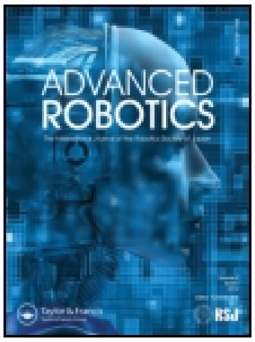

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SHORT PAPER

Measurement of just noticeable difference of hip joint for implementation of self-efficacy: in active and passive sensation and in different speed

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Self-efficacy, which is a belief to achieve a goal, is important for sufficient enhancement of physical ability of elderly people. For implementation of self-efficacy to assistive systems, it is necessary to subliminally change reference trajectories of the system within the range at which people cannot recognize the difference (just-noticeable difference: JND). This study clarified that elderly people have weaker position sense rather than young people when they are moved passively in relatively fast speed. New reference hip trajectories are computed to gradually extend hip flexion of human standing-up motion based on the measured JND.

Keywords: just-noticeable difference; standing-up motion; self-efficacy; assistive robotics

1. Introduction

In this paper, we measure the just-noticeable difference (JND) of human body position, and a new reference trajectory for assistive robots is suggested to gradually extend a person's functional mobility. These days, our aging society is facing the problem of decreased physical capabilities. In order to improve the physical ability of elderly people, standing-up motion is considered an important basic activity.

Previously, we had developed an assistive system for the standing-up motion.[1] It was composed of a bed and a support bar system to lead people to a reference trajectory. However, this assistive machine just strengthened the user's dependence on the machine or orthostatic hypotension occurred. Also, our previous study reveals that elderly people have weaker functions of bending trunk initially than young people do.[2] Particularly, hip flexion is an important movement to generate momentum and move the center of mass forward.[3] This impaired functional mobility is caused by physical disorders, psychological fear, or physiological factors.

For example, physical disability subliminally changes their behavior, such as less hip flexion, to adapt to entrenched physical body change.[4] Meanwhile, people hesitate to bend their hip due to fear of falling,[5] or they cannot clearly recognize their behavior change because of the gap between afferent and efferent nerves. These factors result in unconscious self-imposed limit which constricts their motion. It is important for them to have self-efficacy, which is a belief of capability to achieve a goal, in order to overcome this unconscious limitation.

In other medical areas that have tried it to date, self-efficacy has been taught by medical doctors or physical therapists. They usually observe the symptoms of the patients carefully and give them sufficient encouragement based on their own assessment. It has been suggested that self-efficacy results in better patient functioning.[6] However, the effectiveness of this approach depends mainly on the individual practitioner's personality or their experience.

The possibility exists that robotic therapy may overcome their reluctance and improve functional capabilities if robotic systems can provide self-efficacy with precise measurements and repeatable intervention. Developing such an assistive system necessitates the gradual extension of functional mobility of users, although they do not clearly notice the confronted difficulties. The range at which people are unable to notice is called the JND.

One rehabilitation system trains pinching and extension of the finger movement using the JND of the finger position and exerting force.[7] The required range of finger movement is increased gradually within the amount of JND as the trials progress. For the implementation of the idea of self-efficacy to assistive robots, previous study implies the necessity to investigate the characteristics of human sensation about their body movement.

Focusing on the standing-up motion, the flexion of the hip joint is specifically examined. However, there is no study

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which has investigated how people sense their hip flexion in a seated position. Although it was revealed that the JND of the hip joint angle is about 2–3°,[8] they only investigated it in a standing position, and subjects in the experiment extend or flex only one leg.

Therefore, our objective in this paper is to first evaluate the characteristics of human sensation about their body position in young and elderly people. Afterwards, we suggest new reference trajectories which can gradually extend the flexion of hip joint in standing-up motion.

