Human velocity-change perceptual characteristics in passive movements of shoulder and/or elbow joint

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Abstract
Focusing on humans’ velocity perceptual characteristics, this study clarified the velocity JNDs that is minimal velocity differences humans can discriminate. For this purpose, using a 2-DOF SCARA-type haptic device, we conducted an experiment, assuming a pattern in which velocities were increased from constant values to other constant ones for shoulder and/or elbow joints. In the experiment, subjects’ upper limbs were enforced to move by the device, while the subjects focused on their hand velocity change using their proprioceptive sensations. After the movements, the subjects answered whether they perceived a velocity change during the movement. Iterating this trial with various velocity difference, velocity JNDs were obtained for each of the subjects and the following two factors. The two factors to be evaluated were the joint factor and the before-acceleration velocity factor: (1) the joint factor was the joints to be moved, of which levels were set as the shoulder, the elbow, and the shoulder-and-elbow, (2) the before-acceleration velocity factor was the nearly-constant tangential velocity of hand motions before velocity change, \( V_{\text{before}} \). As a result, it was confirmed that a linear relationship of the velocity JND against the \( V_{\text{before}} \) was confirmed for all the joint factor levels, i.e., the shoulder only, the elbow only, and both the shoulder-and-elbow. Here, it should be noted that the joint angular velocities corresponding to hand tangential velocities are greatly different between the three joint factor levels. Nevertheless, the correspondence between \( V_{\text{before}} \) and the velocity JNDs were approximately the same between the three joint-factor levels. Therefore, it is concluded that the hand velocities, not the joint angular velocities, are dominant in human velocity-change perception for passive movements in the shoulder and/or elbow joint.

Keywords: Proprioceptive sensations, Velocity perception, Velocity JND, Shoulder, Elbow

1. Introduction

Motor learning through visual stimuli such as those by pictures and movies is the popular method for motor learning from the usefulness and the large information amounts. However, Smeets et al. (2006) suggested that the visual information didn’t necessarily contribute for calibrating the proprioceptors that were the receptors for perceiving positions and velocities of our own body parts. Lüttgen and Heuer (2006) suggested that the visual sense is superior to the proprioceptor in the learning of static features like stroke lengths, while the visual sense is inferior to the proprioceptor in learning of dynamic features like motion velocities. It is because we cannot experience the actual motions and the our own-exerted forces through the visual sense. In contrast to those, in recent years, as methods of motor learning through the proprioceptors, haptic devices have been introduced and studied. There are many studies using haptic devices. Boulanger et al. (2006) studied on a haptic device for practicing movements and presenting the degrees of exerting force in an operative procedure. Wang et al. (2006), Liu et al. (2006), and Williams et al. (2016) compared learning effects on hand trajectories through the visual sense with those through proprioceptor. Asseldonk et al. (2009) and Bernardi et al. (2015) compared learning effects of hand trajectories through active movements with those through passive movements. Here, let’s assume that learners learn motions through the movements enforced by device. In this case, once humans’ motion perceptual characteristics are clarified, it is possible to present reference motions more accurately. Then, in the motor learning, it is, moment by moment, necessary for each body part to be clarified not only with position (Goble, D. J. and Susan H. B., 2010), but also with the position changes, i.e., velocities. As a representative indicator evaluating
velocity perceptual characteristics, Just Noticeable Differences (JNDs) have been explored. The JND is the smallest amount of a physical quantity difference like a velocity difference that can be discriminated by humans with a probability of 50% when velocity is changed from a certain reference value to another value.

