Discrimination and Identification of Finger Joint-Angle Position Using Active Motion

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The authors report six experiments on the human ability to discriminate and identify finger joint-angle positions using active motion. The PIP (proximal interphalangeal) joint of the index finger was examined in Exps. 1–3 and the MCP (metacarpophalangeal) joint in Exps. 4–6. In Exp. 1, the just noticeable difference (JND) of PIP joint-angle position was measured when the MCP joint was either fully extended or halfway bent. In Exp. 2, the JND of PIP joint-angle position as a function of PIP joint-angle reference position was measured when the PIP joint was almost fully extended, halfway bent, or almost fully flexed. In Exp. 3, the information transfer of PIP joint-angle position was estimated with the MCP joint in a fully extended position. In Exps. 4–6, the JND and the information transfer of MCP joint-angle position were studied with a similar experimental design. The results show that the JNDs of the PIP joint-angle position were roughly constant ($2.5^\circ - 2.7^\circ$) independent of the PIP joint-angle reference position or the MCP joint-angle position used (Exps. 1 and 2). The JNDs of the MCP joint-angle position, however, increased with the flexion of both the PIP and MCP joints and ranged from 1.7° to 2.7° (Exps. 4 and 5). The information transfer of the PIP and MCP joint-angle position were similar, indicating 3–4 perfectly identifiable joint-angle positions for both joints (Exps. 3 and 6). The results provide the basic data needed for estimating, for example, the resolution of fingertip position during active free motion. They are compared to the results from previous studies on joint position, length, and thickness perception.

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1. INTRODUCTION

How well can people sense the position of their fingertips during active free movements? This question arises often when a user interacts with a virtual haptic environment via a thimble interface commonly used in some force-feedback devices. To the best of our knowledge, few studies have directly measured the sensitivity to displacement at the fingertip and the factors affecting it. Instead, researchers have examined resolution of joint-angle perception based on the widely accepted view that proprioception encodes joint-angle information from which position of the extremities can be derived (although see Biggs et al. [1999], for a model based on cadaver measurements that suggest the possibility of the direct estimation of fingertip location from extrinsic muscles in the forearm without a sense of finger joint angles). Accordingly, we also approach the problem of fingertip position resolution by studying human perception of joint-angle position.

A comprehensive review of past research on joint-angle perception can be found in Clark and Horch (1986). Careful distinction was made between perception of joint movement and position. In terms of detection of passive joint movement where the target joint was guided to a position by the experimenter, proximal (closer to one's torso) joints tended to exhibit smaller detection thresholds than distal joints, with the minimum detectable angles ranging from 0.2° to 0.7° for different joints, including shoulder, elbow, wrist, hip, knee, ankle, and finger (e.g., Laidlaw and Hamilton [1937]). Rate of passive movement affected detection threshold: a higher velocity resulted in a smaller minimum detectable angular excursion and a lower velocity led to a larger threshold [Hall and McCloskey 1983]. Interestingly, whereas the proximal joints (shoulder and hip joints) showed the smallest detection thresholds in angular rotation, the distal joints (finger joints) emerged as more sensitive when threshold data were converted from angular rotation of the joint to linear velocity of the fingertip [Hall and McCloskey 1983; Tan et al. 1994]. There was some evidence that performance at proximal and distal joints was similar when thresholds were expressed in terms of the proportional change in muscle fascicle lengths [De Domenico and McCloskey 1987; Hall and McCloskey 1983].

Perception of joint position has been assessed by the accuracy of matching target positions placed passively by an experimenter or actively by a participant. In a typical experimental setup, a joint on one side of the body (e.g., right elbow) was moved either passively by an apparatus controlled by the experimenter or actively by the participant to a predefined location. The participant was then asked to either match the perceived joint position with the same joint on the other side of the body (e.g., left elbow), or reproduce the perceived joint position with the same joint (i.e., right elbow). The mean error in matching was interpreted as a measure of *accuracy* or *bias* and the standard deviation of matching error a measure of *precision*. It appeared that, at least for elbow, ankle, shoulder, and knee joints, the highest accuracy (lowest mean matching error) occurred near some midpoint of the range of motion (e.g., when the shoulder was held close to the horizontal position or the knee lay at an angle of about 90°), but the greatest precision (lowest standard error) in matching was revealed near the two extremes [Clark and Horch 1986; Erickson 1974; Monster et al. 1973]. There was some evidence that matching accuracy improved when participants actively moved a target arm to a shoulder-joint position as compared to when the target arm was passively moved by an experimenter [Paillard and Brouchon

1968]. Muscle loading, isometric force production, and time elapsed between target presentation and response all interfered with the estimation of joint position [Clark and Horch 1986]. Evidence of a joint position sense separated from an awareness of joint movement has been demonstrated in studies concerned with the rotation of one of two aligned knees. Even though participants could not always tell which of the two legs had been moved, they were nonetheless able to detect a misalignment between the two knees after a few degrees of displacement had occurred [Clark et al. 1979; Horch et al. 1975]. It is generally accepted that kinesthetic (muscle spindle receptors, Golgi tendon organs) and cutaneous cues (skin stretch), as well as signals from the central nervous system (corollary discharge), contribute to our sense of joint position and movement [Clark and Horch 1986].

