Sitting Assistance that Considers User Posture Tolerance

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Abstract: This paper proposes a novel sitting assistance robot, which considers the posture tolerance of its user. The standing and sitting motion are different essentially because the standing is lifting motion against gravitational force and sitting is posture coordination to sitting position according to the gravity. Therefore, the robot should lead the patient's posture within a stable range during sitting and the required performance is different from standing assistance. However, in previous studies, conventional assistive robots used the sitting motion which is "reverse" motion of standing. Furthermore, these robots helped patients by using a fixed motion reference pathway in spite of their original intention, and as the results, these robots failed to assist by confliction between their intended motion and reference path. Therefore, we propose a novel sitting assistance robot, which allows its user to move their body within a prescribed degree of posture tolerance during the process of moving from a standing to a sitting position. Our key findings cover two fundamental research topics. One is the investigation into posture tolerance during a sitting motion. The other topic is a novel assistance control algorithm that considers the investigated posture tolerance by combining position control and force control. A prototype assistive robot, based on the proposed idea was fabricated to help patients sitting down safely according to their original intention.

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1 INTRODUCTION

Activities such as standing, walking, and sitting may be the most serious and important activities in the day-to-day lives of elderly people as they lack physical strength (Alexander et al., 1999; Hughes et al., 1996). In a typically bad case, an elderly person who does not have enough physical strength will not be able to stand up and sit down, and as the result, they may then be restricted to life in a wheelchair life or become bedridden (Cabinet Office, Government of Japan, 2016). Furthermore, once an elderly person falls into such lifestyle, the decrease in their physical strength becomes more pronounced due to the lack of exercise (Hirvensalo et al., 2000). For increasing their QOL (Quality of Life), they need a personal assistive robot which enables them to perform daily activities alone easily even if their physical strength reduces by aging.

In previous works, many researchers have been developed assistance devices for a standing motion (Nagai et al., 2003; Funakubo et al., 2001). However, these devices are specialized in only a "standing assistance" and they do not discuss on a sitting motion. Some previous researchers say a sitting motion is only "reverse" motion of standing (Ehara et al., 1996). However, standing and sitting motion are different essentially because standing is lifting motion against gravitational force and sitting is posture coordination to sitting position according to the gravity. In general, a sitting motion has high risk for falling down compared with a standing motion for elderly people (Yoneda, 1998) and it is difficult to realize a sitting assistance using only "reverse" motion of standing. Furthermore, a sitting assistance requires the posture coordination within stable range, not a force assistance as a standing assistance because sitting motion follows a gravity direction. Therefore, the robot should assist the

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patients according to their intended sitting motion, and should help only when their posture are unsuitable and have high risk for falling down.

In this paper, we propose a novel sitting assistance robot, which considers the variation in the range of movements of a patient's body when sitting from a standing position. To achieve this objective, we initially investigated the posture tolerance during the process of sitting down. In this range, patients can sit down, stably and safely, using their own physical strength. Secondly, we extend a published assistance algorithm, (Chugo et al., 2014) which combines position control and force control, to adapt to the parameters of the prior investigation into posture tolerance. Using the proposed algorithm, our robotic device only assists them to sit down when necessary.

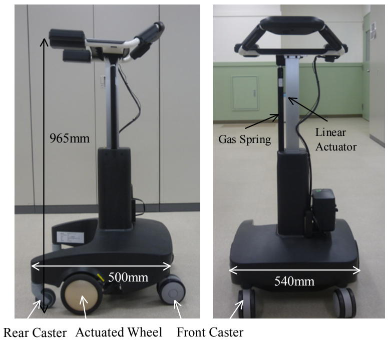
2 SYSTEM CONFIGURATION

2.1 System Overview

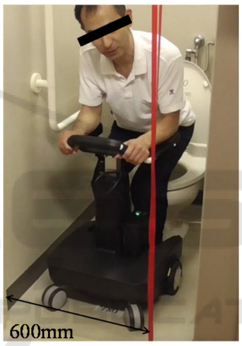
Previously, we have developed robotic walkers which have a standing/sitting assistance function, (Chugo et al., 2014; Chugo et al., 2017) and Fig. 1 shows our recent latest prototype (Chugo et al., 2017). The design of our proposed assistive device is based on a powered walker. It has a standing/sitting support manipulator, which moves the user in an upward/downward direction. Fig. 1(a)-(b) shows the default position of the walker's manipulator at a standing and walking heights. Its width is 54 cm and can pass through a typical toilet door with a standard width of 60 cm (JIS - Japan Industrial Standard – 1526:1997) as Fig. 1(c). Its height is 71.0–96.5 cm and fits users whose heights are in the range of 145–160 cm.