In the studies on humans’ velocity-difference discrimination ability, Djupsjöbacka and Domkin (2005) measured velocity JNDs by the following procedure. The subjects’ shoulder joints were enforced to make pairs of horizontal extension movements. That is, subjects’ upper limbs were enforced to move continuously twice at different movement velocities by the device: the first velocity is regarded as a reference stimulus, and the second is as a test stimulus. Immediately after the pair of movements, subjects answered whether the two movement velocities were identical or not. Kerr and Worringham (2002) also measured velocity JNDs in enforced extension movements of elbow joints. In both of the studies, the tendency was reported that the velocity JNDs increase with the larger reference velocity. Differently from the previous studies, this paper clarified the velocity JNDs, in particular, not only of either the shoulder or the elbow 1-DOF movement, but also the shoulder-and-elbow combined 2-DOF movements. In addition, since humans accept velocity changes during motions in device-assisted motor learning, this study presented a pair of velocities in a single movement, not by two movements as in the previous studies using: one was a specific constant velocity before acceleration, and the other was stepwise increased another constant velocity after acceleration.

For making human motion-assisting robots to be practical, the perceptual characteristics under the multiple-DOF condition with multiple-DOF robots shall be examined: since we do not know how humans integrate multiple senses, i.e., the shoulder and elbow joint sense in the case of 2-DOF arm robot as in this work, the multiple sense integration characteristics never be obtained from the single sense characteristic. In fact, most of the studies on the motor learning evaluated hand position and velocity as in Asseldonk et al. (2009), Bernardi et al. (2015), Liu et al. (2006), and Williams et al. (2016). This study evaluates based on the joint angular velocity and hand velocity, and evaluates in terms of dominance for velocity-change perception.

2. Experiment
2.1 Experimental device

A 2-DOF SCARA-type haptic device was designed and used for this experiment. In the device, one link corresponding to upper arm is called the upper link (the length is denoted as $l_u$), and the other link corresponding to forearm is called the fore link (the length, $l_f$). Figure 1 (a) shows an appearance the subject’s wearing the device, and Fig. 1 (b) shows the parameters representing joint-rotation angles of the shoulder and elbow joint and the lengths of the upper and fore arm. The mechanical joints corresponding to shoulder and elbow were controlled by two geared servo motors: shoulder (Maxon EC-4pole 22 323218, a gear ratio of 370:1) and elbow (Maxon EC-4pole 22 323218, a gear ratio of 157:1). The angles and angular velocity in the shoulder and elbow joints were measured by the encoders (Maxon HEDL 5540 110514) embedded in each of the two servo motors. Since the device structurally compensates its gravity acting subject’s arm, it needn’t bear the burden of gravity of both the device and the subject in its flexion/extension movements even if subjects relax their muscles and don’t support their arm weight. Consequently, by exerting their torques just corresponding to the system impedance, the device is able to enforce flexion/extension movements on the subjects, and in this experiment the subject arm was passively moved by angular velocity control scheme.
elbow angular-velocity differences proposed by Flash et al. (1985) that is considered to represent human natural movements. Then, using the shoulder and velocity change trajectory model to be employed in this work. That is, we employed the minimum-jerk trajectory

\[ D_{vh} = \Delta \omega \] (2) Minimum jerk trajectory of joint motion

2.2.1 Existing work

2.2 Passive movement given to upper limbs

2.2.2 Determination of joint-angular velocity trajectory from hand-velocity trajectory

In the experiment, following three kinds of horizontal movements were enforced on the subjects: (i) “the shoulder, single-joint motion” in which only the shoulder joint flexes (see the velocity profile of Fig. 2 (a)), (ii) “the elbow, single-joint motion” in which only the elbow joint flexes (see the velocity profile of Fig. 2 (b)), (iii) “the double joint motion with same direction” in which the two joints flex (see Fig. 3), (iv) “the double joint motion with opposite direction” in which one joint flexes and the other joint extends (see Fig. 4). The device-enforced human arm movements were divided into three sections: (a) the before-acceleration section: a constant velocity section before velocity-change; (b) the acceleration section: a velocity-changing section; (c) the after-acceleration section: another constant velocity section after
velocity change. For the three sections, the hand velocity $V$ was derived as follows.