Whereas the aforementioned studies have shed light on the neural mechanisms for perception of joint movement and position, the issue of how best to characterize joint-angle resolution remains unresolved. It has been argued that the mean matching error alone does not provide an adequate account of joint position sense: one can be very accurate, on average, but with a large trial-by-trial variation (small mean error with large standard deviation) or have a large bias, but with a high degree of matching consistency (large mean error with small standard deviation) [Clark and Horch 1986; Clark et al. 1995]. A new metric, based on information theory, that takes into account the variance (noise) in perception has been proposed for assessment of joint-position resolution [Clark et al. 1995]. It is our view that all three measures (matching error, its variance, and information transfer) are needed in order to fully characterize a human's ability to judge joint positions. Under a framework developed for auditory intensity perception, signal-detection theory is useful for independently measuring the ability to *discriminate* two joint positions and the associated response bias. Information theory can be used to assess the ability to *identify* a joint position in the context of other possible positions. The two signal-detection metrics of sensitivity index and response bias are related to measurements of matching precision and accuracy/bias, respectively, obtained in previous studies employing a matching paradigm. Discrimination performance is thought to be limited by peripheral sensory noise and identification performance further limited by memory noise [Braida and Durlach 1970; Durlach and Braida 1969].

In the present study, we conducted six experiments to catalog the discrimination and identification performance of PIP (proximal inter phalangeal) and MCP (meta carpo phalangeal) joint-angle position of an index finger using active motion. The PIP and MCP joints are the two independent joints most commonly used in the pointing and positioning of fingertips. It was our goal to derive the resolution of fingertip position from the data obtained in the present study in order to assess the contribution of joint-angle position in other tasks, such as thickness discrimination or perception of virtual textures rendered with a force-feedback device. Toward this goal, our experimental setup deviated from that of most previous joint position studies in that (a) we used the same joint in one hand, instead of matching the corresponding joints in two hands, and (b) the participants moved their fingers actively to reach a joint-angle position. We believe that the setup closely follows the conditions under which most users perform tasks in real or virtual environments that require the discrimination or identification of joint-angle positions and, therefore, our experimental results are most relevant to typical applications.

2. METHOD

2.1 Participant

Eleven individuals (S1–S11), six males and five females, aged 19-to-54 years old, took part in the present study. Except for S9 who was blind and S6 who was both blind and deaf, the participants had normal vision and hearing. All participants reported normal sensory-motor capabilities with their hands. Except for S8, who was also an experimenter, all participants were paid on an hourly basis.

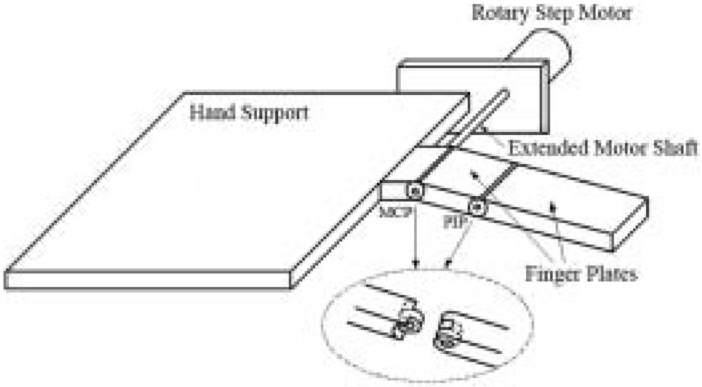

Fig. 1. Diagram of experimental apparatus depicting set-up for testing of MCP joint angle.

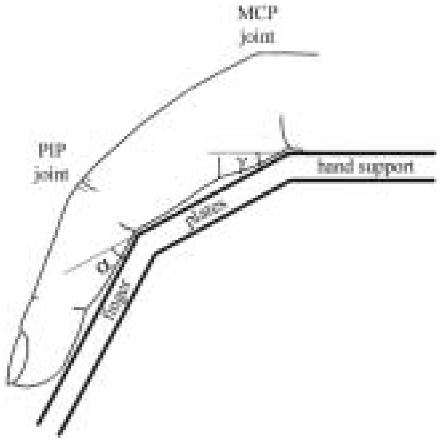

Fig. 2. Definition of PIP and MCP joint-angle positions (α and γ, respectively) of an index finger.

2.2 Apparatus

Figure 1 shows a diagram of the custom-made experimental apparatus used in the present study. The device was driven by a rotary-step motor (0.9° per step). When the PIP (or MCP) joint was tested, the extended motor shaft was inserted into the PIP (or MCP) part of the finger plates and the MCP (or PIP) joint of the finger plates was locked at a desired angle. The joint-angle positions of the MCP and PIP joints were defined as depicted in Figure 2 for an index finger.