2. Methods

2.1. Just-noticeable difference

Just-noticeable difference (JND) is the threshold at which people can only barely sense a difference. In this study, human sensation about one's body position is expressed as a probabilistic distribution. When people sense their body position θ, they judge it by all integrated sensory information S related to vision, joint receptors, or proprioceptors such as the muscle spindles. Therefore, the probability p that applies when people think their body position is θ when they receive sensory information S is defined as $f_\theta(S)$ (sense distribution).

Although people receive the same sensory information, they cannot always discern their body positions clearly. Consequently, sense distributions of different body positions usually overlap and cannot be divided. Figure 1 illustrates the overlapped sense distributions. Black solid lines indicate two distributions to sense their body position as θ and $\theta + \Delta\theta$, and dashed lines show other distributions.

In this paper, JND is calculated from distance d' between two distribution (f_θ and $f_{\theta+\Delta\theta}$). The larger the d' is, the higher the probability p will be, and therefore the difference ($\Delta\theta$) can be clearly recognized. In contrast, p becomes smaller and more false recognition occurs when people receive the same sensory information S if d' is smaller.

2.2. Signal detection theory

This paper calculates JND by signal detection theory. To calculate the sensitivity d', it is necessary to judge a threshold (the vertical black line in Figure 1). That judgment threshold is a criterion to judge their body position; people judge their body position as $\theta + \Delta\theta$ when sensory information S is above the criterion and they feel it is θ when S is below it. d' is calculated from Equation (1).

$$d' = F_{\text{norm}}^{-1}(1 - p_F) - F_{\text{norm}}^{-1}(1 - p_H), \qquad (1)$$

where a false alarm ratio (p_F) is the probability by which people sense their body position as $\theta+\Delta\theta$ when actual body position is θ, and hit ratio (p_H) is the probability by which people sense their body position as $\theta + \Delta\theta$ when the actual body position is $\theta + \Delta\theta$. Additionally, F_{norm}^{-1} is the inverse function of accumulated standard normal distribution. The JND (δ) is expressed in percentage and computed from sensitivity d' as in Equation (2).

$$\delta = \frac{\Delta\theta}{d'} \times \frac{100}{\theta}. \qquad (2)$$

2.3. Postural sensation

For this study, the JND of the hip joint is calculated in two different situations, such as active movement or passive movement. It is known that people have different JND in different movement types which are the motions they perform actively by themselves or they are forced to move passively by an external equipment.[9] Additionally, the speed of the standing-up motion affects the movements of the hip, knee, and ankle joints.[10] Therefore, three different postural sensation (ACTIVE, PASSIVE-FAST, and PASSIVE-SLOW) are studied.

In the ACTIVE sensation, people need to bend their back actively by themselves. In contrast, people are forced to move by the external bar in PASSIVE-FAST and PASSIVE-SLOW sensation. In passive session, people are asked to move according to the speed of the bar pushing their back. The speeds of the motion are, respectively, set to v_{fast} and v_{slow} in PASSIVE-FAST and PASSIVE-SLOW sessions.

2.4. Generation of reference trajectory

To improve the functional ability of elderly people, it is important for them to have self-efficacy. Self-efficacy is provided to people when they overcome their limitation. However, there is an unconscious limitation in the movement of elderly people due to physical pain, psychological barrier, or physiological impairment. Therefore, it is important for people to gradually increase their mobility without recognizing the confronted difficulties.

This study conducts a simulation experiment to propose a methodology to determine the reference trajectories of an assistive system based on the characteristics of human sensation. When people repeatedly use the assistive system, it is important for the assistive robots to change their reference trajectories gradually to overcome unconscious limitation within the amount that people do not recognize clearly.