Although JNDs were measured, based on hand velocity, the servomotors of the 2-DOF SCARA-type haptic device were to be moved under the angular velocity control scheme. Therefore, in the following, the ways of determining the angular velocity are mainly explained. Some variables are first defined: the angular velocity of the shoulder joint and that of the elbow one in the before-acceleration section were denoted by $\omega_{s, \text{before}}$ and $\omega_{e, \text{before}}$, respectively. In addition, those in the after-acceleration section were denoted by $\omega_{s, \text{after}}$ and $\omega_{e, \text{after}}$. The hand velocities at the beginning of the acceleration section and that at the end were denoted by $V_{\text{before}}$ and $V_{\text{after}}$, respectively.

Then, the hand speed $V$ was defined as follows for each of the motions.

(1) Single joint motion of either shoulder or elbow

Since, the hand velocities are simply proportional to “the moment arm” × “the angular velocity” in the single joint motions either of (i) shoulder or of (ii) elbow, the angular velocity difference of shoulder $D_{\omega_s}$ and that of elbow $D_{\omega_e}$ are derived from the hand velocity difference $D_{\omega}$ that is given by the PEST procedure described in 2.2.1 (1). That is,

$$D_{\omega} = D_{\omega_s} = D_{\omega_s} / (l_s + l_f), \quad D_{\omega} = D_{\omega_s} / l_f. \quad (2)$$

Next, the secant angular accelerations of $\omega_s$ and $\omega_e$ were set to 15 deg/s$^2$ in all runs in (i) and (ii). Then the time-duration of shoulder and elbow $T_{\text{accel},s}$ and $T_{\text{accel},e}$ for velocity-change in (i) and (ii) was given by

$$T_{\text{accel},s} = D_{\omega_s} / \alpha_s, \quad T_{\text{accel},e} = D_{\omega_e} / \alpha_e. \quad (3)$$

Finally, by using $D_{\omega_s}, D_{\omega_e}$, and $T_{\text{accel}}$, the angular velocity trajectories in (i) and (ii) are given by Eq. (1).

(2) Double joint motion

As for the double joint motions, (iii) the double joint motion with the same direction and (iv) the double joint motion with opposite direction were employed as described above. Here note that, in the experiment, the PEST procedure was applied not to the hand velocities but to the angular velocities for making velocity control be directly related with servomotor control and for satisfying the prerequisite of the minimum-jerk trajectory although the JND was examined with respect to the velocity. Consequently, in the description of the PEST procedure in 2.2.1(1), the hand velocity $V$ is to be replaced into the joint-angule velocities $\omega_s$ and $\omega_e$, and the subscript and superscript $h$ was into $s$ and $e$. As examples, $D_{\omega}^{(k),(l-1)} = D_{\omega}^{(k),(l-1)} = D_{\omega}^{(k),(l-1)} - D_{\omega}^{(l),(k)}, \quad \Delta D_{\omega}^{(k),(l)}$ was set at 0.8 $\omega_{s, \text{before}}$, and the final $K$-th JND-precision $\Delta D_{\omega}^{(k),(l)}$ was set at 0.05 $\omega_{s, \text{before}}$.

First, similar to the single joint motion, the angular velocities of the shoulder and the elbow servomotor was changed from a constant to another constant via the minimum-jerk trajectory as in 2.2.1 (2). In addition, another constraint was derived from the hand velocity difference $D_{\omega}$ and that of elbow $D_{\omega_e}$, respectively. In addition, those in the after-acceleration section were denoted by $\omega_{s, \text{after}}$ and $\omega_{e, \text{after}}$. The hand velocities at the beginning of the acceleration section and that at the end were denoted by $V_{\text{before}}$ and $V_{\text{after}}$, respectively.

Then, the hand speed $V$ was defined as follows for each of the motions.

$$\alpha_s = \alpha_s / \omega_{s, \text{before}}, \quad \alpha_e = \alpha_e / \omega_{e, \text{before}}. \quad (5)$$

As an example, in the case of $\omega_{s, \text{before}} = 2 \omega_{s, \text{before}}, \quad \alpha_s = 15 \text{ deg/s}^2, \quad \alpha_e = 15/2 \text{ deg/s}^2$.