To lift down a user, our proposed walker uses a linear motion DC motor and a gas spring. This motor can generate a force in the up/downward direction, whereas the gas spring helps this force in the up/downward direction. In total, our system can lift a weight of 40 kg, which is enough to assist someone in standing or sitting. Using the gas spring, our system can use a smaller actuator, which means that its design can be fairly inexpensive. Furthermore, the gas spring prevents the device from moving suddenly when the power is down.

The wheels on each side of the walker have an actuator and an electric parking brake as Fig. 1(a). The actuated wheels are located in the almost same position as that of a user and four caster wheels help in maintaining its balance so that the user can turn around on the spot when they walk using the device. The actuator has enough power to control its own position references, but when a user wants to fix its position over a long time, they should make use of the parking brake, because it is a mechanical brake and its energy efficacy is better than that of the control scheme containing the actuators.



(a) Side view (b) Front view

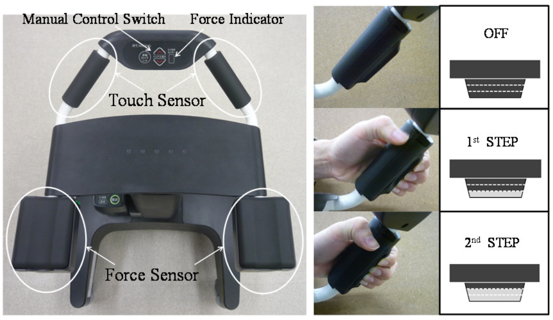


(c) Typical situation in the bathroom

Figure 1: Our assistive walker.

2.2 User Interface

A handle, armrest, and controller are provided on the top of the walker, as shown in Fig. 2(a). There are force sensors inside the armrests and touch sensors on the handles. When a user wants to move, they have to put their arm on the arm-rest and grip the handles. Using the two sensors, our device judges whether the user is ready to movement. A gripping switch is provided on each handle, as shown in Fig. 2(b). This switch has two input steps that can be changed by the strength used for the grip. Usually, in emergency situations, elderly people tend to release the control switch or push it strongly because of the fear of falling (Maki et al., 1991). Therefore, we use the two-step switch in such conditions, as shown in Fig. 2(b), and our device provides assistance for standing/sitting only in the case of the first step, whereas in the case of the second step, our device regards the user as being in an emergency situation.



(c) Typical situation in the bathroom

Figure 2: Our assistive walker.

3 SITTING MOTION TORERANCE

3.1 Difference between Sitting Motion and Standing Motion

From previous works, a sitting motion is same to “reverse” motion of standing (Ehara et al., 1996). In our preliminary experiment, we assist a sitting operation with this reverse motion using our prototype. Subjects are 6 young people and 2 elderly people. As the result, all subjects feel fear of falling and a reverse motion seems to be unsuitable for a sitting assistance. Thus, in this paragraph, we analyze a standing motion and a sitting motion which the nursing specialist recommends.

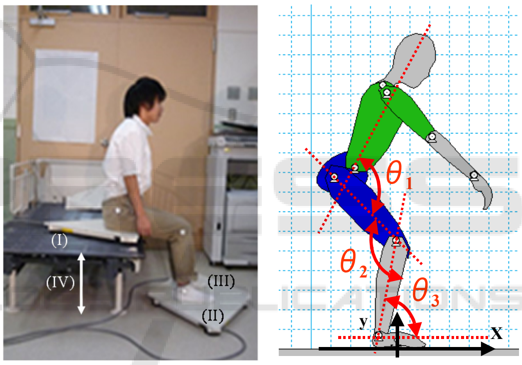
For analysis, we assume a standing and a sitting motions are symmetrical and we discuss the motion as movement of the linkages model on 2D plane (Nuzik et al., 1986). We measure the angular values among the linkages, which reflects the relationship of body segments using a motion capture system. The angular value is derived using the body landmark as shown in Fig. 3(a). Furthermore, we measure the position of the center of pressure (COP) using a force plate system (MG-100, ANIMA Corp., Japan) as the index of body stability. The coordination is shown in Fig. 3(b). Subjects are 6 young healthy people and they operate both motions based on the recommended motion by the nursing specialist.