Figure 2 illustrates the idea of new reference trajectories of the assistive system. In our suggested methodology, an initial functional ability, unconscious limitation, is measured first. In the figure, the horizontal dashed black line indicates the unconscious limit of users. The reference trajectory in the first trial (base trajectory) is set to be below the unconscious limit in order to start from the easier trajectory to follow (the solid black line in Figure 2). However, the reference trajectory of the next trial (the dashed red line in the figure) is made to be harder for the amount of JND (δ). As the trials of the assistive system progress, the reference trajectory in n-th trial of the system (the solid green line

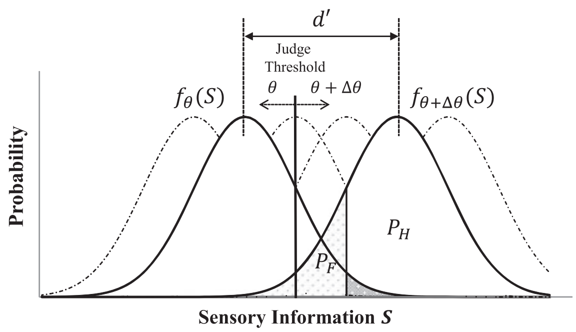


Figure 1. Schematic design of sense distribution.

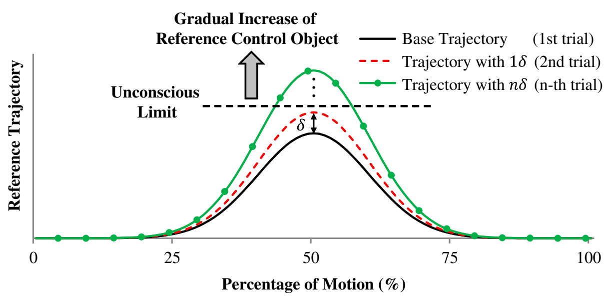


Figure 2. Schematic design of sense distribution.

with circle markers in the figure) can exceed the initial unconscious limitation.

When the base trajectory (θ) is decided, latter reference trajectories (θ') are calculated based on the base trajectory (θ) as in Equation (3).

$$\theta'(t) = \theta(t) + n\delta(\theta(t) - \theta_{\text{init}}). \quad (3)$$

In the equation, reference trajectory θ' at time t is decided based on the number of trials (n), JND (δ), and the change of trajectory from the initial position ($\theta(t) - \theta_{\text{init}}$). The change between base trajectory at time t ($\theta(t)$) and initial state (θ_{init}) is proportionally increased with the amount of JND during trials.

3. Results

3.1. Environment

In order to compute p_H and p_F, participants are asked to perform two motions in one trial. The first motion is always the same: participants bend their back to θ. They bend either the same amount (θ) or a different amount ($\theta + \Delta\theta$) in the second motion. After the second motion, participants are asked to answer orally whether they think the second motion is the same as the first motion or not. p_F is the ratio at which subjects answer $\theta + \Delta\theta$ when they bend θ whereas p_H is the ratio at which they answer $\theta + \Delta\theta$ when they bend $\theta + \Delta\theta$. In this paper, the JND of the hip joint (δ) is defined as the same difference as previous studies where people can recognize correctly at 75%.[7]

Figures 3(a)–(c) show the motions performed in the ACTIVE sensation; an optical motion capture system (MAC3D; Motion Analysis Corp.) with eight cameras (HMK-200RT, Motion Analysis Corp.) was used to calculate the hip joint angle from four markers attached to right and left acromioes and great trochanter. The sampling rate was set to 200 Hz for measurement taken in this study. Figure 3(d) illustrates the setup in the PASSIVE sensation. In this session, people are forced to move by the external bar which pushes their back.

