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Pressing movements and perceived force and displacement are influenced by object stiffness

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HIGHLIGHTS

- Number of presses and pressing duration were constant along a wide stiffness range.
- Pressing strength was adjusted to fit object stiffness.
- Force differences between two compared specimens became small at higher stiffness.
- Perceived differences in force and displacement were influenced by object stiffness.

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ABSTRACT

Despite many previous studies on stiffness perception, few have investigated the exploratory procedures involved. This study evaluated whether stiffness range influences pressing movements and perception of force and displacement during stiffness discrimination tasks. Force and displacement data were obtained from 30 participants. Peak values of force and displacement, pressing duration and number of presses were analyzed. Two kinds of subjective evaluations were also recorded: perceived difference in force/displacement used to discriminate between specimens, and perceived effort. Although the number of presses and pressing duration were constant across a wide stiffness range, pressing strength was adjusted for the stiffness of objects, with harder specimens pressed more strongly. Further, even if the stiffnesses of two compared specimens were different, the pressing forces applied to the specimens approached the same magnitude at a higher stiffness range. Differences in force were most easily perceived at lower stiffness ranges, while displacement differences were perceived more readily at higher stiffness ranges. These results were consistent with those of previous studies. Finally, the reasons why stiffness range influenced pressing movements and perceived differences in force/displacement are discussed.

1. Introduction

We encounter many kinds of elastic objects in our daily lives. We perceive their elastic characteristics by applying forces to deform them, and stiffness is defined as the ratio between applied force and displacement. Haptic exploratory procedures have been studied for more than half a century [1,2]. These procedures purposively adapt to both the perception and state of sensed objects [3–6]. Further, exploratory procedures and perceptions influence each other [7–10]. Therefore, characteristics of exploratory procedures are considered to provide useful information for understanding the mechanisms of perception.

When the surface of an object is deformable, as with a rubber block, tactile sense is known to provide important cues in perceiving elasticity [11–14]. Force and displacement information perceived by kinesthesia is also used [15–18], and several cue possibilities have been reported: the ratio between force and displacement [17], mechanical work that is defined as force integrated over displacement [15,18], and displacement and motor commands [16]. Though it is not doubted that force and displacement information obtained by the exploratory procedure relate to stiffness perception, no consistent results were obtained about their use. The principal exploratory procedure for stiffness perception is the pressing movement. It was reported that participants altered their pressing strength depending on the object, with a higher force applied if the object was expected to be hard or if the difference in stiffness between objects was small [4]. The higher pressing force was thought to increase deformation and thus improve perceptual precision. This exploratory movement indicates that acquiring enough displacement is important for stiffness perception. Furthermore, peak force and force-rate were reported not to be significant cues for softness ratings [12]. In contrast, it was reported that application of constant finger displacement to an object might permit the estimation of the object's

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stiffness based on force alone [19]. Under the experimental condition involving pressing with fixed displacement, the mechanical work and terminal-force cues were reported to be used for the stiffness discrimination [18]. Moreover, the mode of contact, that is, the means by which force and displacement are obtained, was shown to influence stiffness perception through various kinds of softness estimation tasks [12]. Thus, since the exploratory pressing movement influences the perception of force and displacement, this movement should be investigated to clarify the mechanism of stiffness perception.

Mugge et al. reported that the range of object stiffness influenced pressing movements [20], though stiffness perception tasks were not performed. During tasks involving the reproduction of force or displacement while pressing an elastic object, sensory weighting between force and position feedback could be explained by an optimal model (maximum likelihood estimation model) of signal integration [21,22], where the weight of the position signal was larger at low-stiffness ranges and the weight of the force signal was larger at high-stiffness ranges. For example, when participants were instructed to reproduce the same pressing magnitude (either force or displacement, depending on the task conditions) against low-stiffness objects, displacement was unconsciously maintained at the same level, and conversely, force approached the same level at high-stiffness ranges. These motor control results suggest one possible explanation of pressing movements during stiffness discrimination tasks. If the pressing movements for two specimens were repeated to reproduce the same magnitude of force/displacement, a specimen pair in the low-stiffness range might be pressed with the same displacement, whereas a pair in the high-stiffness range might be pressed with the same force.

Although many studies have investigated stiffness perception using stiffness discrimination tasks [4,11,13–19,23], and several possible cues for stiffness perception have been reported [15–18], the relationship between the exploratory pressing movement and the perception of force and displacement have not attracted much attention. Identifying the characteristics of motor control in the exploratory pressing movement should provide us with greater understanding of stiffness perception. Therefore, this study investigated the exploratory pressing movement during stiffness discrimination tasks by examining the relationship between force and displacement across a wide stiffness range.