Fig. 4 shows the angular value of each joint and Fig. 5 shows the position of COP during a sitting motion. In Fig. 3(b), the Y-axis shows the angular values of the pelvis and trunk, knee and ankle, whereas the X-axis shows the movement pattern (Chugo et al., 2014), which is the ratio of the standing motion, as shown by (1). Fig. 4(a) is sitting and Fig. 4(b) is reverse tracks of standing for easy to analysis.

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

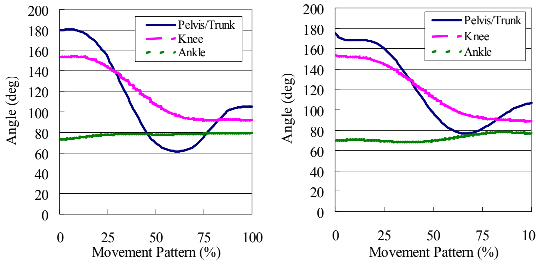
In equation 1, t_s is the time required for completion of the sitting down operation and t is the present time.

From Fig. 4(a), in a sitting motion, the subject lowers his trunk at one motion (10-60[%] movement pattern). On the other hand, in Fig. 4(b), the subject keeps his trunk around 10-25[%] movement pattern. In a sitting motion, the subject inclines his trunk and lowers it earlier than in case of a standing motion. Furthermore, in a sitting motion, the subject inclines his trunk larger than in case of a standing motion. These features are same to previous reports (Dubost et al., 2005).



(a) Side view (b) Its coordination

Figure 3: Experimental Setup. (I), (II) and (III) are force plates. We change the height of chair (IV), according to the subjects.



(a) Sitting motion (b) Its coordination

Figure 4: Angular values of each joint during a motion recommended by nursing specialists.

From Fig. 5, the tracks of COP in both motions are different. In a sitting motion, the position of COP moves slowly than in case of a standing motion. From

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tracks of the knee angle in Fig. 4(a), around 60[%] movement pattern, we can verify that the subject sits down the target chair. In Fig. 5, the position of COP moves slowly, especially, around 60[%] movement pattern. This means the subject puts his hip on the target chair and moves his weight from his foot to his hip.

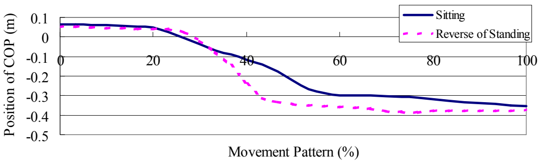


Figure 5: Position of COG during a motion.

In general, a sitting motion does not require the physical strength as a standing motion, because sitting is lifting down body movement to from standing to sitting position according to the gravity. From these results, we can assume the subject may lower his trunk with rough path plan and coordinate his body balance by inclination of his body according to the process of a sitting motion. Therefore, the required conditions for sitting assistance are follows.

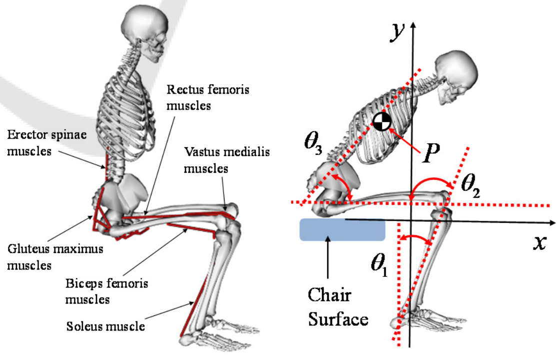
- The robot should allow the patients sitting by their intended motion in the safety range.
- The robot should help the patient if the patient's posture are the outside of safety range and have high risk for falling down.

