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Detection of Torque Vibrations Transmitted Through a Passively-Held Rotary Switch

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Abstract. This study is part of an ongoing research program aimed at understanding how humans perceive the properties and qualities of everyday objects such as rotary switches. This article reports our measurement of detection thresholds for torque vibrations transmitted through a passively-held rotary switch. We show that the torque thresholds are very similar to published displacement thresholds in that both types of threshold vs. frequency curves are U-shaped and both reach a minimum around 100-300 Hz. As far as we are aware, this is likely the first report of detection thresholds for sinusoidal torque vibrations.

1 Introduction

One of the most basic studies in sensory performance is that of detection thresholds. The term “detection threshold” (or “absolute threshold”) is defined as the “smallest amount of stimulus energy necessary to produce a sensation” ([1], p.1). In haptics research, the detection thresholds for the somatosensory system have been well characterized in terms of the smallest perceivable amplitude of sinusoidal movements over the frequency range 0.4–600 Hz [2, 3]. These studies typically involved placing a body site (e.g., the fingertip) in contact with a minishaker with calibrated sinusoidal movement amplitudes. Rigid surround was sometimes used to restrict the area of haptic stimulation. The experiments were typically conducted in a sound-proof and vibration-proof environment. Although the results such as those in [2] have been extremely useful in assessing the perceived intensity of vibrotactile stimuli, they do not generalize well to situations involving the use of tools and everyday objects. This is because that detection thresholds are known to vary substantially when conditions such as contact area and body site change [4]. A recent study examined the detection thresholds for vibrations transmitted through a tool held in the palm of the hand [3]. Thresholds were found to be lower than those reported earlier in the literature. The higher sensitivity was attributed to the larger contact area between the tool and the skin of the palm, the direction of vibration (parallel as supposed to perpendicular to the skin surface), and the stimulation site (palm was found to be more sensitive to lateral vibration than fingerpads). The study underscores the need for additional studies to assess detection thresholds associated with everyday tools.

Our interest in assessing detection threshold was motivated by our previous study on a common haptic interface — a rotary switch [5]. Using an active turning procedure, we found that human users could detect a sinusoidal torque[1] variation in the range 0.37–26.17% of the offset torque (30 N·mm) when the spatial period of the sinusoidal torque variation was from 2.8° to 180°. These results attested to the extraordinary sensitivity of the human hand to dynamic torque events in a rotary switch, especially when the spatial period of the torque ripple was small. In our previous study, the torque variations were specified in angular spatial periodicity in degrees/cycle — a common practice used by switch manufacturers. As a subject turned the rotary switch, temporal torque variations whose characteristics depended on the turning velocity were felt through the subject's hand. It was therefore important to ask the question of whether the measured detection thresholds depended on the spatial or the temporal frequency characteristics of the simulated rotary switch. One way to investigate the question would be to convert the spatial frequency characteristics of the stimuli used in our previous study to the corresponding temporal frequency profiles using velocity data recorded during the experiments, and then compare the resultant detection thresholds to those in the literature. This approach assumes the availability of data on the detection of torque variations specified in temporal frequencies. To the best of our knowledge, however, such data do not exist. The detection threshold data available in the literature, including those from the Brisben *et al*. study [3], are expressed in displacement amplitude, not force or torque magnitude, as a function of vibratory frequency in Hz. It is also unclear whether threshold data specified in displacement and force/torque should follow a certain relation [personal communication with M. Srinivasan and K. Johnson]. Therefore, it was necessary to first estimate the detection thresholds for torque vibrations in the form of a *torque-magnitude* vs. temporal-frequency function. This article is perhaps the first to report the detection threshold of vibrations characterized by force/torque instead of displacement.

In the rest of this paper, we present the methods used in our experiments (Sec. 2) and the results (Sec. 3), followed by a brief discussion (Sec. 4).

2 Methods

The experimental apparatus used in this study was the same as that used in our previous study [5].

2.1 Subjects

Four subjects (3 males and 1 female, aged 29-38) participated in the current study. Three of the subjects were familiar with the experimental apparatus. One subject (AI) had not used this apparatus before, but is familiar with vibrotactile stimulators in general. None of the subjects had any impairments in the sensory-motor capabilities of their left hands.

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[1] Torque is a measure of the force applied to produce rotational motion. It is determined by multiplying the applied force by the distance from the pivot point to the point where the force is applied.

2.2 Stimuli

Torque vibration was programmed to be a small-amplitude sinusoidal function superimposed on a constant torque offset (Fig. 1). The sinusoidal torque vibration was specified by its magnitude (N·mm), temporal frequency (Hz), and duration (500 ms). To eliminate any possible step change in torque magnitude at the beginning or the end of a stimulus delivery, a Hanning window was applied to the sinusoidal portion of the signal. The Hanning window consisted of a 50-ms rise portion, a 50-ms fall portion, and a 400-ms constant portion in-between.

