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STANDING ASSISTANCE WHICH REALIZES VOLUNTARY MOVEMENTS OF THE PATIENT WITHIN A SAFETY MOTION TOLERANCE

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This paper proposes a novel standing assistance robot, which realizes voluntary movements of the patient within a safety motion range. In previous studies, conventional assistive robots did not require patients to use their own physical strength to stand, which leads to decreased strength in the elderly. Such general assistive robots helped patients by using a fixed motion reference pathway in spite of their original intention, and as a result, these robots failed to use the physical strength of the patients. Therefore, we have clarified the range of motion that allows patients to move their body safely and applied this safety tolerance for assistive robot control. However, determining whether a patient's movements are within a safe tolerance may not be enough to successfully assist the patient. For example, the robot should assist its patient immediately if the patient falls down even if this motion is done within safety tolerance. Thus, in this paper, we extend from our previous safety tolerance to safety “motion” tolerance. Furthermore, we implement this idea to our assistive robot control using damping control algorithm. Proposed idea is implemented to our new prototype and its effectiveness is verified by experimental results with elderly subjects who lives in the nursing care house.

1. Introduction

1.1. *Background and Motivation*

Standing is one of the most serious and important activities of daily living because of the possible lack of strength and stability in the elderly [1, 2]. Typically, in bad cases, an incapacitated elderly person may not be able to stand up and subsequently become limited to wheelchair living or bedridden [3]. Furthermore, when the elderly fall into this lifestyle, the lack of exercise and consequent decline in physical fitness becomes more pronounced [4]. Therefore, there is a need for an assistive robot to help the use of residual muscle strength during orthostatic movements in order to maintain the patient's muscle strength.

To achieve this goal, the assistive robot must be designed to accept some degree of variability in the patient's body movements, as human movement does not always conform to the established reference pathway [5]. During the standing motion, these robots interfered with the patient's body movements and were adjusted to conform to the reference pathway. Such external interventions would prevent the patient from using his or her own strength in the process of standing up, which would result in a decrease in the patient's muscle strength.

1.2. *Problems in our Previous Research and Objective of this paper*

In order to address this problem, we defined the “safety tolerance” as the range in which a person can continuously perform standing motions from the standpoint of physical balance and muscle strength [6]. Furthermore, we developed a standing assistance robot as Fig.1(a) which allowed the patient's voluntary movements as long as the patient's posture was within the safety tolerance. Using this idea, our robot could use the patient's physical strength as much as possible.

This idea works if the patient's motion is essentially the same, though with errors, as the robot's expected motion. However, when the patient does not perform the movements assumed by the robot, the robot may assist extraordinarily or, conversely, the robot’s assistance may be delayed. For example, if the patient falls, the robot should assist the patient immediately, but with our previous algorithm [6], the robot prioritizes the patient's spontaneity until it gets out of the safety tolerance. Furthermore, as shown in Fig. 1(b), if the patient raises her hips earlier than the robot expects and she exceeds the safety tolerance, the robot will force her to return to the original motion. These problems occur because the patient's movements are considered only in terms of the safety tolerance. Therefore, the objective of this study is to extend the concept of the safety tolerance and propose a concept called the “safety motion tolerance” that defines the range of movements which ensure the safety of the patient.

(1) (2) (3) (4)

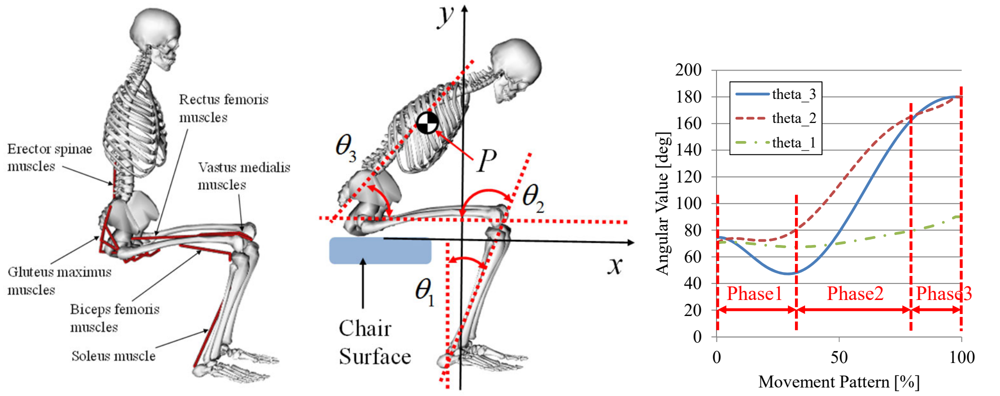
(a) Our prototype (b) She tried to stand up early in (2) and was forced back by the robot in (3).