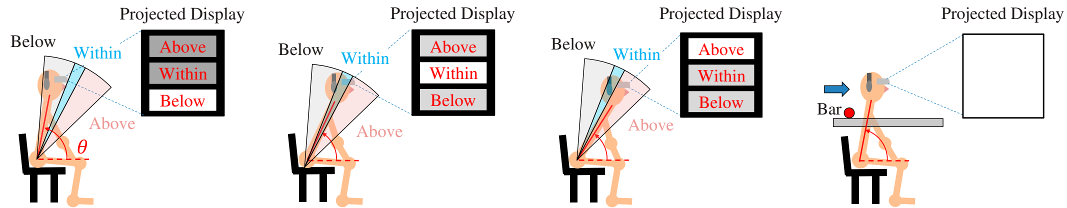
The difference between their current hip joint angle and target angle is provided via visual information (right black box with three squares in Figures 3(a)–(c)). The participants would see three squares through a head mount display (HMZ-T2; SONY Corp.) during trials. When their hip joint angle is within the target range, which is 98–102% of target joint angle, the middle square is highlighted, but either the top or bottom square is highlighted when their hip joint is above or below the target range. In the PASSIVE session, subjects wore the same head mount display, but it only projected a blank scene.

In the ACTIVE session, 50 trials were performed. Among them, participants were asked to bend to θ in the second motion in half of the trials. The remainder of them were to bend to $\theta + \Delta\theta$. The trials of the two types were distributed randomly. In the PASSIVE session, 100 trials were done. Twenty-five trials of four different conditions were distributed randomly, such as bending to θ or $\theta + \Delta\theta$ with fast speed (v_{fast}), and to θ or $\theta + \Delta\theta$ with slower speed (v_{slow}).

From our preliminary study, it is known that 70° is the hip joint angle when people rise their hip from a seat. Therefore, in this study, θ was decided as 70°. On the other hand, $\Delta\theta$ was determined as 3° based on the previous result which indicated JND of the hip joint as about 2–4° in standing position.[8] Additionally, v_{fast} was set to 1.3 m/s and v_{slow} was set to 0.7 m/s in this study.

Participants were asked to sit on a chair whose height was 0.45 m. Their hip joint angle was fixed to 90° from a horizontal direction, and they were asked to put their feet in a comfortable position at the beginning of every trial. When they performed the bending motion, they were told to put their hands on their thigh. In all sessions, participants wore a noise cancelling headphone (MDR-NC60, SONY Corp.) to prevent auditory information.

In total, 14 people participated in our experiment. They can be divided into two groups, such as young people (6 male and 1 female; mean age = 26.4, SD = 3.3 years) and elderly group (3 male and 4 female; mean age = 65.1, SD = 3.9 years). Average and standard deviation of their trunk length was 0.42 ± 0.04 m, and other segment length was not measured. All subjects were recommended to take a break whenever they felt tired during our experiment in order to



(a) ACTIVE;Below Target (b) ACTIVE; WithinTarget (c) ACTIVE;Above Target (d) PASSIVE

Figure 3. Different postural sensation.

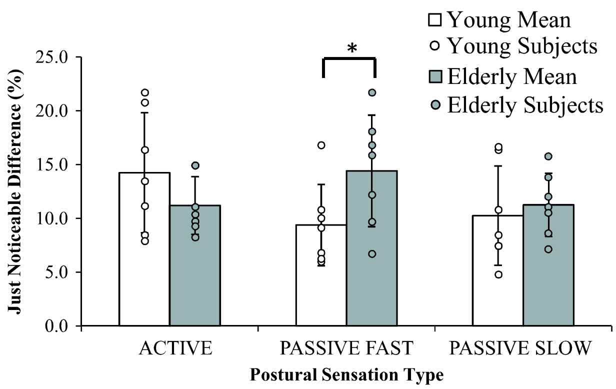


Figure 4. Results of just-noticeable difference.

avoid fatigue. The study was conducted with approval by the Institutional Review Boards of the University of Tokyo, and all participants provided written informed consent.

3.2. *Results of just-noticeable difference*

In the ACTIVE sensation, the mean and standard deviation of horizontal trunk velocity was 0.34 ± 0.05 m/s. Figure 4 presents the results of JND obtained in three different postural sensations. The white and gray bars in the figure, respectively, show the average JND of young and elderly participants while error bars indicate standard deviation. Mean and standard deviation of JND of young people were 14.2 ± 5.6, 9.4 ± 3.8, and 10.3 ± 4.6%, and those of elderly people were 11.2 ± 2.7, 14.4 ± 5.2, and 11.3 ± 2.9% for ACITVE, PASSIVE-FAST, and PASSIVE-SLOW sensations. Circle markers show the computed JND for each participants; white and gray circles show the data of young and elderly people.