3.2 Sitting Posture Conditions

In our previous works, we investigate the posture condition from the viewpoint of body dynamics during standing (Yokota et al., 2019). However, sitting and standing are completely different motion and required conditions for sitting assistance are also different as the previous paragraph. Considering above, the sitting posture should be fulfilled by three conditions from the viewpoint of body dynamics.

- Stability condition: The patient should be able to keep their body balanced in this posture. This study defines the condition as follows: the position of the center of gravity (COG) should be located within the range of the patients footprint, while keeping the body balanced during sitting down.
- Muscle condition: The patient should be able to control their body motion in this posture. In general, the output force generated by muscles, changes according to the human posture because the positional relationship between the muscles and bones changes with the adopted posture (Chugo et al., 2014). This means an unsuitable posture cannot generate a sufficient upper direction output force for proceeding through with the sitting motion. This study defines this condition as follows: the output force of the muscles listed in Fig. 6 should not exceed the muscle's maximum output during sitting.
- Landing condition: The patient should be able to control the sitting posture at landing the seating surface. When landing, the patient should reduce lowering velocity enough because strong impact between buttocks and the seating surface has high risk of injuring (Yamamoto et al., 2015). This study defines this condition as follows: the output force of the muscles should not exceed the muscle's maximum output when stopping the sitting motion just before landing the seating surface.

This paper investigates the tolerance level, which fulfills these three conditions through computer simulation studies using OpenSim, a human motion dynamics simulator package. In this simulation, we used a 3DGait-Model2392 (Opensim documentation, 2018) as human model and modified its body parameters to fit a typical Japanese elderly person (Okada et al., 1996). The sitting motion was based on the references recommended by nursing specialists (Kamiya, 2005) as shown in Fig. 4(a).



(a) muscles (b) coordination

Figure 6: Human Model.

Generally, the sitting motion consists of three phases, as shown in Fig. 7(a). Thus, we set a variation of ± 30[deg] range on the reference posture at the end of each phase (Postures (A)-(C) in Fig. 7(b)) in the computer simulation. Note posture (D) is the final posture and therefore we did not set a variation on this phase.

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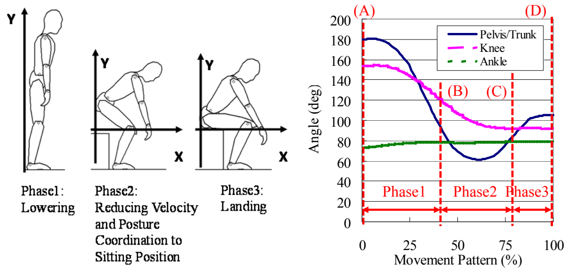


(a) sitting phase (b) references

Figure 7: Simulation Setup.

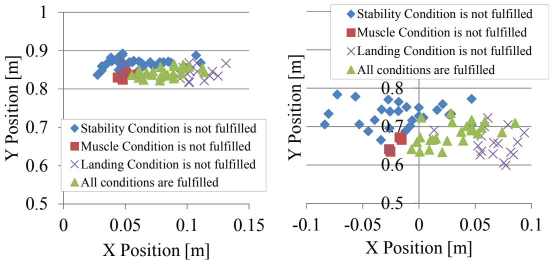
3.3 Sitting Posture Conditions

Fig. 8 shows the acceptable position of point P, identified in Fig. 6(b), derived from the computer simulation. Figs. 8(a), 8(b) and 8(c) show the acceptable tolerance at 30[%], 50[%] and 70[%] movement during the pattern of the sitting motion. Acceptable tolerance fulfills three required conditions, stability condition, muscle condition and landing condition.