Third, the time durations of in the acceleration section, $T_{\text{accel},s}$ and $T_{\text{accel},e}$, resultantly becomes an identical value of $T_{\text{accel}}$, and is given by
\[ T_{\text{accel}} = D_{\omega s} / a_s = D_{\omega e} / a_e. \] (6)

Finally, the device angular velocities \( \omega = [\omega_s, \omega_e]^T \) are transformed into the hand velocity differences in order to represent JND based on the hand velocity. That is, if the hand Cartesian coordinates are represented by \( r = [x, y]^T \), the flexion angles of the shoulder and elbow joints represented to \( \theta = [\theta_s, \theta_e]^T \), the hand velocity, \( v = \partial r / \partial t \), is related to the joint angle velocity \( \omega = [\omega_s, \omega_e]^T \) by

\[ v = J\omega \] (7)

where \( J \) is a Jacobian and is defined by

\[ J = \partial r / \partial \theta. \] (8)

In particular, in the 2-DOF SCARA-type haptic device, \( J = \begin{bmatrix} -l_s \sin \theta_s - l_f \sin(\theta_s + \theta_e) & -l_f \sin(\theta_s + \theta_e) \\ l_s \cos \theta_s + l_f \cos(\theta_s + \theta_e) & l_f \cos(\theta_s + \theta_e) \end{bmatrix} \). (9)

Then, in the double joint motions of (iii) and (iv), the hand velocity difference \( D_{v_h} \) are derived from the angular velocity difference of shoulder \( D_{\omega s} \) and that of elbow \( D_{\omega e} \).

\[ D_{v_h} = || J [D_{\omega s}, D_{\omega e}]^T || \] (10)

Here, since the Jacobian is nonlinearly changed along with the arm configuration in the double joint motions, the velocity suffers some drift in (a) the before-acceleration section and in (c) the after-acceleration section. Nevertheless, the drifts are at most about 10%, and this is one quarter as compared with velocity JNDs. Therefore, the hand speeds can be regarded as constant speeds.

Fig. 2 Velocity trajectory of a single joint motion. The initial angles are assumed to be \( \theta_s = \theta_e = 0 \) [deg].
Fig. 3 Velocity trajectory of a double joint motion where both of the shoulder and elbow joint flex in the same direction. \( V \) in (a) is calculated from \( \omega \) in (b) and \( \theta \) in (c). The initial angles are assumed that \( \theta_s = \theta_e = 0 \) deg.

Fig. 4 Velocity trajectory of a double joint motion where the shoulder joint flexes and elbow joint extends. \( V \) in (a) is the calculated value based on \( \omega \) and \( \theta \) in (b) and (c). The initial angles are assumed to be \( \theta_s = 0, \theta_e = 90 \) deg.

2.3 Experimental conditions

2.3.1 Single joint motion experiment

In the single joint motion experiment for either shoulder or elbow joint, we prepared three levels for the \( V_{\text{before}} \) factor as an evaluation factor, together with the joint factor. Table 1 shows the factors and levels, and Fig. 5, shows an example of the parameters and velocity profile of single joint motion. The time durations of the before-acceleration section and the after-acceleration section were set at 1.2 s, 1.0 s respectively. In perceptual experiments, it is necessary to give subjects enough time for perceiving stimuli, i.e., the velocity-difference in this work. In the study, the time of presenting stimuli is given by the duration from the acceleration section to the after-acceleration section. Regarding the stimulus-presenting time, a previous study examined the velocity JNDs in elbow flexion movements (Yasui et al., 2019): there was no significant difference of the velocity JNDs between the time durations from 0.1 ~ 4.0 s. On the other hand, in this study, the time durations of presenting stimuli were set at 1.1 ~ 1.5 s, and is considered to be sufficient for perception. The secant accelerations in the acceleration section were set at \( a_s = 15.7 \) cm/s\(^2\) for shoulder joint, \( a_e = 7.9 \) cm/s\(^2\) for elbow joint (note that the secant angular acceleration \( \alpha \) was set at 15 deg/s\(^2\) in either joint). Three runs for each of the three \( V_{\text{before}} \)-factor levels, and the two joint-factor levels, i.e., the total six runs, were assigned to all the 12 male subjects.
Table 1 Experimental condition in single joint movement experiment.