Figure 1. Our standing assistance robot and its unsuitable assistance.

2. Safety Tolerance

In terms of body mechanics, the safety standing motion must meet two conditions. The first condition is stability condition. The patient should be able to maintain body balance during standing motion. We define this condition as: the center of gravity position (COG) is within range of the patient's feet, while maintaining body balance when standing.

The second condition is muscle condition. The patient should be able to control his or her body movements when standing. In general, the positional relationship between muscle and bones changes depending on a subject's posture, so the output force generated by a muscle changes with posture. In other words, in an unsuitable posture, it is not possible to generate enough upward output force to advance the standing motion. In this study, this muscle condition is defined as the required output force of the muscle shown in Fig. 2(a) should not exceed the maximum output of the muscle during standing up.



(a) Muscles (b) Its coordination (c) Standing motion recommended by physical therapist

Figure 2. Human model.

In our previous studies [6], we have examined the acceptable range that satisfies these conditions through computer simulation using OpenSim [7], a human motion dynamics simulator package. In this simulation, 3DGait-Model 2392 was used as the human body model and the body parameters were changed to match a typical Japanese elderly person [8]. The standing movements were based on references recommended by physical therapist [9], as shown in Figure 2(c). In Figure 2(c), the Y-axis shows the angular values of the pelvis and trunk and the knees and ankles, and the X-axis shows the movement pattern [10], which is the ratio of the standing movement, as shown in (1).

$$\hat{s} = \frac{t}{t_s} \tag{1}$$

t_s is the time required for completion of the standing operation and t is the present time.

In this computer simulation, the variation of the movements was increased by adding fluctuations to the basic movements by the physical therapist, and it was verified whether the human model could satisfy the stability and muscular conditions in each movement.

The simulation results are shown in Figure 3. Figure 3 shows the position where the subject's center of gravity, P, can satisfy the stability and muscular conditions. In other words, the red-filled area in Figure 3 indicates the safety tolerance, which extends before and after the standing trajectory recommended by the physical therapist. If the patient adopts a posture in which the P point is within the safety tolerance, the patient's postural stability is maintained and guaranteed to be able to continue standing with his or her own muscle strength.

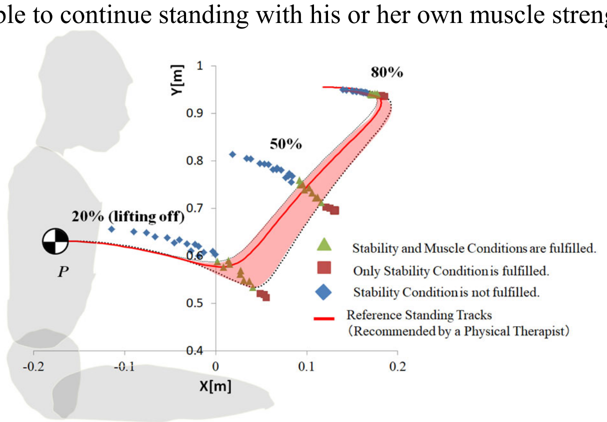


Figure 3. Investigated posture tolerance by simulation. From 0[%] to 10[%], there was no range because during this period, the subject sat on the chair before lifting up.