2. Material and methods

2.1. Participants

Thirty participants (19 males and 11 females, 29 right handers and one left hander, age range 20–30 years) gave informed consent and took part in the experiment. They affirmed that they had no motor or sensory abnormalities in their hands. The ethics committee for human experimentation at the National Institute of Advanced Industrial Science and Technology approved the experimental procedures.

2.2. Specimens

Specimens were created with thermoplastic elastomer (SEPTONTM, Kuraray). The elastomer was dissolved in heated paraffin oil and then poured into a mold and cooled to harden. The stiffness of specimens could be varied by altering the ratio of elastomer and paraffin oil [24]. Specimens were cylindrical with a height of 30 mm and a diameter of 60 mm. To achieve a wide stiffness range, 11 specimens were created with an equal difference in stiffness between adjacent specimens on a logarithmic scale (Specimen IDs: S1–S11; only the 11th specimen (S11) was made from a commercially available silicone block) (Fig. 1). The stiffness difference between adjacent specimens was set so as to be detectable by most participants to evaluate perceived difference in force/displacement (discussed later). The stiffness of the softest specimen was 0.059 N/mm and that of the hardest was 2.36 N/mm, with the stiffness of the specimens measured with a materials testing machine (Instron 5542, Illinois Tool Works) using a probe with a diameter of 9.54 mm and a chamfer of 1 mm.

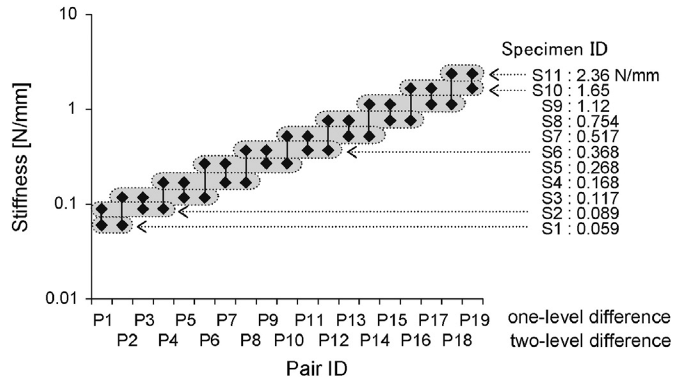

Fig. 1. Stiffness of specimens and their pairs in the discrimination tasks. Of the 11 specimens (S1–S11), 19 pairs (P1–P19) that differed by one or two levels of stiffness were compared. Regarding the pair IDs, odd numbers indicate pairs with a one-level difference, whereas even numbers indicate pairs with a two-level difference. The stiffness of the specimens shown in the figure was measured using a probe with a diameter of 9.54 mm; this size was smaller than that of the disk used in the discrimination tasks (18 mm).

2.3. Discrimination tasks

The experiment consisted of two-alternative, forced-choice discrimination tasks. Two specimens that differed by one or two levels of stiffness were paired, and 19 pairs were used in one session (pair IDs: P1–P19) (Fig. 1). Participants' exploratory pressing movements were performed with the index finger of the dominant hand (Fig. 2). The participants were instructed to press with the index finger only, and to avoid using their arm. To encourage the participants to press the specimen naturally, the pressing strength and number of presses were not restricted (the participants were allowed to press the specimens as often as they liked). However, to evaluate the force and displacement, only vertical movements were permitted while pressing, while horizontal movements and tapping were prohibited.

Because one of the purposes of this study was to investigate whether perceived difference in force/displacement was influenced by stiffness range, tactile information derived from finger skin deformation was excluded to enhance kinesthesia. This was done by concealing the specimen's surface information, an approach used in previous studies [11,13,14]. An undeformable thin plastic disk (with thickness of 2 mm and diameter of 18 mm) was placed on the center of the specimen and the participants were instructed to press the center of the disk (Fig. 2). Visual information was also excluded by placing a screen between the participants and the work space.

The experimental procedure was as follows. The participant was presented with the first specimen, and was asked to press it. When the participant finished the exploratory pressing movements and raised their finger from the specimen, an investigator changed the specimens so that the participant could again perform presses without changing their hand position. The pressing procedure was repeated four times (two repetitions for each specimen). If the participant could not discriminate between specimens within four repetitions, they were allowed to repeat the procedure until they identified the target specimen (harder or softer). They were also encouraged to complete the exploratory pressing movements without idling even if they had identified the target specimen within two or three exploratory movements. Half of the participants were instructed to identify the harder specimen and the other half were instructed to identify the softer specimen. No feedback regarding the correct answer was given. The order of pairs (P1–P19) and the stiffness of the specimen presented first (harder or softer) were varied randomly. Five sessions were performed (the first session was considered as practice and was excluded from the analysis).