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A multi-digit tactile motion stimulator

Yu-Cheng Pei[a,b,*], Tsung-Chi Lee[a], Ting-Yu Chang[a], Donald Ruffatto III[c], Matthew Spenko[c], Sliman Bensmaia[d,**]

[a] Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital at Linkou, Taoyuan, Taiwan
[b] Healthy Aging Research Center, Chang Gung University, Taoyuan, Taiwan
[c] Department of Mechanical, Materials, and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL, United States
[d] Department of Organismal Biology and Anatomy, University of Chicago, Chicago, IL, United States

HIGHLIGHTS

- Little is known about how tactile information is integrated across digits.
- We describe a tactile motion stimulator that can stimulate multiple digits independently.
- We use the stimulator to probe subjects' ability to discriminate tactile motion.
- We replicate previous findings with single digit stimulation.
- Stimulation of multiple digits reveals biases in the perception of tactile motion.

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ABSTRACT

Background: One of the hallmarks of haptic exploration is that it typically involves movement between skin and object. Explored objects may contact multiple digits simultaneously so information about motion must be integrated across digits, a process about which little is known.
New method: To fill this gap, we have developed a stimulator that allows for the simultaneous and independent delivery of motion stimuli to multiple digits. The stimulator consists of individual units that deliver motion with three degrees of freedom: rotation (to produce motion), vertical excursion (to control depth of indentation into the skin) and arm orientation (to control the direction of motion). Each degree of freedom is controlled by a single motor. The compact design of the simulator allows for the side-by-side arrangement of the stimulator units such that they impinge upon adjacent fingers.
Results: To demonstrate the functionality of the stimulator, we performed a series of psychophysical experiments that investigate the perception of motion on multiple fingers. We find that, while the sensitivity to changes in motion direction is equivalent whether stimuli are presented to the same or to different fingers, the perceived direction of motion depends on the relative configuration of the digits.
Comparison with existing methods: We replicated the results of previous experiments investigating motion discrimination with a single digit and were able to extend these findings by investigating motion perception across multiple digits.
Conclusion: The novel motion stimulator will be an invaluable tool to investigate how motion information is integrated across multiple digits.

1. Introduction

When we interact with an object, much information about the object is conveyed through signals from the hand. Information about the shape of the object, its texture, its compliance, and its thermal properties, is carried in the pattern of activity evoked in a variety of types of receptors embedded in the skin, joints, and muscles. This information allows us to recognize objects based on tactile exploration alone, when, for instance, our visual system is not available, as is the case in the dark or when one object is occluded by another. One of the hallmarks of tactile object recognition is that it involves movement between the skin and the object. Because

* Corresponding author at: Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital at Linkou, Taoyuan, Taiwan. Tel.: +886 33281200x3846; fax: +886 33281200x2667
** Corresponding author at: Department of Organismal Biology and Anatomy, University of Chicago, Chicago, IL, United States. Tel.: +1 312 320 4315; fax: +1 773 702 0037.
E-mail addresses: yspeii@gmail.com (Y.-C. Pei), sliman@uchicago.edu (S. Bensmaia).

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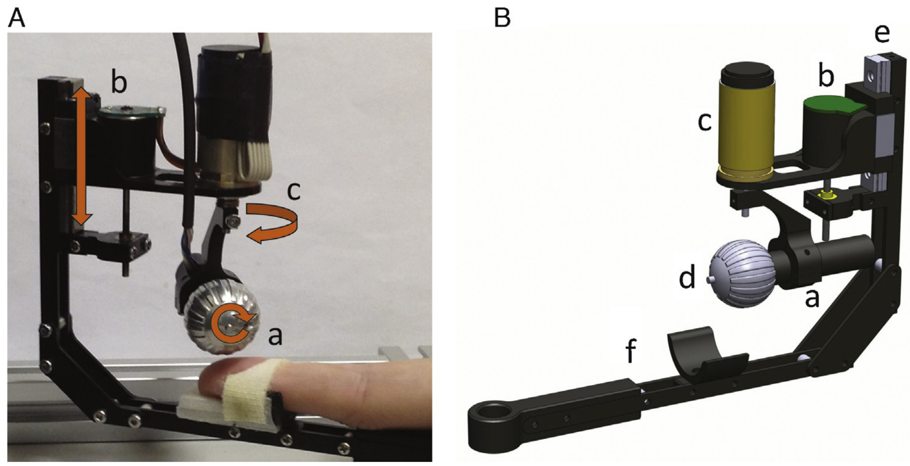

Fig. 1. Design of a stimulator unit. (A) Each unit has three degrees of freedoms, including (a) ball rotation, (b) vertical excursion of the stimulus ball and (c) orientation of the rotating arm and stimulus ball. (B) The stimulator consists of a DC motor that controls speed of the stimulus ball (a), a stepper motor with spiral shaft that controls vertical indentation of the stimulus ball into the skin (b), a DC motor that controls the direction of motion (c), a stimulus ball that makes contact with the skin (d), a precision slide that guides the vertical movement of stimulus ball (e), and a finger holder (f). In this example, the stimulus ball has a diameter of 20 mm and is engraved with square-wave grating of 3.9 mm wave length, 250 μm peak-to-peak amplitude, and 0.6 duty cycle.

scanning is such an important part of tactile object recognition, information about the motion of the sensory sheet relative to the object is important to extract information about the spatial properties of the object. (Johnson, 2001; Lederman and Klatzky, 1987).