2.3 Procedure

The apparatus was always hidden from view. The participant was instructed to place the thumb and the palm of the right hand on the hand support (see Figure 1) with the index finger resting over the finger plates and the rest of the fingers flexed around the hand support. The apparatus accommodated different PIP–MCP interjoint lengths well. We always made sure that the target joint was well aligned with the extended motor shaft. This might have resulted in a slight misalignment of the background joint for people with very large or very small hands, which should not have significantly affected the experimental results on the target joint. On each trial, the participant lifted the index finger off the

Table I. Experimental Conditions

Exp.	Target Joint (Reference Angle)	Background Joint	Type of Experiment	Participants
1	PIP (39.6°)	MCP (0°, 45°)	Discrimination	S1, S2, S3
2	PIP (9.9°, 39.6°, 80.1°)	MCP (0°)	Discrimination	S3, S4, S5
3	PIP	MCP (0°)	Identification	S4, S6, S7
4	MCP (36°)	PIP (0°, 45°)	Discrimination	S8, S9, S10
5	MCP (9°, 36°, 72°)	PIP (0°)	Discrimination	S8, S9, S11
6	MCP	PIP (0°)	Identification	S8, S9, S10

apparatus, the movable plate was brought to the desired joint-angle position,[1] and the participant brought the index finger back to the finger plates in order to sense the joint-angle position.

All experiments used a one-interval forced-choice paradigm with trial-by-trial correct-answer feedback. On each trial, the participant was presented with one of K joint-angle positions (chosen randomly with equal *a priori* probabilities), was forced to choose one of K predefined responses, and was then told the correct response. Each experimental run consisted of 100 trials. In the discrimination experiments ($K = 2$ joint-angle positions), one of two joint-angle positions (*reference* α_0 and *reference-plus-increment* $\alpha_0 + \Delta\alpha$ for PIP; γ_0 and $\gamma_0 + \Delta\gamma$ for MCP) was presented with an equal *a priori* probability of 0.5. The participant was required to respond "1" to the reference joint-angle position (α_0 or γ_0) and "2" to the reference-plus-increment joint-angle position ($\alpha_0 + \Delta\alpha$ or $\gamma_0 + \Delta\gamma$). In the identification experiments ($K = 10$ joint-angle positions), one of ten joint-angle positions was presented with an equal *a priori* probability of 0.1 and the participant was required to respond with an integer between "1" and "10," with 1 corresponding to the smallest angle and 10 the largest.

2.4 Design

Six experiments were conducted, with three participants assigned to each experiment. As shown in Table I, the first three experiments (Exp. 1–3) studied the PIP joint and the other three (Exp. 4–6) examined the MCP joint. In Exp. 1, the discrimination threshold for PIP joint-angle position was measured with the reference PIP joint position set to roughly the mid-point within its range of motion, 39.6°.[2] In order to examine the possible effect of MCP joint-angle position on PIP joint-angle discrimination threshold, the MCP joint-angle position was set to either 0° (fully extended) or 45° (about half-way bent). In Exp. 2, the effect of reference PIP joint-angle position on PIP joint-angle discrimination threshold was measured at three PIP joint-angle reference positions of 9.9°, 39.6°, and 80.1°. The MCP joint was always kept at the fully extended (0°) position. In Exp. 3, the number of distinct PIP joint-angle positions that could be correctly identified was measured with an absolute identification paradigm with the MCP joint-angle position kept at 0°. Participants S1–S7 were involved in Exp. 1–3 with S3 participating in both Exp. 1 and 2 and S4 in both Exp. 2 and 3. The design of Exp. 4–6 was similar to that of Exp. 1–3, except that the MCP joint was now the target joint and the PIP joint the background joint. Participants S8–11 were involved in Exp. 4–6 with S8 and S9 participating in all three experiments and S10 in both Exp. 4 and 6. Other details specific to each experiment are presented in Section 3.

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[1] The following procedure was followed in order to disassociate motional cues from joint-angle positions. The finger plate was always brought back to the 0° position at the beginning of a trial. The participant lifted his/her index finger off the device. The finger plate was "wiggled" around the range of joint-angle positions to be tested for five or six excursions (with equal *a priori* probabilities) before it was brought to the target position. The participant lowered the index finger until his/her MCP and PIP joints conformed to the finger plates.

[2] The angles were set to multiples of 0.9°, the smallest step size of the rotary step motor used in the present study.

2.5 Data Analysis

Analysis of discrimination data was based on signal-detection theory [Macmillan and Creelman 2004]. Data from identification experiments were processed using information theory [Garner 1962].

2.5.1 *Discrimination.* A 2-by-2 stimulus-response matrix was formed using data collected from multiple experimental runs under the same condition. Data from different participants were processed separately and were never pooled. The sensitivity index d' and response bias β were derived from these matrixes to characterize the results. In this method of data processing, it is assumed that the underlying density functions associated with the two stimuli being discriminated are normal and of equal variance (means M_1 and M_2, and variance σ^2). The sensitivity index d' is then defined as the normalized difference between the means, i.e.,

$$d' = \frac{(M_2 - M_1)}{\sigma}.$$

According to signal-detection theory, d' provides a measure of the discriminability of two stimuli independent of a participant's response bias β. Response bias β is defined as the normalized deviation of response criterion (c) from the average of the two means, i.e.,

$$\beta = \frac{c - (M_1 + M_2)/2}{\sigma}.$$

It is assumed that a user responds with "2" when the perceived signal magnitude is greater than or equal to c and "1" when the signal magnitude is less than c. The optimal placement of c is in the middle of the two means. Therefore, $\beta = 0$ corresponds to unbiased response behavior. Since the response biases were generally small in the present study (roughly less than 10% of the corresponding d' values), they are not reported here.