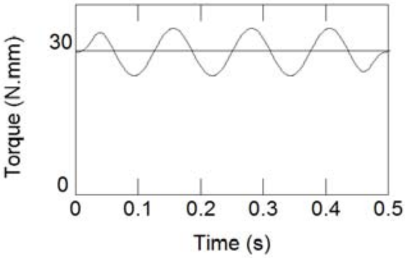

Figure 1. Torque vs. time profile of a typical stimulus (8 Hz). Notice the slightly reduced amplitudes of the two peaks at the beginning and the end due to Hanning windowing. The offset torque level was kept at 30 N·mm. The amplitude of the superimposed sinusoidal signal varied from trial to trial depending on whether the subject was able to detect the presence of the torque ripple on the previous trial

2.3 Procedure

The subject sat in front of a table with the apparatus on the left and a computer monitor and a keyboard on the right. During the experiments, the subject was instructed to rest the left elbow on the table in a comfortable position, and to grasp the interface knob with the thumb and the index finger of the left hand. The subject was then instructed to turn the knob slightly counterclockwise (to take it off a mechanical hard stop), and to hold the knob still in space throughout an experimental run. In other words, unlike the active turning motions required in our previous study [5], a passive condition was used in this study. The knob and the subject's hand holding it were covered with a curtain that served as a visual shield. The subject wore ear plugs and a noise-reduction earphone to mask any sound emanating from the motor.

Training was provided at the beginning of each run. The subject was allowed to feel a constant torque of 30 N·mm or a variable torque profile similar to the one shown in Fig. 1. Training was terminated when the subject was confident in telling the constant and variable torque profiles apart. Data collection began immediately after the training procedure ended. No feedback was provided during data collection.

Detection thresholds were determined with a three-interval forced choice (3IFC) paradigm combined with a one-up three-down adaptive procedure (see [6] and a review of adaptive procedures [7]). On each trial, the subject felt three stimuli: two of the stimuli were of constant torque (30 N·mm), and the other one contained the sinusoidal torque vibration. The subject's task was to indicate which of the three intervals ("1", "2" or "3") contained the torque vibration. Timing of the stimulus delivery is shown in Fig. 2. The magnitude of the sinusoidal torque variation was reduced after the subject had made three consecutive correct responses. The magnitude was increased after each incorrect response. The initial torque-vibration magnitude was always set to be higher than the anticipated detection threshold at the corresponding frequency. It changed initially by 4 dB and then by 1 dB after the first three reversals. A reversal occurred when the torque-vibration magnitude changed from increasing to decreasing, or vice versa. An experimental run was terminated after 12 reversals at the 1-dB step size. Detection threshold was estimated by averaging the peaks/valleys at the last 12 reversals. To estimate the standard error of the threshold, 6 estimates of the threshold were calculated from the 6 pairs of the peaks/valleys at the 12 reversals, and the corresponding standard error was obtained (see [3] for details).

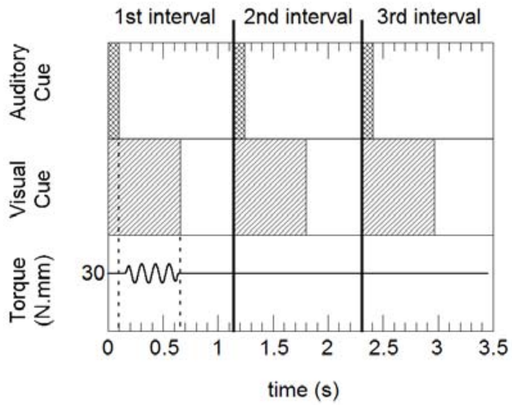

Figure 2. Timing diagram of the 3-interval forced choice (3IFC) paradigm. Shortly after the subject entered a response, a 100-ms 2-kHz auditory tone indicated the beginning of the first of the three intervals for the next trial. A 650-ms visual cue (a text string on the computer monitor) indicated the current interval ("1st", "2nd" or "3rd interval"). The visual and auditory cues had the same onset time. The haptic stimulus began 150 ms after the onset of the auditory and visual cues, and lasted for 500 ms. The offset of the visual cue coincided with that of the haptic stimulus, thereby served to signal the end of a haptic stimulus. This was necessary because, during two of the three intervals, no change in torque magnitude occurred (e.g., intervals "2" and "3" in this diagram). The interval during which torque vibration occurred was randomly selected from the three intervals. After a short pause of 500 ms, the auditory and visual cues for the next interval started all over again

3 Results

Detection thresholds for the four subjects over the frequency range 2-300 Hz, as well as their averages, are shown in Fig. 3. The data indicate a general trend of decreasing threshold as frequency increased, with the lowest thresholds occurring at the 200–300 Hz frequency range. Individually, detection thresholds ranged 0.034 N·mm (SY at 256 Hz) to 5.04 N·mm (SC at 2 Hz), or 0.11% to 16.80% of the 30 N·mm offset torque, respectively. The averaged thresholds started at 2.82 N·mm at 2 Hz and reached a minimum of 0.080 N·mm at 200 Hz, before it picked up again. The average torque thresholds are very similar to the published displacement thresholds in that both types of threshold vs. frequency curves exhibit U shapes and both reach a minimum around 100-300 Hz (see, for example, [2]).