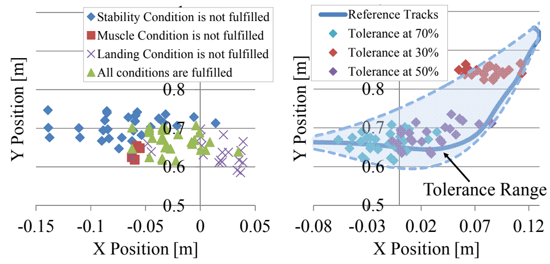
The sitting motion will be realized within the tolerance shown in Fig. 8(d) and in this range of motion, the patient can physically achieve final sitting posture. The reference tracks are the sitting motion by Fig. 4(a) and dashed lines shows the tolerance. In general, a sitting motion has high risk for falling down to forward direction for elderly people (Maki et al., 1991) and inclining to forward direction should be avoided during sitting motion. In Fig. 8(d), there are the tolerance in backward direction and this result fits the knowledge of previous study (Dubost et al., 2005). From this result, it is important to consider the patient's capable muscle output force in the sitting posture.

4 ASSISTANCE CONTROL ALGORITHM

To allow patients to move their intended motion during sitting down, our controller uses a combination of damping control and position control. Damping control can change the strength of assistive power, thus, it can allow for an offset from the reference pathway of motion, allowing the patient to move freely during the sitting down process.



(a) 30% (b) 50%



(c) 70% (d) Investigated tolerance

Figure 8: Simulation Results.

Considering these characteristics, damping control should be used in the tolerance discussed in previous section. By contrast, position control is useful for maintaining body posture, however, its pathway is fixed. Thus, it is useful when the patient's posture exceeds the acceptable range.

In our previous work (Chugo et al., 2017), we proposed an assistance control algorithm based on the voluntary movement of the patient. We know from previous research (Yokota et al., 2019) that the motion of the human body consists of voluntary movements, which generate the total body motion, and a posture adjustment action, which keeps the body stable during motion. This means the robot should only provide a force that assists the physical activity in response to the voluntary movement of the patient, and our proposed algorithm only assisted the patient when physical strength was required for doing a voluntary movement. However, the previously reported algorithm did not consider the variation in the range of movements during human motion, so this paper extends this control algorithm as follows:

- First, we defined the body movement vector $\mathbf{P}$ as (2). This shows the velocity direction of point P (Fig. 4(a)), which is the COG of the upper body. The position of P $\left(x_p^{ref}, y_p^{ref}\right)$ is a motion reference point based on the sitting motion recommended by nursing specialists. Details regarding the generation of this

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reference point are given in our previous paper (Chugo et al., 2014).

$$\mathbf{P} = \mathbf{v}_p^{ref}\left(\hat{s}\right),$$

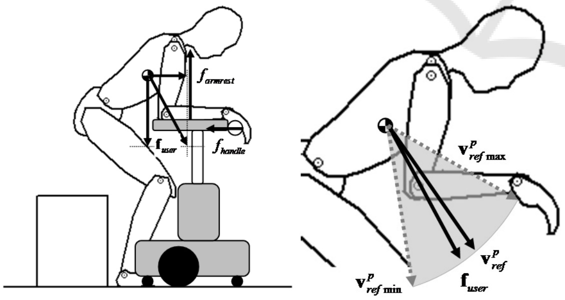
$$\mathbf{v}_p^{ref} = \begin{vmatrix} \dot{\mathbf{x}}_p^{ref} \\ \dot{\mathbf{y}}_p^{ref} \end{vmatrix}^T = \begin{vmatrix} \dot{x}_p^{ref}\left(0\right), \cdots, \dot{x}_p^{ref}\left(\hat{s}\right), \cdots, \dot{x}_p^{ref}\left(1\right) \\ \dot{y}_p^{ref}\left(0\right), \cdots, \dot{y}_p^{ref}\left(\hat{s}\right), \cdots, \dot{y}_p^{ref}\left(1\right) \end{vmatrix}^T \quad (2)$$

Furthermore, our robot has control references for each actuator as detailed in (3), which realize the designed sitting motion (2). $\dot{x}_p^{ref}$ is the motion reference for a powered walker and $\dot{y}_p^{ref}$ is for an assistance manipulator.