| Factor | Level                           |
|--------|--------------------------------|
| Subject| 12                             |
| \( V_{\text{before}} \) | 1.3, 2.6, 5.2 cm/s |
| \( \omega_{s, \text{before}} \) | (1.24, 2.48, 4.97 deg/s) |
| \( \omega_{e, \text{before}} \) | (2.48, 4.97, 9.93 deg/s) |
| Joint  |                                |
| Shoulder | Elbow                         |
| \( \alpha \) | \( \alpha_s = 15 \text{ deg/s}^2 \) |
| \( \alpha_e \) | \( \alpha_e = 15 \text{ deg/s}^2 \) |
| \( \alpha_{\text{sec}} \) | \( \alpha_{\text{sec}} = 15.7 \text{ cm/s}^2 \) |
| \( \alpha_{\text{sec}} \) | \( \alpha_{\text{sec}} = 7.9 \text{ cm/s}^2 \) |

Fig. 5 Example of single joint movement velocity profiles of angular velocities and hand tangential velocities: \( V_{s, \text{before}} \), \( V_{e, \text{before}} \) are 5.2, 2.6 cm/s respectively.

2.3.2 Double joint motion experiment

In the double joint motion experiment, the variations of the angular-velocity-magnitude ratio of the shoulder and elbow joints were added as another evaluated factor: \( \omega_e/\omega_s = \{1, 1/2, 2, -1, -1/2, -2\} \), and the total number ratio was six.

Table 2 shows the factors and the factor-levels. The double joint motion experiment was conducted by the same 12 subjects as the single joint motion experiment. The \( V_h \) in table 2 denotes the hand velocity in the before-acceleration section in the double joint motion experiment. Figure 6 shows an example of the actual velocity profile. As mentioned in the previous section, since the velocities were accelerated based on angular velocity, the hand secant accelerations \( \alpha_{\text{sec}} \) differed within the range of 5.1 ~ 23.6 cm/s\(^2\), depending on the combinations of the shoulder and elbow joints. In the experiment, the subject not only perceives a velocity change to be examined, but also may perceive a change in acceleration and angular acceleration. As for the effect of the acceleration, the velocity JNDS didn’t show significant differences in the range of \( a_e = 2.1 \sim 16.8 \text{ cm/s}^2 \) (Akatsuka and Nomura, 2017). In this study, the range of \( a \) in all the condition was 5.1 ~ 23.6 cm/s\(^2\), and it is approximately overlapped with the range in the previous study, so the variation of accelerations is considered not to influence the velocity JNDS.

Table 2 Experimental condition in double joint movement experiment.

| Factor | Level                           |
|--------|--------------------------------|
| Subject| 12                             |
| Joint  |                                |
| Shoulder-and-elbow |                      |
| \( \omega_{s, \text{before}}, \omega_{e, \text{before}} \) | \[3.3, 3.3\] deg/s |
| \( R_{\text{sec}} = \alpha_{\text{sec}}/\omega_s \) | 1 |
| \( V_h \) | 5.2 cm/s |
| \( \alpha_{\text{sec}} \) | 23.6 cm/s\(^2\) |
Twelve male volunteers (11 males were right-handed, and the remaining one was left-handed) aged from 21 to 24 participated in the experiment. They sat at a chair so that the rotation center of horizontal flexion/extension of shoulder joint was in the vertical axis of the shoulder servomotor. They put their right upper-arm and fore-arm at the arm rests of the device, and their arm were fixed by wrapping in a bandage. There is a discrepancy between the human upper-arm and forearm length and the device upper-link $l_u$ and fore-link $l_f$. As a result of measuring the lengths, the discrepancies were $0.5 \pm 1.3$ cm (mean error $\pm$ SD, standard deviation) and $-0.5 \pm 1.3$ cm, respectively. If we evaluate the angular velocity errors due to the arm length discrepancies as relative errors against the magnitudes of angular velocity, the mean relative error and the random error (SD) were $1/10$ and $1/25$, respectively. Therefore, the errors were considered negligible small.