As a result of statistical analysis (t-test), there was a significant difference in the JND of PASSIVE-FAST between young and elderly people with a significance level of $p < 0.05$. In contrast, there was no significant difference in the JND for ACTIVE and PASSIVE-SLOW among the two groups.

3.3. *Results of simulation experiment to generate suggested reference trajectory of assistive system*

This paper shows the results of the simulation experiment to generate an example of reference trajectories which can be used for our assistive systems of standing-up motion. Figure 5(a) portrays a schematic design of the developed assistive system.[1] The machine leads people to a desired trajectory with a support bar and a bed system. Users of this system are asked to sit on the bed and hold the bar in front of them. The bar moves vertically and horizontally to control their upper body with two actuators (ACT1 and ACT2). The bed moves up and down to push their hip vertically with an actuator (ACT3).

It is assumed that one of the elderly subjects (Male, 63 years) uses our system. Trajectories of each actuator ($P_{\mathrm{ACT1,ACT2,ACT3}}$) are derived from a human geometric link model as in Equations (4)–(6). During the use of assistive machine, it is assumed that users keep their elbow straight to hold the support bar; θ_4 is fixed to 15°. Since hip joint flexion is especially focused, target trajectories for ankle and knee are fixed as well in the simulated example of reference trajectory.

$$P_{\mathrm{ACT1}} = \sum_{i=1}^{4} l_i \cos\theta_i, \tag{4}$$

$$P_{\mathrm{ACT2}} = \sum_{i=1}^{4} l_i \sin\theta_i, \tag{5}$$

$$P_{\mathrm{ACT3}} = \sum_{i=1}^{2} l_i \sin\theta_i. \tag{6}$$

The base trajectories of joint angles, except θ_4, were derived from one measured body trajectory of the same subject performing the standing-up motion in this study, and the link length ($l_{i=1,2,3,4}$) was decided based on the measured data. In this example, $l_{i=1,2,3,4}$ are 0.40, 0.52, 0.47, and 0.58 m, respectively. Figures 5(b) and (c) show the measured joint angles and angular velocities for hip, ankle, and knee. Black solid lines indicate those of hip joint, blue solid lines with circle markers indicate those of ankle, and blue dashed lines indicate those of knee.