3. Safety "Motion" Tolerance and Standing Assistance based on it

3.1. *Posture Estimation using low cost sensor*

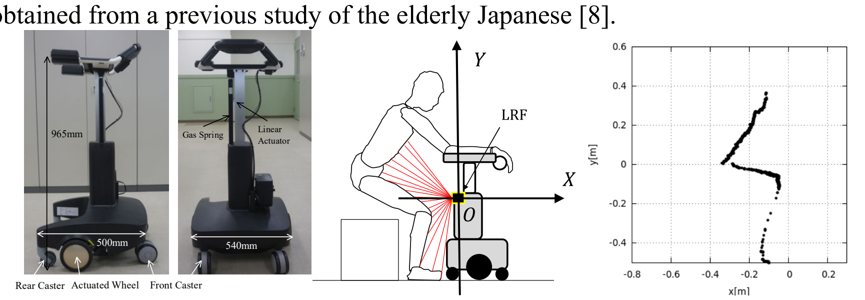
In our previous research, we have developed robotic walkers with an assisted standing function [11, 12, 13]. A latest prototype [14] is shown in Fig. 4(a). The robotic walker has a motorized walker and a standing support manipulator with an armrest to move upward so that the user can be lifted. The wheel actuators on the powered walker are used to stabilize the user when a standing support manipulator lifts the user.

To estimate the posture of the patient, we used an inexpensive two-dimensional laser range finder. As Fig. 4(b), our robot equips the laser range finder. The range of movement of the body during the standing motion is limited, and the main problem is the body movement in the X and Y directions shown in Fig. 4(b). Therefore, if the laser range finder is installed at an appropriate position, it is possible to measure the patient's posture even with an inexpensive 2D laser range finder as shown in Fig. 4(c).

In this study, the human body was approximated as a linked model as shown in Figure 5(a). From the point data measured by the laser range finder as shown in Fig. 4(c), the end points of each link are estimated as shown in Fig. 5(b). The estimation algorithm was developed in our previous work [11]. Please refer to the details there. The position of the center of gravity (COG) of each link ((x_i, y_i), i is 3, 4 and 5.) was estimated from the endpoints of each link. In this study, the COG position of the link was assumed to be at the midpoint of the link. From the position of the COG of each link and the weight of each link, the position of the COG of the patient can be expressed by (2).

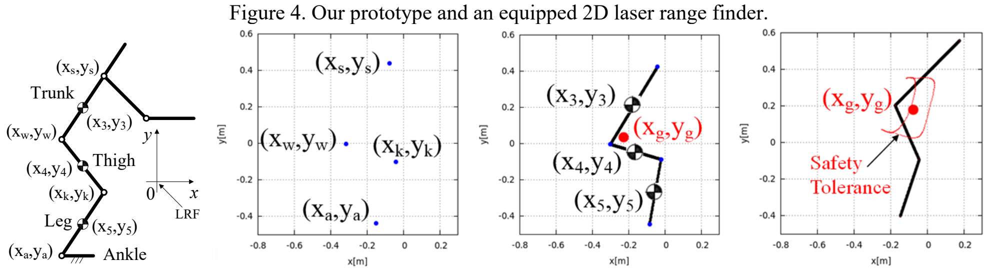
$$\mathbf{P} = \begin{vmatrix} x_p \\ y_p \end{vmatrix}^T = \frac{\sum_{i=3}^{5} \left(m_i \cdot \begin{vmatrix} x_i \\ y_i \end{vmatrix}^T \right)}{\sum_{i=3}^{5} m_i} \tag{2}$$

where m_i is mass of each link. The mass of each link, which is one of a physical parameter, was obtained from a previous study of the elderly Japanese [8].



(a) Our prototype (b) The position of LRF (c) Measuring data by LRF

Figure 4. Our prototype and an equipped 2D laser range finder.



(a) Linkage model (b) Estimation of each joint (c) Estimation of COG (d) Estimation of COG and tolerance

Figure 5. Real time estimation of the center of the gravity of the patient.

As described above, our robot can estimate the center of gravity of a patient's body and his or her safety tolerance in real time as shown in Fig. 5(d).

3.2. *Proposal of Safety Motion Tolerance*

When the center of gravity is within the margin of stability, the patient's body stability is maintained and the caregiver is able to continue standing up with his or her own muscle strength.