During the experiments, their eyes were closed, muscles were relaxed, and wore a headphone with music running in order not to notice velocity change through mechanical sound. They were instructed to concentrate on perceiving velocity-change of the hand, that is, the handle. The velocity JNDs in velocity-change perception were measured accordingly PEST procedure (Taylor and Creelman, 1967).

Each run of the experiment was performed by the following procedure.

I) The subject’s upper limb is fixed to an initial position.

II) One second after the signal sound of “Movement start”, the device starts to enforce a movement with constant velocity $V_{\text{before}}$ on the subject’s upper limb.

III) When 1.2 s elapsed, the device begins to accelerate with the minimum-jerk trajectory.

IV) Reaching a comparative velocity, the device holds the velocity for 1.0 s, then stops moving.

V) The subject answers whether a velocity-change has been perceived in the movement or not.

3. Results and Discussion

The JNDs measured for the angular velocity and the hand velocity are shown in Fig. 7 (a) and (b), respectively. In the double joint motions, $\omega_{\text{before}}$ and $\text{JND}_\omega$ are defined by the sum of the shoulder- and elbow-joint angular velocities as a way of integrating shoulder and elbow motions. Each symbol represents the means of the 12 velocity-JNDs obtained for 12 subjects, for each joint-conditions and for each of the $\omega_{\text{before}}$- and $V_{\text{before}}$-conditions. The error bars indicate the standard errors of the means.

As shown in Fig. 7 (a), (b), a tendency for the velocity JNDs were seen to increase as the larger $\omega_{\text{before}}$ and $V_{\text{before}}$ factor. Similarly, other increasing tendency of human velocity-difference discrimination abiliy have also been reported in shoulder joints by Djupsjöbacka and Domkin (2005) and in elbow joints by Kerr and Worringham (2002): the range of the reference velocities, $\omega_{\text{before}}$, of $1.2 \sim 9.9$ deg/s in this work were much different from this experiment: the former employed $30 \sim 50$ deg/s, and the latter $15 \sim 75$ deg/s. Nevertheless, it is interesting that similar tendency was observed in this experiment as the previous two experiments. In addition, the increasing tendency reminds us of the Weber’s law including absolute threshold. The regression line in Fig. 7 (a), (b) was derived by applying linear regression to all the
obtained velocity JNDs. Comparing Fig. 7 (a) and Fig. 7 (b), Fig. 7 (b) shows better regression than Fig. 7 (b). In order to confirm the difference, the ANCOVA (analysis of covariance) was applied to both data as follows.

(1) Joint angular velocity-based ANCOVA

There is seen two categories in Fig. 7 (a): the elbow joint motion and the opposite-directional, double joint motion is seen in the upper side of the regressed line, and the shoulder joint motion and the same-directional, double joint motion in the lower side. Therefore, an ANCOVA was applied to the two categories. In the ANCOVA, first, the distances of all data to the regressed line were calculated, and, then, one-way ANOVA (analysis of variance) was applied between the distances of the two categories. As a result, there was significant difference between the two categories: $F(1, 142) = 5.60, p = 0.02 < 0.05$. It was confirmed that the joint angular velocity-based JNDs cannot be explained by the joint angular velocity at all.

(2) Hand velocity-based ANCOVA

In contrast to Fig. 7 (a), Fig. 7 (b) doesn’t show no discrepancy and does show a consistency between (i) the shoulder single joint motion, (ii) the elbow single joint motion, (iii) the same-directional double joint motion, (iv) the opposite directional double joint motion. Similar to the joint angular velocity-based ANCOVA, another ANCOVA was applied to the four categories from (i) to (iv). As a result of one-way ANOVA, there was no significant difference between the four categories: $F(3, 140) = 0.67, p = 0.57 > 0.05$. It was confirmed that the hand velocity-based JNDs can be explained by the hand velocity for all the joint motions. The result is referable to the experimental condition that subjects concentrate their attention on their hand tangential velocity in passive movements.