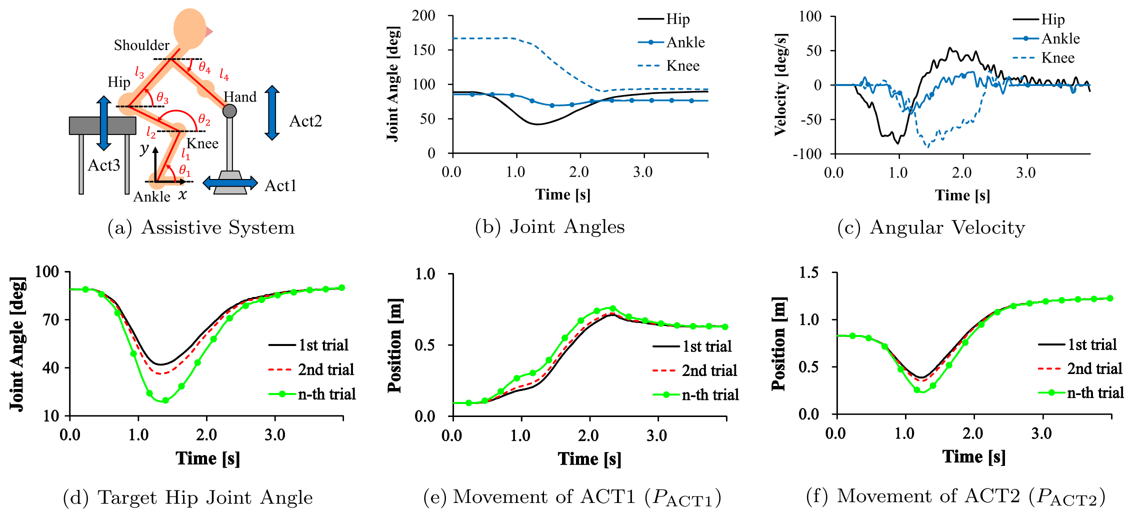


Figure 5. Reference trajectory for the assistive system.

Figure 5(d) shows the reference trajectory of hip joint which our assistive system should generate. In this example, since the participant's maximum horizontal speed is less than 0.7 m/s, JND was set to 12.0% which is obtained from the same elderly subject in PASSIVE-SLOW sensations. The black solid line indicates the base trajectory at which the system would emulate at the first. The dashed red line shows the reference hip joint angles for the next trial, and the green line with circle markers illustrates the joint angles at the n-th trial ($n = 4$ in this example). Our result illustrates that reference trajectory is gradually decreased within the amount of JND.

Figures 5(e) and (f) show the movement of two actuators in the support bar. In both figures, the solid black line indicates the movement of actuators to generate the base trajectory. Likewise the dashed red lines and solid green lines show the actuators' movement to generate trajectories of the second and n-th trial. The modified movements of two actuators (ACT1 and ACT2) of the support bar could be generated corresponded to the reference trajectories.

4. Discussion and conclusion

Characteristics of human sensation are studied in this study. The JND of position sense differs among people depending on their individual sensory system, such as proprioceptor. The mean of calculated JND in this study (1.88–2.88°: corresponded to the range of calculated JND, 9.4–14.4%), is smaller than ones of the previous study (2.70–4.30°).[8] Also, standard deviation of JND in this study (0.54–1.12°) is within the previous work (2.20–2.84°).[8] Those differences are thought to be caused by the different posture in the experiment, such as sitting in the current study compared to standing in the previous work. Our results of JND show that elderly people have lower ability to sense their body positions when they are passively moved in relatively fast speed. It implies that decreased functional mobility is possibly caused by the lower position sense.

In order to improve their physical ability, reference trajectories of the assistive device are suggested which employ the idea of self-efficacy. In this study, we compute the JND of hip joint angle and show the example of implementation of JND to the assistive system for the standing-up motion. Results of reference trajectories are generated based on the JND of passive slow movement of the elderly person (12.0%). However, reference trajectories should be changed when users perform different types of motion, such as active motion or comparatively faster motion. Therefore, our methodology is supposed to be utilized for subjects or different motions depending on its purpose.

In order to implement the new reference trajectories, the JND of motion speed will be investigated. Although the change of reference trajectories is within the amount of individual JND, users might notice the different speed of the assistive machine. Additionally, it is known that the speed of standing-up motion affects the joint movement of knee and hip. Therefore, optimized reference trajectories can be obtained based on the JND of position and speed sensation.

Moreover, this methodology is applicable to other assistive systems as well. For example, it is possible to extend and improve human walking motion as long as the JND of knee and ankle is measured in addition to that of a hip joint. It also enables other types of systems, such as force or speed training, by computing the JND of sense of force or speed other than position sense.

In conclusion, the characteristics of human sensation about their body position is studied to implement the idea of self-efficacy to assistive systems. The JND of hip flexion is measured in different postural sensations. It has clarified that elderly people have lower position sense than younger people when they are moved in fast speed. Based on the just-noticeable difference, new reference trajectories are suggested to gradually extend human body movement.

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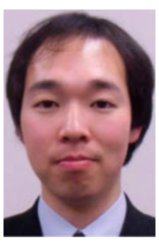

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