psychometric function [16]. The stimulus level changed by 4dB for the first 3 reversals and by 1dB for the subsequent 12 reversals (see [1] for further details). Measurement at each frequency took 5-8 minutes. The entire experi-

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ment took about 2 hours, conducted in two sessions on two different days for each participant. The total contact area between the participant's fingers and the ball-interface was estimated to be 710 to 1377 mm^2 (average = 1097 mm^2) (see [1] for method).

In Exp. 2, the mechanical impedance of the finger skin at supra-threshold levels were estimated. Five participants from Exp. 1 took part in Exp. 2. They were asked to hold the ball as they did in Exp. 1, and the shaker was excited with sinusoidal vibrations 10 dB (×3.16) and 20 dB (×10) above the position detection thresholds measured in Exp. 1 at the seven frequencies. The force values under unloaded condition were also measured at the two stimulation levels, and were subsequently used to cancel out the impedance of the shaker device itself (see [1] for details).

2.4. Data Analysis

For threshold estimation, the last 12 reversals (six peaks and six valleys) at the 1-dB step size were used to calculate the position detection threshold (mean of the averages of the six peak-valley pairs) and its standard deviation (from the six averages) for each participant at each test frequency.

To process force data, the forces measured in the unloaded condition was subtracted from those in the loaded condition, in order to isolate the net forces applied to the fingers holding the ball interface (see [1] for details). The mechanical impedance was then calculated as the net applied force divided by velocity.

3. Results

The position detection thresholds for vibrations applied on all five fingertips contacting the ball interface measured in Exp. 1 are shown in Fig. 3. Each filled circle represents the average over the ten participants, along with the standard errors. For comparison, the detection thresholds measured at the thenar eminence [8], those for a power grip of a cylindrical tool [9], and those estimated for holding a stylus [1] are reproduced here using dashed and solid lines and open circles, respectively. As expected, the shape of the threshold curve found in the present study was very similar to those reported earlier: the thresholds decreased as frequency increased, reached a minimum at around 160-320 Hz, and increased again at higher frequencies.

A two-way (frequency and participant) ANOVA showed that both factors were statistically significant for position threshold as well as their interaction [*F*(6,350)=11689 for frequency, *F*(9,350)=224 for participant, *F*(54,350) = 69 for the interaction term; $p<0.001$ for all]. Another two-way (frequency and experience) ANOVA revealed that the participants' prior experience did not significantly affect the measured thresholds [*F*(1,406)=3.86, p=0.05].

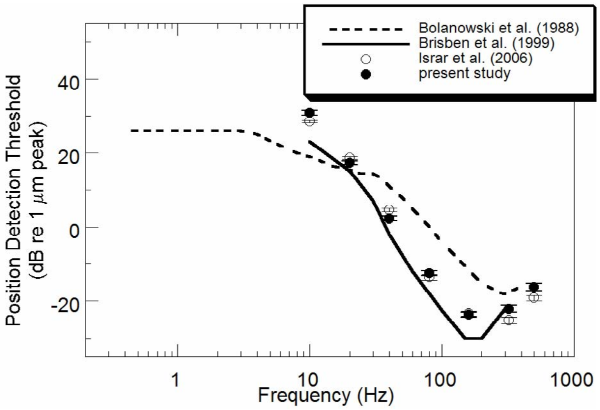

Fig. 3. Measured position detection thresholds and comparison with published data.

The force detection thresholds averaged across all participants are presented as filled circles in Fig. 4, along with standard errors. The force detection thresholds measured from holding a stylus are also shown as open circles. We can observe that the force threshold data are similar for holding a stylus and a ball, with the latter shifted slightly upwards at higher frequencies. The force thresholds exhibited a conventional U-shaped curve with a minimum at around 160 Hz.

Similar to the position threshold data, a two-way (frequency and participant) ANOVA showed that both factors as well as their interaction were significant [*F*(6,350)=1638 for frequency, *F*(9,350)=161 for participants, and *F*(54,350)=40 for the interaction term; $p<0.001$ for all]. Unlike the position threshold data, experience was a significant factor in measured force threshold data [*F*(1,406)=9.05, p=0.003].