Here, Morasso (1981) conducted a motion control experiment in which the subjects drew straight lines connecting two predetermined points, and showed that the efferent motor control command not for the joint angle and angular velocity, but for the hand position and velocity played an important role. While his study dealt with the efferent motion control, this study dealt with the afferent movement perception. It is interesting that the hand velocity is dominant in both of the efferent and afferent signal.

In the PEST procedure, subjects can anticipate the changing pattern of velocity difference to be presented in correspondence with their answers, and the anticipation might influence the velocity JNDs. Referring to the experimental results in Fig. 7 (b), we can see a linear relationship between velocity JNDs and the hand velocity: since it is quite unlikely to hold such a linearity as a result of the anticipation, the anticipation is considered not to affect the velocity JNDs. Relatedly, Fig. 8 shows the change pattern of velocity difference until the velocity JNDs were measured in a condition (elbow joint, $V_{e. before} = 5.2$ cm/s) as a result, in a form of putting all 12 subjects. In the run where $D_{V_e}$ decreases from the one before shows the case where the subject could perceive the velocity-change, and the run where $D_{V_e}$ increases shows the case where the subject couldn’t perceive the velocity-change. As shown in Fig. 8, it is small that the changing of velocity difference exceeds 3 runs until it reverses. This is mostly similar in the other all condition. Therefore, the subjects’ perception accompanied by overshoot and undershoot are small, and it is considered the appropriate velocity difference stimuli was presented.

When human joints are passively moved by experimental devices, muscle contractions due to spinal reflex will occur. The muscle contraction may affect velocity JNDs. First, let’s estimate the magnitude of the muscle contractions by introducing a result on the human hand impedance characteristics (Tsuji et al., 1995). Since we are examining velocities, the velocity-related viscosity can be useful for evaluating the spinal reflex. As a result, in the elbow, single-joint motions, the torques of 0.02~0.04 Nm might have occurred due to the spinal reflex and the magnitudes may not be negligible. Here, note that, in the double joint motions, not only the shoulder joint torque but also the elbow joint torque will occur. Then, the subjects should integrate the pair of joint torques, and may encounter the same difficulty as the angular velocity integration (compare Figs. 7 (a) and (b)). Thus, it is considered that there may be no influence of the spinal reflex on the velocity JNDs.
4. Conclusion

In this paper, measuring velocity JNDs through a psychophysical experiment, we clarified velocity-change perceptual characteristics through proprioceptors. In the experiment, we employed passive movements in the shoulder and elbow joints with the minimum-jerk trajectory for increasing the velocity from a constant velocity to another constant velocity. Subjects were instructed to concentrate their attention on their hand speed. Then, the constant velocity $V_{\text{before}}$ in the before-acceleration section and the joints preforming the movements were set as the evaluation factors. As the results, the following findings were obtained.

1. Within the range of 1.3 ~ 5.2 cm/s of the $V_{\text{before}}$, the tendency that the velocity JNDs linearly increase with the larger $V_{\text{before}}$ was observed.

2. The factor effects of the hand velocities $V_{\text{before}}$ were dominant on the velocity JNDs over the joint angle velocities $\omega_{\text{before}}$, and were approximately the same between the shoulder joint movement, the elbow joint movement, and the shoulder-and-elbow joint movement.

Practically, the ability of perceiving velocity-change may differ from the relaxed condition in this study, depending on musculoskeletal conditions such as that exerting the force. In fact, Taylor et al. (1992) examined absolute thresholds in elbow joint movements and reported that the perceptual ability was improved under the condition in which subjects activate their muscles. In the future, we will extend our velocity JND research to activated musculoskeletal conditions.
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