In our previous study [6], we proposed a method to assist the patient to stand up by simply changing the assistance force control depending on whether the patient is within the stability margin or not, giving priority to the patient's voluntary movements. However, there are problems with this assistance method, as discussed in section 1. From them, it is important not only to consider the posture of the patient, but also to evaluate whether or not the movements the patient is performing will be within the safety tolerance when deciding on standing assistance scheme.

Therefore, we propose an estimation method for the stability of a patient's movement. In order to determine whether a patient's voluntary movement is safe, it is necessary to estimate the movements that are likely to be made within the safety tolerance, such as movement A in Fig. 6(a), and the movements that are likely to deviate from the safety tolerance, such as movement B, from the stage when the patient is still operating within the safety tolerance.

The trajectory that the body's center of gravity takes when the patient performs the standing motion recommended by the physical therapist can be expressed by (3). $\mathbf{P}^{ref}$ is matrix data listed by the movement pattern $\hat{s}$. These data are derived kinematically in advance from body parameters such as height [8].

$$\mathbf{P}^{ref} = \begin{vmatrix} \mathbf{x}_p^{ref} \\ \mathbf{y}_p^{ref} \end{vmatrix}^T = \begin{vmatrix} x_p^{ref}(0), \cdots, x_p^{ref}(\hat{s}), \cdots, x_p^{ref}(1) \\ y_p^{ref}(0), \cdots, y_p^{ref}(\hat{s}), \cdots, y_p^{ref}(1) \end{vmatrix}^T \tag{3}$$

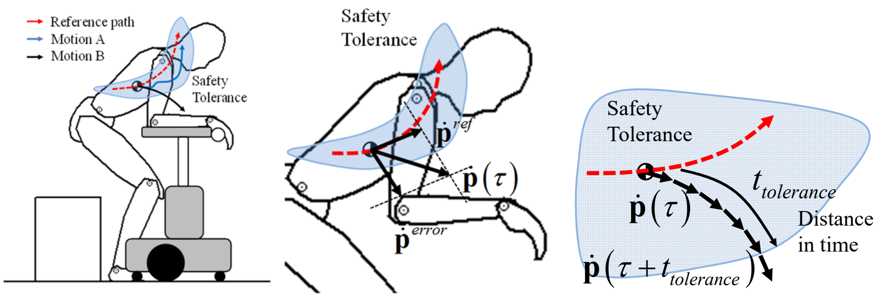
If the patient performs a movement that is different from the trajectory of the reference standing motion at the movement pattern τ as shown in Fig. 6(b), the velocity vector of the actual patient's body $\dot{\mathbf{p}}$, the velocity vector by the reference standing way $\dot{\mathbf{p}}^{ref}$, and the velocity vector of the difference between them $\dot{\mathbf{p}}^{error}$ is expressed as (4).

$$\dot{\mathbf{P}}(\tau) = \dot{\mathbf{P}}^{ref} + \dot{\mathbf{P}}^{error} \tag{4}$$

If the patient continues the motion at the movement pattern τ, the position of the center of gravity at t can be expressed by (5) as shown in Fig. 6(c).

$$\mathbf{p}(t) = \int_{\tau}^{t} \left(\dot{\mathbf{p}}^{ref}(t) + \dot{\mathbf{p}}^{error}(\tau) \right) dt \tag{5}$$

Using (5), we can calculate the time t_{out} when the center of gravity deviates from the safety tolerance by real time computer simulation.



(a) Reference path and the patient's motion (b) The error motion (c) Estimation of distance to the outside of tolerance

Figure 6. Safety tolerance and safety "motion" tolerance.

From the above, assuming that the patient continues to act at movement pattern τ , the time $t_{tolerance}$ when the patient can stay within the safety tolerance is (6).

$$t_{tolerance} = t_{out} - \tau \tag{6}$$

$t_{tolerance}$ represents the distance in time to the wall in the safety tolerance of the patient's movement. In other words, it is an indicator of the safety of the patient's movements. If $t_{tolerance}$ is larger value, the patient's motion will be done within the safety tolerance and its risk is low. On the other hand, $t_{tolerance}$ is smaller value, the patient's motion has high risk. In this paper, we call $t_{tolerance}$ as safety motion tolerance.