$$\mathbf{v}_{rbt}^{ref} = \begin{vmatrix} \dot{\mathbf{x}}_{rbt}^{ref} \\ \dot{\mathbf{y}}_{rbt}^{ref} \end{vmatrix}^T = \begin{vmatrix} \dot{x}_{rbt}^{ref}\left(0\right), \cdots, \dot{x}_{rbt}^{ref}\left(\hat{s}\right), \cdots, \dot{x}_{rbt}^{ref}\left(1\right) \\ \dot{y}_{rbt}^{ref}\left(0\right), \cdots, \dot{y}_{rbt}^{ref}\left(\hat{s}\right), \cdots, \dot{y}_{rbt}^{ref}\left(1\right) \end{vmatrix}^T \quad (3)$$

- Second, we assumed the subject applies all forces $\mathbf{f}_{user}$ at position P because the armrest and the handle of our assistive robot are connected rigidly. We can calculate $\mathbf{f}_{user}$ from the force applied to the armrest $\mathbf{f}_{armrest}$ and the handle $\mathbf{f}_{handle}$ using force sensors in the robot's body (Fig. 9(a)) as (4).

$$\mathbf{f}_{user} = -\left(\mathbf{f}_{armrest} + \mathbf{f}_{handle}\right) \quad (4)$$



(a) Applied force and body movement vector (b) Body motion and its range

Figure 9: Voluntary movement during sitting.

- Third, we assumed the patient also applies a force for doing a voluntary movement of their own intention, therefore $\mathbf{f}_{user}$ shows a voluntary component. At the same time, our controller calculates a motion reference $\mathbf{v}_p^{ref}$ at this posture (Fig. 9(a)) and refers its investigated tolerance (gray area at Fig. 9(b)).

  Our controller evaluates if $\mathbf{f}_{user}$ is within the tolerance at this posture, the patient's motion fulfills the both conditions as discussed in section two.

- Finally, our robot controls two actuators by (5).

$$v_{rbt}^{upref} = \begin{vmatrix} \dot{x}_{rbt}^{upref} \\ \dot{y}_{rbt}^{upref} \end{vmatrix}^T = \begin{vmatrix} \dot{x}_{rbt}^{ref} - B\left(f_{handle} - f_{handle0}\right) - K\left(x_{rbt} - x_{rbt}^{ref}\right) \\ \dot{y}_{rbt}^{ref} - B\left(f_{armrest} - f_{armrest0}\right) - K\left(y_{rbt} - y_{rbt}^{ref}\right) \end{vmatrix} \quad (5)$$

where v_{rbt}^{upref} is the updated reference value that our robot actually uses for delivering sitting assistance. $\left(x_{rbt}, y_{rbt}\right)$ is the actual position of the powered walker and the assistance manipulator of our robot. *B* and *K* in (5) 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 the patient sits.

In order to apply the damping control only when the patient's motion fulfills both the stability condition and the muscle condition, the coefficient *B* that validates the damping control mode is calculated as (6). *B* will be larger value if $\mathbf{f}_{user}$ locates on the center of the tolerance and in this situation, it fits $\mathbf{v}_p^{ref}$. 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* which validates the position control mode, to be constant. The values of *b* and *K* were determined experimentally.

$$\begin{cases} B = b\dfrac{\mathbf{v}_p^{ref} \cdot \mathbf{f}_{user}}{\left|\mathbf{v}_p^{ref}\right| \cdot \left|\mathbf{f}_{user}\right|} & \left(if\ conditions\ are\ fuifilled\right) \\ B = 0 \quad \left(if\ conditions\ are\, not\ fuifilled\right) \end{cases} \quad (6)$$

Using these ideas, our controller sets the ratio of the damping control mode to a larger value if the patient's trajectory fits the expected reference pathway. Thus, the patient can move freely as intended if their posture is not largely different from the reference posture.

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5 EXPERIMENT

5.1 Validation of Sitting Motion Simulation

To confirm the accuracy of sitting motion simulation, we compare actual EMG results with its simulation results. We measure the surface electromyograms on several body segments, motion data by motion capture system and ground reaction force by force plates during sitting motion. Motion and ground reaction force data are used to realize the sitting motion in the simulation. The subject is young man (22 years old) who do not have physical handicap (height and weight are 174[cm], 60.5[kg]).

Fig. 10 shows the muscle activities about vastus medialis, which are acquired as accurate EMG and calculated by simulation. Muscle activities expressed in percentage. The simulation results have a strong correlation with EMG results and these results show that simulation results are trustworthy.