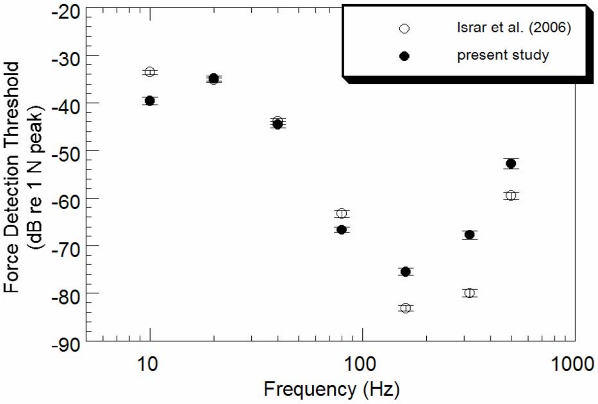

Fig. 4. Measured force detection thresholds

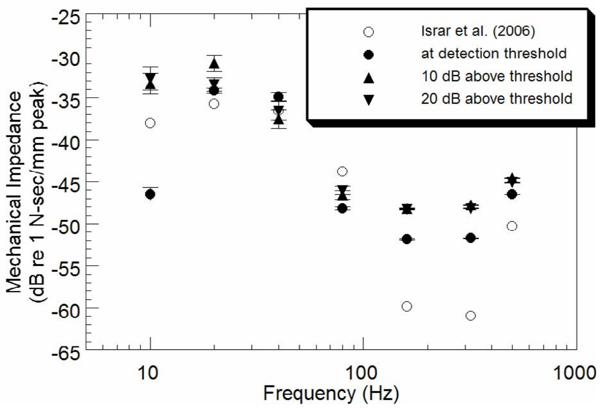

Fig. 5. Mechanical impedance of the hand at threshold and supra-threshold levels

Fig. 5 shows the estimated mechanical impedance for holding the spherical tool at threshold stimulation levels (filled circles, using data from Exp. 1), and at 10 and 20dB above detection threshold (filled upward and downward triangles, respectively, using data from Exp. 2), along with standard errors. The mechanical impedance for holding a stylus at the threshold stimulation level is also shown as open circles for comparison.

At the threshold level (filled circles), the slope of the data was 12 dB per octave between 10 and 20 Hz, varied from 0 dB to –13 dB per octave in the frequency range 20 and 320 Hz, and was 5 dB between 320 and 500 Hz. Comparing the data for holding ball and stylus interfaces (filled and open circles, respectively) at the threshold level, the mechanical impedance data were similar below about 80 Hz (except for an apparent outlier at 10 Hz), and the minimum mechanical impedance was observed between 160 and 320 Hz. However, impedance for holding the ball interface was larger at higher frequencies.

The mechanical impedance at the 10 and 20 dB supra-threshold levels consistently coincided with the mechanical impedance at the threshold level for the ball interface (except for the outlier at 10 Hz). A two-way (frequency and stimulation level) ANOVA showed that frequency was a significant factor [$F(6,469)=7960$, $p<0.001$] and effect of stimulation level was marginally significant [$F(2,469)=3.3$, $p=0.04$]. A two way ANOVA analysis excluding the outlier at 10 Hz showed that the mechanical impedance measures were not significantly different at the three stimulus levels for the ball interface [$F(2,402)=0.93$, $p=0.40$].

4. Discussion

The position detection thresholds obtained in the present study were more similar to those reported by [9] than those obtained in [8], presumably because both the Brisben et al. and present study involved vibrational stimulation that were tangential, as opposed to normal, to the skin surface in the hand and that the contact areas were larger than those involved in the Bolanowski et al. study. It is also apparent from Fig. 3 that the position thresholds for holding a stylus and a ball interface are quite similar. The most sensitive region is similar in all studies (between 160-320 Hz).

It is apparent from Fig. 3 that the slope for position threshold data at low frequencies (below about 20 Hz) was lower for the Bolanowski et al. study than those in the other studies. This was most likely due to the use of a rigid annulus surround that restricted the spread of vibrations on the skin in [8]. It has been shown in several studies that the use of a rigid surround significantly lowered the slope of the position detection threshold curve in the low and medium frequency ranges [7, 17].

The force detection thresholds obtained in the present study, along with those measured in our previous study [1], provide data that have rarely been measured in detection threshold studies. With the prevalent use of force-feedback haptic interfaces, it seems only natural to ask whether detection thresholds should be expressed in terms of displacement (as has traditionally been done) or force (as this is the more relevant parameter for force-feedback displays). Although the two data sets shown in Fig. 4 are quite similar in overall shape, there are nevertheless differences at the low and high frequency regions. To what extent the differences can be attributed to the use of a ball vs. a stylus interface remains to be resolved in future studies.

The general shape of the mechanical impedance curve at the threshold level is very similar to those reported previously: the slope was constant up to about 40 Hz, decreased with increasing frequency before reaching a minimum level at around 160-320 Hz and then increased as the frequency increased. The mechanical impedance of the contact skin exhibited all three components of mass (with a slope of 6 dB/octave), damper (with a slope of 0) and spring (with a slope of –6 dB/octave). The damper-like element was prominent at frequencies below 40 Hz, followed by spring-like element between 40 and 160 Hz. The mass-like element was prominent at frequencies above about 320 Hz. Comparing mechanical impedance of the ball interface with the stylus interface of our previous study [1], the mechanical impedance for the ball interface was shifted upward at low frequencies (<40 Hz) and at high frequencies (>160 Hz). The shift in mechanical impedance was perhaps due to a larger skin contact area for the ball-type interface as compared to the contact areas noted in the previous studies [13, 18].

In our future work, we will use the results from our present and previous studies [1] to access perceived intensities of proximal stimuli and for detailed analyses of haptic perception of real and virtual objects. We also intend to investigate whether position, force or their combination is the most relevant variable for describing haptic perception using force-feedback devices. Based on the experimental data gathered in the present study, there was evidence that the force and position variables are related, at least near detection threshold levels, by a constant. It is therefore speculated that the mechanical impedance is a more succinct variable in characterizing human perception of virtual or remote objects.

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