3.3. *Assistance Control using Safety Motion Tolerance*

In this section, we propose an algorithm that combines the assistance scheme for standing up with those that use the patient's residual physical ability and those that provide quick supporting for risky movements of the patient. Specifically, when the patient's motion is within the safety tolerance, our robot gives priority to the patient's voluntary movement and uses assistance measures that use the patient's own muscle strength. On the other hand, if there is a risk of the patient's movement deviating from the safety tolerance, even if the patient's posture is within the safety tolerance at that point, our robot gives priority to safety and uses assistance scheme to maintain the patient's posture safely.

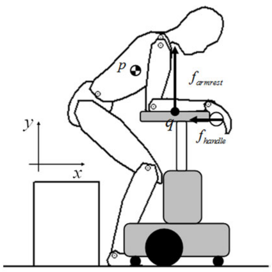
The following is a description of the specific proposal methodology. As shown in Fig. 7(a), our robot has a standing support manipulator (y direction) and motorized walker (x direction). The patient puts his or her weight on the armrest at the top of our assistance robot and grasps the handle to get assistance force from our robot in the x and y directions. Our robot has force sensors on its handle and armrest as Fig. 7(b). Using these equipped sensors, our robot measures applied force to armrest ($f_{armrest}$, y-direction) and handle (f_{handle} , x-direction) by the patient during standing up.

Our robot assists the patient at q point in Fig. 7(a). Our robot has control references for each actuator as detailed in (7), which realize the designed standing motion as (3). $\dot{\mathbf{q}}^{ref}$ is velocity reference vector of q point, $\dot{\mathbf{x}}_q^{ref}$ the motion reference for a powered walker and $\dot{\mathbf{y}}_q^{ref}$ is for a standing assistance manipulator.

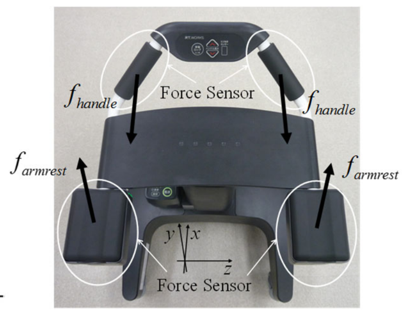
$$\dot{\mathbf{q}}^{ref} = \begin{vmatrix} \dot{\mathbf{x}}_q^{ref} \\ \dot{\mathbf{y}}_q^{ref} \end{vmatrix}^T = \begin{vmatrix} \dot{x}_q^{ref}(0),\cdots,\dot{x}_q^{ref}(\hat{s}),\cdots,\dot{x}_q^{ref}(1) \\ \dot{y}_q^{ref}(0),\cdots,\dot{y}_q^{ref}(\hat{s}),\cdots,\dot{y}_q^{ref}(1) \end{vmatrix}^T \tag{7}$$

Our robot uses the force sensor equipped on its top for switching condition between the position control and the damping control as (8).

$$\dot{\mathbf{q}}^{upref} = \begin{vmatrix} \dot{x}_q^{upref} \\ \dot{y}_q^{upref} \end{vmatrix}^T = \begin{vmatrix} \dot{x}_q^{ref} - B_{pw}\left(f_{handle} - f_{handle0}\right) - K_{pw}\left(x_q - x_q^{ref}\right) \\ \dot{y}_q^{ref} - B_{sm}\left(f_{armrest} - f_{armrest0}\right) - K_{sm}\left(y_q - y_q^{ref}\right) \end{vmatrix}^T \tag{8}$$



(a) Direction of measuring force



(b) Top of our robot

Figure 7. Force sensors equipped on our robot

where $\dot{\mathbf{q}}^{upref}$ is the updated reference value that our robot actually uses for delivering standing assistance. $\left(x_p, y_p\right)$ is the actual position of the powered walker and the standing assistance manipulator of our robot. B_j and K_j (*j*=*sm*: standing manipulator, *pw*: powered walker) in (8) are constants used to coordinate the ratio between the damping and position controls. $f_{handle0}$ and $f_{armrest0}$ are the forces the patient applies to the assistance system before he or she stands.