Generally speaking, the values of d' were roughly proportional to the stimulus increment $\Delta\alpha$ or $\Delta\gamma$ as in auditory perception studies and our previous studies of manual resolution of length [Durlach et al. 1989a], force [Pang et al. 1991], and compliance [Tan et al. 1995]. Given this proportionality, performance can be summarized by the slope $\delta = d'/\Delta\alpha$ (for PIP) or $\delta = d'/\Delta\gamma$ (for MCP), computed for the different values of $\Delta\alpha$ or $\Delta\gamma$ tested for the same α_0 or γ_0, respectively. The JND of joint-angle position, $(\Delta\alpha)_0$ or $(\Delta\gamma)_0$ for PIP or MCP, respectively, was defined by the performance criterion $d' = 1.0$. It was computed as the inverse of the average slope $\bar{\delta}$, i.e., $(\Delta\alpha)_0$ or $(\Delta\gamma)_0 = 1/\bar{\delta}$. The standard deviation of $(\Delta\alpha)_0$ or $(\Delta\gamma)_0$ was estimated from the multiple $1/\delta$ values calculated for the $\Delta\alpha$ or $\Delta\gamma$ values used at the same α_0 or γ_0, respectively.

The threshold criterion of $d' = 1.0$ is commonly used in the literature and was employed in our previous threshold studies (e.g., Pang et al. [1991]). The JND value calculated from $d' = 1.0$ corresponds to a percentage correct score of 69%, assuming no response bias. For comparison purposes, doubling the performance criterion to $d' = 2.0$ (i.e., doubling the JNDs reported in the present study) corresponds to a percentage correct score of 84%, assuming no response bias.

2.5.2 *Identification.* Data from each experimental run formed a 10-by-10 stimulus-response matrix from which information transfer was calculated. The matrixes from the same participant and the same experimental condition were pooled. As in the discrimination experiment, data from different participants were always processed separately. According to Garner [1962], information transfer ψ is defined by

$$\psi = \sum_{j=1}^{10}\sum_{i=1}^{10} P(S_i, R_j)\log_2\left(\frac{P(S_i, R_j)}{P(S_i)P(R_j)}\right)$$

where $P(S_i)$ and $P(R_j)$ are the probabilities of stimulus S_i and response R_j, respectively, and $P(S_{i,}R_j)$ is their joint probability ($i,\ j = 1, 2, \ldots 10$). According to Garner [1962], information is defined as a reduction in uncertainty, with the latter estimated from the log of the probability of a stimulus. Since $\log_2(P(S_{i,}R_j)/P(S_i)P(R_j))$ is the same as $\log_2 P(S_i/R_j) - \log_2 P(S_i)$, where $P(S_i/R_j)$ is the conditional probability of S_i given R_j, the log term in the equation shown above can be interpreted as the reduction in the uncertainty (i.e., transmitted information) of S_i after it has been perceived for the combination of stimulus S_i and response R_j. Therefore, the equation for ψ is essentially a weighted average of transmitted information for all stimulus-response combinations.

The maximum likelihood estimate of information transfer, ψ_{est}, was computed by replacing probabilities with frequencies, i.e.,

$$\psi_{est} = \sum_{j=1}^{10} \sum_{i=1}^{10} \left(\frac{n_{ij}}{n}\right) \log_2 \left(\frac{n_{ij}\, n}{n_i\, n_j}\right)$$

where n_{ij} is the number of the joint event (S_i, R_j) in a sample of n trials, and

$$\begin{aligned} n_i &= \sum_{j=1}^{10} n_{ij} \\ n_j &= \sum_{i=1}^{10} n_{ij}. \end{aligned}$$

It is well known that ψ_{est} is biased and the bias can exceed sampling errors when an insufficient number of trials has been collected. However, when the total number of trials is $5K^2$ (K, number of stimulus alternatives) or greater, the main component of the bias (ignoring all terms of the order $1/n^2$ or higher) is 0.117 bits or less [Miller 1954; Houtsma 1983]. In the present study, we used $K = 10$ stimulus alternatives in the absolute identification experiments. At least 500 trials were collected per participant under each experimental condition.

3. RESULTS

3.1 JND of PIP Joint-Angle Position at Two MCP Joint-Angle Positions (Exp. 1)

In this experiment, the PIP joint-angle resolution was studied at two MCP joint-angle positions. For each run of 100 trials, the PIP joint-angle reference position, α_0, was kept at 39.6° to keep the index finger in a relaxed half-way flexed position. The PIP joint-angle increment, $\Delta\alpha$, was set to 1.8°, 2.7°, or 3.6°. The MCP joint-angle position, γ_0, was set to either 0° or 45°. Two runs were conducted for each of the six experimental conditions ($1\ \alpha_0 \times 3\ \Delta\alpha \times 2\gamma_0$). The order of the 12 runs was randomized with a different sequence for each participant.

The results are summarized in Table II. Each data point is from 600 trials (100 trials/run × 2 runs/$\Delta\alpha$ × 3 $\Delta\alpha$). The PIP joint-angle JND appears to be the same at the two MCP joint-angle positions. A two-way (participant, MCP position) ANOVA confirmed that neither participant [$F(2, 12) = 1.22; p = 0.3307$] nor MCP position [$F(1, 12) = 1.23; p = 0.2898$] was a significant factor.