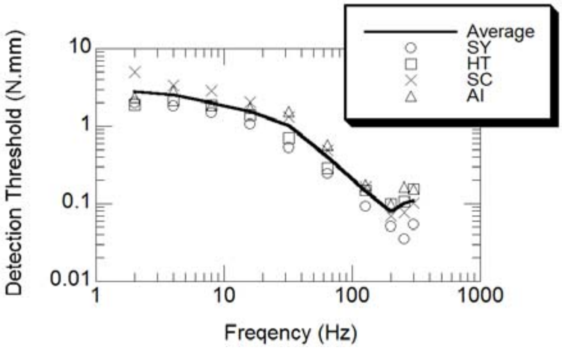

Figure 3. Detection thresholds for torque vibration as a function of temporal frequency. Standard errors averaged 6.2%, 5.0%, 4.7% and 4.4% for subjects SY, HT, SC and AI, respectively. For clarity, the standard errors are not shown in this graph.

4 Discussion

In this study, we estimated the detection thresholds for torque vibrations over the frequency range 2–300 Hz. Our data are unique in that unlike published threshold results that are expressed in the minimum perceivable displacements, we estimated the minimum *torque* that could be reliably detected. The torque thresholds are more relevant than displacement thresholds when we consider tools and devices that are designed to deliver force/torque (e.g., switches, force-feedback displays, etc.).

There is a striking similarity between the shape of the torque threshold curve obtained in this study and the displacement threshold data widely available in the literature. Shown in Fig. 4 are the torque threshold curve reproduced from the average threshold data obtained in this study (the solid line in Fig. 3) and the displacement threshold curve from the Bolanowski *et al.* study (Fig. 1 in [2]). It is apparent that to the first order of approximation, these two curves overlap over the frequency range 2–300 Hz. We are amazed by this simple linear relationship as demonstrated in Fig. 4 because the experimental setups in the two studies (in terms of the body sites tested, total contact areas, temperature control or the lack thereof, surround conditions, and procedures) are quite different. Furthermore, the force-displacement relation at a body site is generally quite complex. We can express this relation as $F = F_0 + Kx + B\dot{x} + M\ddot{x} + \cdots$ (F: force, F_0: offset force, K: stiffness, x: displacement, B: viscosity, $\dot{x}$: velocity, M: mass, $\ddot{x}$: acceleration). The fact that we were able to align the two threshold curves shown in Fig. 4 with a simple linear equation $F = F_0 + Kx$ suggests that the skin and its underlying tissues can be modeled as a first-order elastic spring as far as detection thresholds are concerned.

From Fig. 4, it is also apparent that the most efficient way to deliver haptic stimuli (in terms of least power consumption) would be to use signals in the 100–300 Hz region. This result has implications for many applications where simple, small,

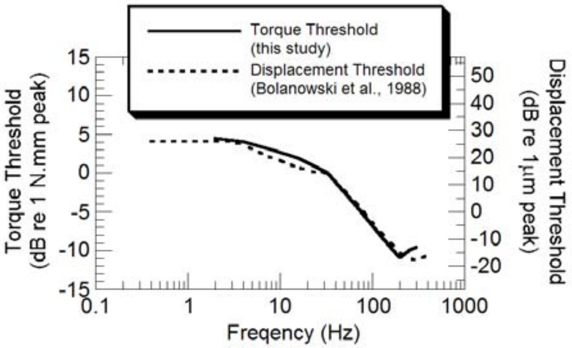

Figure 4. Comparison of displacement and torque threshold data. See text for details.

low degree-of-freedom haptic devices are used ubiquitously (e.g., haptic devices in automobile interior). There have been several studies in the recent years concerning the power consumption issue of haptic interfaces (see, for example, [8]).

In the near future, we will continue to investigate the underlying mechanisms for torque perception, with the goal to discover whether the temporal or spatial frequency contents determine torque thresholds such as those measured in the current study. For example, if different detection thresholds are obtained for a rotary switch of a particular spatial profile turned at different velocities, we will then be able to conclude that it is the temporal frequency contents, not the spatial frequency contents, that determine the thresholds for torque perception in rotary switches.

Acknowledgment

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