In order to apply the damping control only when the patient's motion fulfills safety "motion" tolerance discussed in previous paragraph, the coefficient B_j that validates the damping control mode is calculated as (9). B_j will be larger value if the safety motion tolerance has enough time distance $\left(t_{tolerance} \geq 0\right)$ and as the result, our robot allows the patient to move according to his or her intention.

$$\begin{cases} B_j = b_j\left(1 - e^{-t_{tolerance}^2}\right) & if\ t_{tolerance} \geq 0 \\ B_j = 0 & if\ t_{tolerance} < 0 \end{cases} \tag{9}$$

By contrast, the position control is always useful because it helps the patient maintain a stable posture during motion. Therefore, we set the coefficient, K_j which validates the position control mode, to be constant. The values of b_j and K_j were determined experimentally.

4. Experiment

4.1. *Experimental Setup*

We implemented our proposed idea to the prototype (Fig. 1(a), Fig. 4(a)) and conducted a practical experiment with it. To confirm the efficiency of our standing assistance scheme, we tested two cases.

- Case1: Using only position control, without our proposed idea. (Fix reference path)
- Case2: Using our proposed idea. (Reference path with posture tolerance)

We used five subjects and each subject attempted all two cases, two times each. Subjects were elderly whose care levels [15] are 1 or 2 as Table 1. Furthermore, we measure the surface electromyograms on several body segments, motion data (using motion capture system) and ground reaction force (using force plate) during a standing motion.

Table 1. Elderly Subjects

Subject	Height [cm]	Weight [kg]	Age	Gender	Care level
A	160	57.2	83	Male	1
B	157	54.9	81	Female	2
C	150	38.5	78	Female	1
D	159	52.9	85	Male	1
E	149	52.1	82	Female	2

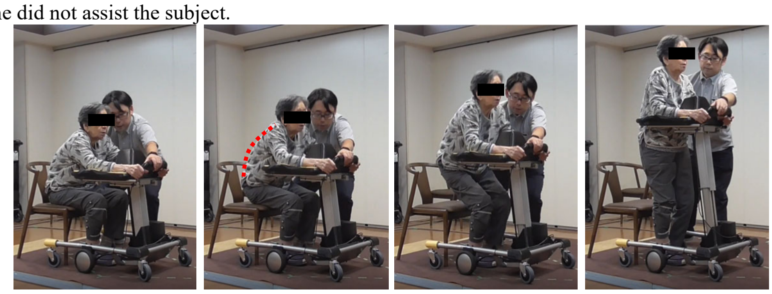
4.2. *Experimental Results*

Figs. 8 and 9 show the standing process of subject A and B. In each case, subject A and B succeeded to stand with our assistive robot. No subject failed to stand as Fig. 1(b) with our proposed assistance. In this experiment, all subjects inclined their upper body at the begging of standing process with our proposed scheme. This motion moves COG to the sole of the foot and it is important for its user to stand up by own physical strength. Thus, we can assume that using our proposed assistance scheme, the subject stood with his/her intended movement.

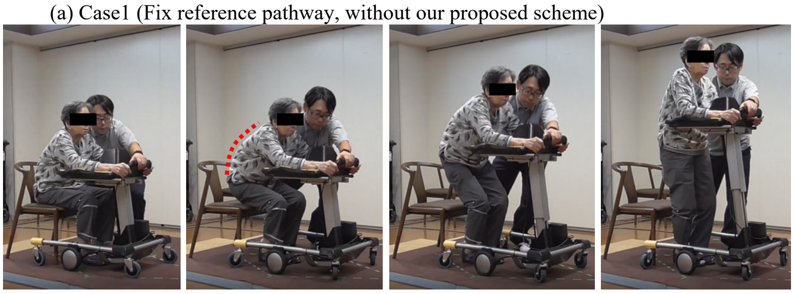
(a) Case1 (Fix reference pathway, without our proposed scheme)

(b) Case2 (considering tolerance posture, with our proposed scheme)

Figure 8. Standing motion (Subject A) For safety reasons, the physiotherapist waited next to the subject. During the experiment, he did not assist the subject.