3.2 JND of PIP Joint-Angle Position at Three PIP Joint-Angle Reference Positions (Exp. 2)

In this experiment, the PIP joint-angle resolution was studied at three PIP joint-angle reference positions. For each run of 100 trials, the MCP joint-angle position, γ_0, was kept at 0°. The PIP joint-angle reference position, α_0, was set to 9.9°, 39.6°, or 80.1°. The PIP joint-angle increment, $\Delta\alpha$, was set to 1.8°, 2.7°, or 3.6°. Two runs were conducted for each of the nine experimental conditions ($1\ \gamma_0 \times 3\alpha_0 \times 3\Delta\alpha$). The order of the 18 runs was randomized with a different sequence for each participant.

Table II. Results of Exp. 1: PIP JNDs at Two MCP Positions

	PIP $\alpha_0 = 39.6^\circ$	
	MCP $\gamma_0 = 0^\circ$	MCP $\gamma_0 = 45^\circ$
Participant	JND (S.D.)	JND (S.D.)
S1	2.5° (0.10°)	2.6° (0.09°)
S2	2.8° (0.33°)	2.5° (0.23°)
S3	2.2° (0.19°)	2.7° (0.24°)
Average	2.5°	2.6°

Table III. Results of Exp. 2: PIP JNDs at Three PIP Reference Positions

	MCP $\gamma_0 = 0^\circ$		
	PIP $\alpha_0 = 9.9^\circ$	PIP $\alpha_0 = 39.6^\circ$	PIP $\alpha_0 = 80.1^\circ$
Participant	JND (S.D.)	JND (S.D.)	JND (S.D.)
S3	2.5° (0.25°)	2.2° (0.19°)	2.7° (0.30°)
S4	2.6° (0.23°)	3.1° (0.42°)	2.5° (0.11°)
S5	2.5° (0.25°)	2.8° (0.31°)	2.4° (0.14°)
Average	2.5°	2.7°	2.5

Table IV. Results of Exp. 3 and 6: Information Transfer for PIP and MCP

Exp. 3: PIP Joint		Exp. 6: MCP Joint	
Participant	ψ_{est} (bits)	Participant	ψ_{est} (bits)
S4	2.02	S8	1.92
S6	1.87	S9	1.44
S7	1.92	S10	1.85
Average	1.94	Ave	1.74

The results are summarized in Table III. Each data point is from 600 trials (100 trials/run × 2 runs/$\Delta\alpha$ × 3 $\Delta\alpha$). The PIP joint-angle JND appears to be independent of the PIP joint-angle reference position. A two-way (participant, PIP reference position) ANOVA confirmed that neither participant [$F(2, 18) = 2.67; p = 0.0966$] nor PIP reference position [$F(2, 18) = 1.64; p = 0.2224$] was a significant factor.

3.3 Identification of PIP Joint-Angle Position (Exp. 3)

In this experiment, the information transfer for PIP joint-angle position was studied using an absolute identification paradigm. The MCP joint-angle position was kept at $\gamma_0 = 0^\circ$. The stimuli consisted of 10 PIP joint-angle positions: $\alpha_1 = 0^\circ, \alpha_2 = 9^\circ, \alpha_3 = 18^\circ, \alpha_4 = 27^\circ, \alpha_5 = 36^\circ, \alpha_6 = 45^\circ, \alpha_7 = 54^\circ, \alpha_8 = 63^\circ, \alpha_9 = 72^\circ$, and $\alpha_{10} = 81^\circ$. The participants were instructed to use the integers "1" to "10" to respond to the 10 PIP joint-angle positions, with "1" corresponding to α_1 (the most extended position) and "10" corresponding to α_{10} (the most flexed position). Five 100-trial runs were conducted for each participant.

The estimated information transfer ψ_{est} for the PIP joint are shown in Table IV. The average ψ_{est} corresponds to $2^{\psi_{est}} = 3.8$ items. This result suggests that participants were likely to identify PIP joint-angle positions within each of three ranges: fully extended, fully flexed, and midway between these two extremes.

A similar experiment was conducted with PIP joint-angle positions equally spaced on a logarithmic scale over the same range. Similar results were obtained. The average information transfer was 1.92 bits. These results confirm our earlier finding that information transfer is not greatly influenced by whether the stimulus alternatives are equally spaced along a linear or logarithmic scale [Tan 1997].

Table V. Results of Exp. 4: MCP JNDs at Two PIP Positions

	MCP $\gamma_0 = 36°$	
	PIP $\alpha_0 = 0°$	PIP $\alpha_0 = 45°$
Participant	JND (S.D.)	JND (S.D.)
S8	1.8° (0.21°)	2.2° (0.32°)
S9	2.2° (0.34°)	3.1° (0.27°)
S10	2.1° (0.14°)	2.7° (0.20°)
Average	2.0°	2.7°

Table VI. Results of Exp. 5: MCP JNDs at Three MCP Reference Positions

	PIP $\alpha_0 = 0°$		
	MCP $\gamma_0 = 9°$	MCP $\gamma_0 = 36°$	MCP $\gamma_0 = 72°$
Participant	JND (S.D.)	JND (S.D.)	JND (S.D.)
S8	1.3° (0.22°)	1.8° (0.21°)	2.4° (0.27°)
S9	1.9° (0.29°)	2.2° (0.34°)	2.9° (0.26°)
S11	1.9° (0.23°)	2.0° (0.30°)	2.3° (0.14°)
Average	1.7°	2.0°	2.5°