A long-standing question is how information about stimuli impinging upon different fingers is combined to form a holistic percept such that we perceive one rather than multiple objects. As far as motion processing is concerned, the evidence suggests that, when a single digit is stimulated, the somatosensory system implements a mechanism (vector average) to compute tactile motion direction that bears similarities to its visual counterpart (Pei et al., 2008, 2010, 2011). In a series of psychophysical experiments, Rinker and Craig investigated how motion impinging upon two digits was integrated. They found that moving stimuli delivered to the thumb and index finger interacted perceptually only when they were spatially parallel, suggesting that the local tactile motion information could be combined into a common coordinate system under some circumstances (Craig, 2003; Rinker and Craig, 1994). However, because the motion stimuli were relatively bulky, the ability to investigate the relationship between hand conformation and motion integration across digits was limited.

In the present study, we introduce a novel motion stimulator that allows for simultaneous and independent delivery of motion stimuli to multiple fingers. In a pair of psychophysical experiments, we show that this stimulator can be used to investigate how motion information is integrated across fingers.

1.1. *Previous tactile stimulators*

Tactile motion has previously been generated with a variety of different apparatuses. One approach consists of generating motion in the horizontal plane (Bicchi et al., 2008; LaMotte and Whitehouse, 1986; Olausson and Norrsell, 1993; Romo et al., 1993; Sinclair et al., 1996). Another approach involves activating tactors in sequence to generate simulated motion (Bliss et al., 1967; Killebrew et al., 2007; Summers and Chanter, 2002; Van Doren et al., 1987). A third approach consists in generating rotational motion (Depeault et al., 2008; Essick and Whitsel, 1985; Johnson and Phillips, 1988; Keyson and Houtsma, 1995; Salada et al., 2004; Tomassini et al., 2011; Webster et al., 2005). While these tactile stimulators are capable of delivering smooth real or simulated motion, they are too large to be arranged such that they can stimulate different digits with independently controlled stimuli. Moreover, the heavy weight of these stimulators imposes constraints on the experimental design. Some of these stimulators have to be anchored to the ground or wall, and thus can only deliver tactile stimuli to the subject in a fixed plane. For example, the 400-probe stimulator (Killebrew et al., 2007) can only be presented in the transverse plane with subject's palm facing up. Finally, more compact vibratory arrays such as the OPTACON (Bliss, 1967), which can be used to deliver motion stimuli to multiple fingers (Craig, 2003; Rinker and Craig, 1994), only activate rapidly adapting and Pacinian but not slowly adapting type I afferents (Gardner and Palmer, 1989a,b), thus excluding a major tactile submodality. Aiming to eliminate these constraints, we have designed a novel tactile motion stimulator that allows for simultaneous and independent delivery of motion stimuli to adjacent fingers.

1.2. *Design of the stimulator*

The multi-digit stimulator consists of two or more identical units (one of which is illustrated in Fig. 1), which in combination yield three degrees of freedom: rotation for producing motion, vertical excursion for controlling depth of indentation into the skin, and arm orientation for controlling the direction of motion. Each degree of freedom is controlled by a single motor: two DC motors drive the rotational motion and direction of motion, a stepper motor drives the depth of indentation. The use of a ball, as opposed to a cylinder, eliminates the covariation of orientation and motion direction. The surface of the ball can be textured, with grooves or dots if one wishes to investigate the effect of surface geometry on the processing and perception of motion. The compact design of the simulator allows for side-by-side arrangement of multiple stimulator units such that they impinge upon adjacent fingers (Fig. 2). Moreover, given its light weight (each stimulator unit and finger holder weighs 130 and 10 g, respectively) and small size, the stimulator unit can be placed at any orientation in space by attaching it directly to the subject's fingers. In one experimental setup, we use a custom-made finger holder for positioning the metacarpophalangeal (MCP) joint in a specified abduction–adduction posture for each finger. Two example multi-digit posture settings are shown in Fig. 2. One in which adjacent fingers are parallel (0°), the other in which the fingers are at an angle of 20°. The adjustability of finger postures allows for studying the integration of motion information across digits in a variety of hand conformations.