(a) Case1 (Fix reference pathway, without our proposed scheme)



(b) Case2 (considering tolerance posture, with our proposed scheme)

Figure 9. Standing motion (Subject B) She is round-backed. For safety reasons, the physiotherapist waited next to the subject. During the experiment, he did not assist the subject.

Fig. 10 is muscle activity of rectus femoris muscle, gluteus maximus muscle and erector spine muscle. Fig. 10 shows how large the muscle activity is at case2 if the muscle activity at case1 is 1. From Fig. 10, we can verify that with proposed scheme, all muscles works harder than without proposed scheme. This means proposed assistance control uses its user's physical strength effectivity.

Fig. 11 shows physical activity of rectus femoris muscle during standing process at subject A. From these results, the subject A used his own physical strength from he lifted off his buttocks from chair to he finished his standing process. Lifting off phase requires his COG on the sole of the foot, thus, we can verify that allowing intended motion is effective for using the remaining of physical strength of its user.

Fig. 12 shows the ratio of muscle activity during standing process between case2 (with proposed scheme) and case1 (without proposed scheme). From Fig. 12, our assistive robot used remaining physical strength of subject A, C, D and E with our proposed control algorithm. On the other hand, subject B did not use own physical strength because she did not incline her upper body during standing motion as Fig. 9. In other word, she failed to stand with her own intention and her motion exceeds the safety tolerance. However, even if she failed, our robot succeeded to assist stand up motion safely using our proposed assistance scheme. She finished her stand up motion with our robot, not as Fig. 1(b).

According to these results, our robot succeeds to provide assistance to subjects while also allowing them to use their own physical strength. Furthermore, even if unsuitable movement, our robot succeeded to assist the patients and finish their standing motion safely.

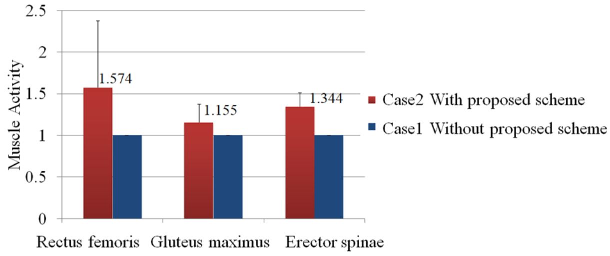


Figure 10. Muscle activity during standing motion

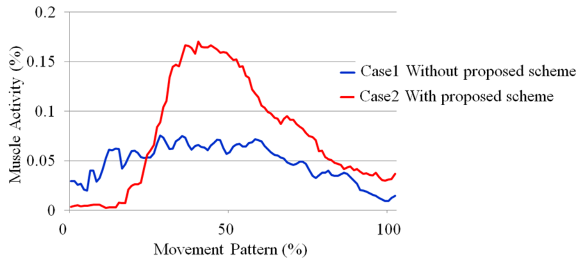


Figure 11. Activity of rectus femoris muscle during standing process (Subject A)

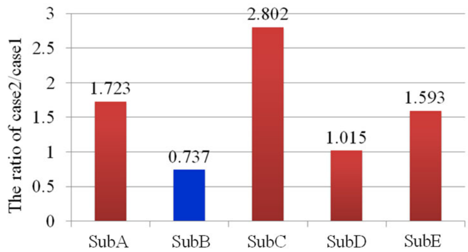


Figure 12. The ratio between the activity of rectus femoris muscle at case2 and case1. If the value is larger than 1, case2 uses larger physical strength comparing with case1.

5. Conclusion

This paper proposes a novel standing assistance scheme, which allows patients to maximize the use of their physical strength. To realize this, we proposed posture estimation scheme with low cost sensors and voluntary movement evaluating method from the view point of safety "motion" tolerance. Furthermore, novel assistance control scheme which selects more appropriate control method from position and damping control using safety "motion" tolerance as an index. We conducted practical experiments to confirm the efficiency of the proposed idea implemented in our prototype of a robotic standing assistance device.

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