3.4 JND of MCP Joint-Angle Position at Two PIP Joint-Angle Positions (Exp. 4)

In this experiment, the MCP joint-angle resolution was studied at two PIP joint-angle positions. For each run of 100 trials, the MCP joint-angle reference position, γ_0, was kept at 36°. The MCP joint-angle increment, $\Delta\gamma$, was set to 1.8°, 2.7°, or 3.6°. The PIP joint-angle position, α_0, was set to either 0° or 45°. Two runs were conducted for each of six experimental conditions ($1\gamma_0 \times 3\ \Delta\gamma \times \alpha_0$). The order of the 12 runs was randomized with a different sequence for each participant.

The results are summarized in Table V. Each data point is from 600 trials (100 trials/run × 2 runs/$\Delta\gamma \times 3\ \Delta\gamma$). It is evident from individual participant's data, as well as their average, that MCP joint-angle JNDs increased when the PIP joint-angle position moved from fully extended to half-way extended. A two-way (participant, PIP position) ANOVA revealed that both factors were significant [participant: $F(2, 12) = 12.29; p = 0.0012$; PIP position: $F(1, 12) = 36.36; p < 0.0001$], but not their interaction [$F(2, 12) = 1.97, p = 0.1820$]. A subsequent Tukey test indicated that the JND of S8 (mean = 2.0°) was significant lower than those of S9 and S10 (mean = 2.7° and 2.4°, respectively). It also confirmed that the JNDs at the two PIP joint-angle positions were significantly different (mean = 2.0° and 2.7° for $\alpha_0 = 0°$ and 45°, respectively).

3.5 JND of MCP Joint-Angle Position at Three MCP Joint-Angle Reference Positions (Exp. 5)

In this experiment, the MCP joint-angle resolution was studied at three MCP joint-angle reference positions. For each run of 100 trials, the PIP joint-angle position was kept at $\alpha_0 = 0°$. The MCP joint-angle reference position, γ_0, was set to 9°, 36°, or 72°. The MCP joint-angle increment, $\Delta\gamma$, was set to 0.9°, 1.8°, 2.7°, or 3.6°. The smallest $\Delta\gamma$ of 0.9° was added in anticipation of a better MCP joint-angle position resolution (which did not prove to be the case). Two runs were conducted for each of the 12 experimental conditions ($1\alpha_0 \times 3\gamma_0 \times 4\Delta\gamma$). The order of the 24 runs was randomized with a different sequence for each participant.

The results are summarized in Table VI. Each data point is based on 800 trials (100 trials/run × 2 runs/$\Delta\gamma \times 4\Delta\gamma$). A clear increasing trend is observed for the average JNDs with increasingly flexed MCP joint-angle reference positions. A two-way (participant, MCP reference position) ANOVA revealed that both factors were significant [participant: $F(2, 18) = 8.70; p = 0.0023$; MCP reference position:

$F(2, 18) = 23.76; p < 0.0001$], but not their interaction [$F(4, 18) = 1.80, p = 0.1724$]. A subsequent Tukey test indicated that the performance of S11 was not significantly different from S8 or S9, but S8 and S9 were significantly different from each other (mean = 1.9°, 2.4°, and 2.1° for S8, S9, and S11, respectively). The average JND at $\gamma_0 = 72^\circ$ (mean = 2.5°) was significantly higher than those at $\gamma_0 = 9^\circ$ and 36° (mean = 1.7° and 2.0°, respectively).

3.6 Identification of MCP Joint-Angle Position (Exp. 6)

In this experiment, the information transfer for MCP joint-angle position was studied using an absolute identification paradigm. The PIP joint-angle position was kept at $\alpha_0 = 0^\circ$. There were 10 MCP joint-angle positions: $\gamma_1 = 0^\circ, \gamma_2 = 8.1^\circ, \gamma_3 = 16.2^\circ, \gamma_4 = 24.3^\circ, \gamma_5 = 32.4^\circ, \gamma_6 = 40.5^\circ, \gamma_7 = 48.6^\circ, \gamma_8 = 56.7^\circ, \gamma_9 = 64.8^\circ$, and $\gamma_{10} = 72.9^\circ$. The slightly smaller range (72.9° as opposed to 81° for the PIP joint) was used for the MCP joint due to a slightly smaller range of motion for the MCP joint as compared to that of the PIP joint. The participants were instructed to use the integers "1" to "10" to respond to the 10 MCP joint-angle positions, with "1" corresponding to γ_1 (the most extended position) and 10 corresponding to γ_{10} (the most flexed position). Six, ten, and seven runs were conducted for participants S8, S9, and S11, respectively, based on the availability of each participant.

The estimated information transfer ψ_{est} for the MCP joint are shown in Table IV. The average ψ_{est} corresponds to 3.34 perfectly identifiable MCP joint-angle positions, suggesting that participants were likely to identify MCP joint-angle positions within each of three ranges: fully extended, fully flexed, and midway between these two extremes.