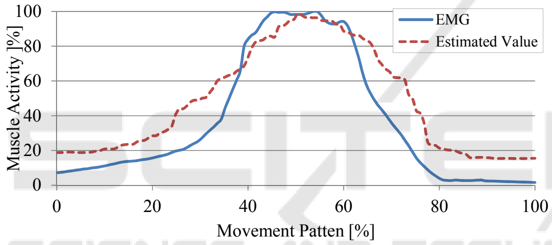


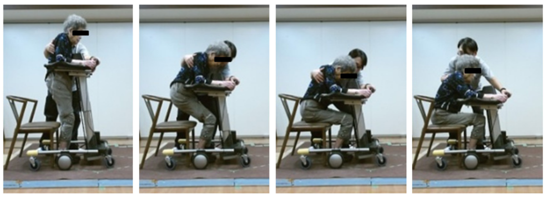
Figure 10: Muscle activity by EMG and simulation results.

5.2 Experiments with Our Prototype

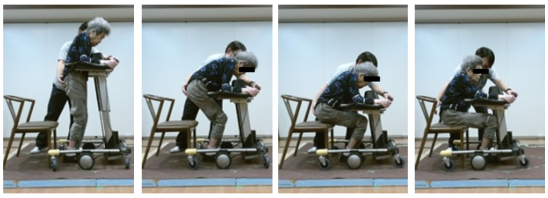
We implemented our proposed idea to the prototype (Fig. 1) and conducted a practical experiment with it. To confirm the efficiency of our sitting assistance, we tested three cases.

- Case1: Using only position control, without our proposed idea.
- Case2: Using our proposed idea.

We used ten subjects and each subject attempted all three cases, five times each. Subjects were elderly whose care level are 1 or 2. As seen in Fig. 11, our prototype succeeds to assist the sitting motion according to the intended motion of the subject. In case1, the subject clings our robot during sitting motion. On the other hand, in case 2, our robot follows the patient’s movement to backward direction and the subject can incline her trunk.



(a) Without proposed controller (Case1)

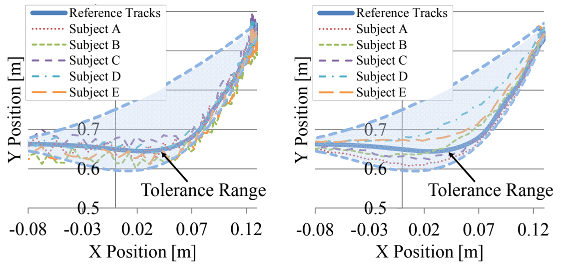


(b) With proposed controller (Case2)

Figure 11: Sitting motion with our assistive walker (Subject A). The therapist stands near the subject for safety reason and he does not assist the subject.

Fig. 12 shows the position of position P during sitting motion. In case 1, the subject's position fits the reference trajectory and this means our robot does not allow the patient to move freely as intended. All subjects has large upset because the robot applies assistance force for fitting the reference trajectory accurately.

On the other hand, in case 2, the subject's position does not fit the reference trajectory but is within the investigated tolerance range. This mean our robot evaluates that the patient's motion fulfills both the stability, muscle and landing conditions, and accepts the body motion of the patient even though it does not fit the reference pathway. As the result, the robot does not apply any unnecessary assistive force and succeeds in allowing the subject to use intended sitting motion.



(a) case1
without proposed method

(b) case 2
with proposed method

Figure 12: The position of P (defined as Fig. 6(b)) during sitting motion. Without our proposed idea (a), the position of COG does not fit the reference and our robot tries to fit it. Therefore, there are large upsets. In contrast with case1, with proposed idea (b), its position moves within the tolerance range and our robot allows the patient to move his/her intended motion.

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6 CONCLUSIONS

This paper proposes a novel sitting assistance device, which allows patients to move through intended movement. To realize this, we investigated the motion tolerance of the sitting posture, which fulfills both body balance and muscle force condi-tions. Furthermore, we proposed a novel assistance control, which maintains body stability whilst using intended body motion of its user during sitting.

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