4. SUMMARY AND DISCUSSION

The present study examined the discrimination threshold and identification performance with the PIP and MCP joints of the index finger. From the discrimination experiments, we found that the JNDs of PIP joint-angle position were roughly constant (2.5°–2.7°) independent of the MCP joint-angle position or the PIP joint-angle reference position (Exp. 1 and 2). The JNDs of MCP joint-angle position, however, increased with the flexion of both PIP and MCP joints (Exp. 4 and 5). The blind participant (S9) performed at a level similar to or slightly worse than the sighted participants in Exp. 4. In Exp. 5, S9's JNDs were not significantly different from those of S11, but were statistically higher than those of S8. Therefore, the blind participant exhibited no special ability in this tactual perception task. The lowest JND of 1.7° was found when the index finger was straight and almost fully extended ($\alpha_0 = 0^\circ, \gamma_0 = 9^\circ$, Exp. 5). The JND increased to 2.0° when the index finger remained straight, but the MCP joint was halfway bent ($\alpha_0 = 0^\circ, \gamma_0 = 36^\circ$, Exp. 4 and 5). A further increase of the JND to 2.5° was obtained when the index finger remained straight, but the MCP joint was fully flexed ($\alpha_0 = 0^\circ, \gamma_0 = 72^\circ$, Exp. 5). Finally, the highest JND of 2.7° was associated with curling the index finger at the PIP joint while the MCP joint was halfway bent ($\alpha_0 = 39.6^\circ, \gamma_0 = 45^\circ$, Exp. 4). The effect of PIP joint-angle position on the JND of the MCP joint-angle position was most apparent by comparing the two JNDs of 2.0° and 2.7° associated with the two PIP joint-angle positions of 0° and 45°, respectively, while the MCP joint remained halfway bent at $\gamma_0 = 36^\circ$. Overall, the MCP joint exhibited a better joint-angle resolution than the PIP joint, with the JNDs of PIP joint-angle position being equivalent to the largest JNDs of MCP joint-angle position.

We compare the JNDs obtained in the present study to the standard deviations (S.D.) of joint movement detection data and bilateral matching errors of finger joints reported by previous investigators. We choose to compare our discrimination results to the S.D.s rather than the mean errors obtained in previous studies, because the S.D.s are more likely to reflect the precision of joint position sense; furthermore, the mean errors can be influenced, in addition, by the internal neural matching of proprioceptive signals (in the case of bilateral matching) and the formulation of fine movements (see Introduction;

also De Domenico and McCloskey [1987]). The S.D. for 70%-correct detection of movement at the distal interphalangeal joint of the middle finger was between 0.1° and 1° (visual inspection of Figure 2 in Hall and McCloskey [1983]). Bilateral matching of the PIP joint of the index finger had a S.D. on the order of 5° (visual inspection of Figure 1A in Ferrell and Smith [1988], and Figure 2 in Ferrell and Milne [1989]). Bilateral matching of the distal joint of the thumb had an S.D. between 2° to 10° (visual inspection of Figure 3 in De Domenico and McCloskey [1987]). Overall, given the many differences in experimental apparatus and experimental procedures among the studies cited above, our JND values are roughly within the same range as the precision (SD) of joint-position matching results from other studies. The precision of joint-angle perception for the wrist, elbow and shoulder joints were generally found to be better than the JNDs measured in the present study (e.g., Tan et al. [1994]; van Beers et al. [1998]), confirming the general trend that proprioception performance is better at proximal than at distal joints when the results are expressed in angular displacement.

The present study found a difference between the PIP and MCP joints in joint-angle position discrimination: while the JNDs for PIP joint-angle position remained roughly constant independent of the PIP or MCP joint-angle positions, the JNDs for the MCP joint-angle position increased with the flexing of both PIP and MCP joints. Other differences between the two joints have also been reported in the literature. Two studies by Clark et al. [1985, 1986] provide evidence of a static position sense of the MCP joint, but only a movement sense with the PIP joint. The authors reasoned that when a joint with a static position sense is rotated at varying speeds, its performance at detecting a fixed rotational displacement should remain the same. A joint with only a movement sense, but not a static position sense, however, would not be able to detect a displacement at a low rotation speed as well as it could at a higher speed. Experimental results indicated that participants could detect a 2.5° flexion-extension of the MCP joint of the index finger at a roughly constant level of 90% over rotation rates of 1 to 128°/min, thereby confirming a static position sense of the MCP joint. In contrast, detection rates of a 5° flexion-extension of the PIP joint of the index finger dropped from 100% to $<10\%$ when the rate of joint rotation decreased from 320 to 2°/min, thereby demonstrating a lack of static position sense with the PIP joint [Clark et al. 1986]. It is possible that the higher sensitivity of the MCP joint is attributable to its static position sense. There is also an important anatomical difference between the PIP and MCP joints in that there exist intrinsic muscles that operate mainly around the MCP joint in the hand, even though both the PIP and MCP joints are moved primarily by the extrinsic muscles in the forearm through tendons [Biggs et al. 1999]. At this time, the explanation of the dependence of the JNDs for MCP joint-angle position on the positions of the PIP and MCP joints remains an open research question.

From the absolute identification experiments conducted in the present study, the average information transfer was 1.94 bits for the PIP joint over a stimulus range of 81° and 1.74 bits for the MCP joints over a range of 72.9° (Exp. 3 and 6, respectively). Again, the deaf–blind and the blind participants (S6 in Exp. 3 and S9 in Exp. 6, respectively) performed similarly to the sighted participants in the identification experiments. Although the information transfer for the PIP joint was slightly higher than that for the MCP joint, the equivalent number of perfectly identifiable joint positions was between 3 and 4 for both joints. It is likely that the participants can identify joint-angle positions within each of three ranges: fully extended, fully flexed, and midway between these two extremes. Clark [1992] reported channel capacities (maximum information transfers) for the PIP and MCP joints to be 1.416 and 1.816 bits, respectively, over a 70° range of joint-angle positions for both joints. The higher information transfer of the PIP joint (1.94 bits) obtained in the present study may be because of the larger stimulus range used (see Braida and Durlach [1970], for a discussion on how information transfer depends on stimulus range for auditory intensity perception). Similar results were reported in a subsequent study by Clark et al. that argued for information transfer (termed "target resolution" by the authors) as a better metric than mean or constant matching error for assessing joint position sense, because information transfer is ultimately based on variance whereas constant error reflects a participant's response bias that is known to drift [Clark et al. 1995].

The results of the present study can be related to JND measurements of human haptic discrimination of length and thickness. Durlach et al. studied the discrimination of length between the tips of the thumb and index finger with reference lengths varying from 10 to 80 mm [Durlach et al. 1989]. The length JND was found to be 1 mm for reference lengths between 10–20 mm, and increased to 2.5 mm for the largest reference length of 80 mm. The JND range of 1 to 2.5 mm corresponds to a change in PIP joint-angle position over a range of 1.1° to 2.9°, which is roughly consistent with the PIP JNDs measured in the present study.[3] John et al. [1989] studied haptic thickness discrimination using metal plates grasped between the thumb and the index finger and reported a JND of 0.075 mm for a reference thickness of 0.2 mm. The authors estimated that a movement of 0.075 mm at the fingertip of the index finger corresponded to about 0.1° of rotation for the PIP joint or about 0.05° for the MCP joint. If information about joint angles were solely responsible for the thickness JND found by John et al. [1989], then a joint-angle precision much better than any published joint-angle JND data would have been required. A later study on haptic thickness discrimination used both plastic and stainless steel plates with reference thicknesses varying from 0.05 to 10 mm that bridged the stimuli used in Durlach et al. and John et al. [Ho and Srinivasan 1997]. Using finite-element modeling, the critical thickness for the boundary condition between bendable and unbendable plates was determined for both types of materials. It was found that as the reference plate thickness increased, thickness JND increased until it reached a plateau (0.4 mm; 0.5° at the PIP joint) when the plates became unbendable. The results suggested that both cutaneous (curvature) and kinesthetic (joint-angle position) information were available for thickness discrimination when the plates were bendable, but kinesthetic sensations were the only source of information when the plates were unbendable. It, therefore, appeared plausible that the participants in John et al.'s study [1989] had relied on additional cutaneous cues from bending to achieve the very small JND of 0.075 mm for thickness discrimination.

The findings of the present study provide the JNDs for PIP and MCP joints and the limitation on the number of correctly identifiable joint-angle positions when the index finger moves actively and freely in space. We can now answer the question posed initially in the Introduction: How well can people sense the position of their fingertips during active free movements? According to the present study, the JND of PIP joint-angle position is about 2.5°, which corresponds to a displacement JND of 2.2 mm at the fingertip of the index finger. This information is useful in explaining perceptual phenomena in a virtual environment, as illustrated by the following example. In an earlier study, we had measured the typical stylus movement caused by the tremor of the hand holding it to be in the range 0.5–1.0 mm, while the user held the hand "stationary" [Choi and Tan 2005]. Based on the results from the present study, we can confirm that the slight movement of the stylus of the force-feedback device was too small to be detected by the user of the device. The haptic rendering algorithm, however, rendered forces that were proportional to the penetration depth of the stylus into the virtual textured surface. The force variations resulting from the stylus movement were up to 0.59 N [Choi and Tan 2005], a magnitude that could be clearly perceived [Pang et al. 1991]. Anecdotal reports indicated that the user felt the "pulsing" of the virtual textured surface, but was unaware of its source. As a result, the user attributed the force variations to an "alive" virtual textured surface [Choi and Tan 2005]. The apparent aliveness of

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[3] To convert the linear displacement between the tips of the thumb and index finger to the angular rotation of PIP, we assumed that as the length between the digits increased, only the PIP joint-angle position of the index finger was changed. We then calculated the PIP joint-angle rotation with the assumption that the linear distance between the fingertip and the PIP joint of the index finger was about 50 mm.

the virtual surface is, therefore, a consequence of the human's inability to sense the small movements caused by finger/hand tremor. It now follows that to improve the perceived quality of virtual haptic objects, it would be desirable to suppress the variation in force when the avatar of the haptic probe is inside the object, but does not exhibit significant movements.

By conducting the six experiments reported in the presented study, we have filled a void in the literature on human perception of joint-angle position and fingertip position during active free movements. It is hoped that the data will prove useful in explaining human performance involving dexterous manipulation at the fingertip, as well as in contributing to further basic research on human haptic perception.

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