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Stand-Up Assist System for Elderly Using Coordinated Motion with a Bed

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***Abstract*—A robotic stand-up assist system from a bed, which utilizes coordinated motion with the bed, has been developed. Through the steps of the research and development process, assisting the motion trajectory during the stand-up motion is found to be more important, rather than assisting the power to stand-up. Natural trajectory for the stand-up motion, with the help of the movement of the bed, has been thus studied, and evaluated from joint burden and stability viewpoints.**

Keywords—Assistive Technology; Rehabilitation Robot; Human-Robot Cooperation; Stand-up Motion

I. INTRODUCTION

Number of elderly people is reported to be increasing, in accordance with the rapid growth of the ageing society in many countries, including Japan [1]. It also means that the number of elderly people with physical disabilities, needing care or assistance, is increasing, because of the decline in physical ability due to ageing. Apparatuses to assist daily living activities of elderly people become thus imperative to be introduced into society, in order to reduce the number of people who require nursing care currently performed manually. In other words, replacing human physical support with apparatuses such as robotic devices, to assist daily living activities of elderly people with disabilities, is expected to significantly contribute the ageing society.

As the word “Bedridden” literally implies, leaving from a bed, thus stand-up motion from a bed, is considered as one of the most important daily living activities to maintain a person’s physical functions. It is quite common, however, that accidents such as “falls” occur, during the stand-up motion, which most likely causes physical handicap and even worsen the symptom of the elderly person [2]. Research and development of self-help stand-up systems are therefore considered as one of the important issues.

Several self-help stand-up systems have already been proposed [3][4][5]. Many of them use a method based on the motion of caregivers, such as physical therapists and nurses, although motion velocity of the systems are much lower than that of a caregiver, causing insufficient force generation for natural stand-up motion of a person. The self-help stand-up system is also required to be adaptive to physical size and status of the person who uses the system, as well as to maintain stable posture during stand-up process. The authors have been conducting research and development on this issue, and several results, such as the control strategy based on the motion trajectory of a caregiver [6], a control scheme to combine position control and damping control, and to modify the moving velocity based on the information from a force sensor [7], have already been reported. Furthermore, an evaluation method for the stand-up phases to determine parameters such as a handrail position [8], is also proposed. Ref. [9] shows that the evaluation method for human burden during stand-up motion described here can be applied not only for robotic devices but also simple tools or rigs, such as an elbow support pad attached to a bed.

In this paper, a quasi-static method for assisting self-help stand-up motion using the robotic system including a bed, for the persons who are difficult to stand-up even with the help of handrail, has been studied and evaluated.

II. MECHANICAL DESIGN OF THE SYSTEM

A. *Preliminary Model*

As the first step of the research and development, a power assist system, the overview shown in Fig.1, has been developed.

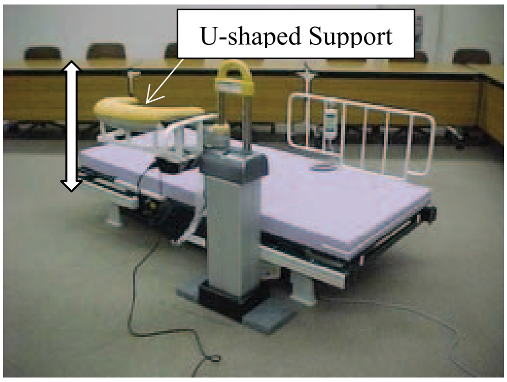


Fig. 1. Vertical Lift-Up System

The system is designed to lift-up a person's trunk of the body vertically by supporting the person's elbow and upper arm with a U-shaped support pad. The system is equipped with a force sensor to detect the person's force to push the support pad, which is not supplied with sufficient quantity, and to assist the lacking force with the support pad.

The strategy has been found to be successful in lifting the person's body, as far as the body trunk is leaned on the support pad. The result of organoleptic evaluation, however, has been found to be unnatural. The reason of the result, presumably caused by the fact that the trajectory pattern for the lift-up motion is vertical straight line, is further studied in the next section.

B. *Evaluation of Support Methods*

An experiment to evaluate differences between various support methods for a person's body, i.e. differences of required power of the person being supported, due to support part or portion when lifting up the body, has been conducted to determine the structure of the system. Support methods (support part) are chosen among such as i) hands: placed in front of the body trunk, ii) hands: placed near the hip, iii) lower arms, iv) elbows, v) upper arms, vi) hip, as shown in Fig.2.

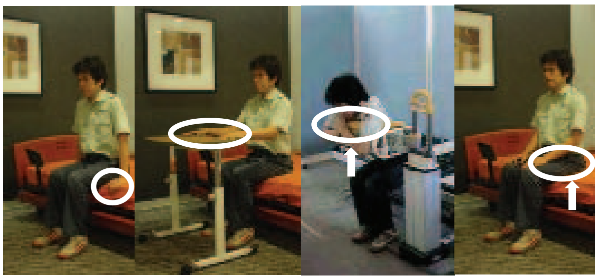
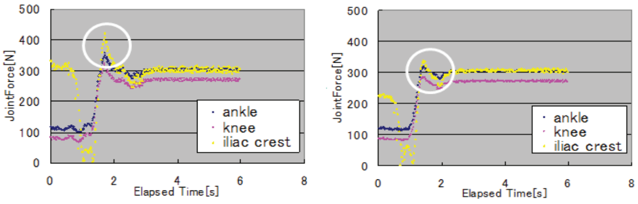
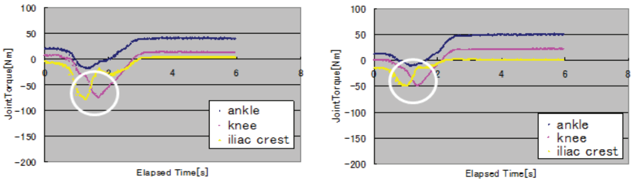


Fig. 2. Various Support Methods

One of the results, in the case of vi) supported at hip, is shown in Fig.3, compared to the case without any support, to reveal 20% decrease in waist joint burden, and 35% decrease in knee muscle burden because of the support. (The method for calculating joint and muscle burdens is explained in the latter Chapter.) The candidates for the effective part to support a person's body for the lift-up motion are thus determined through this study.



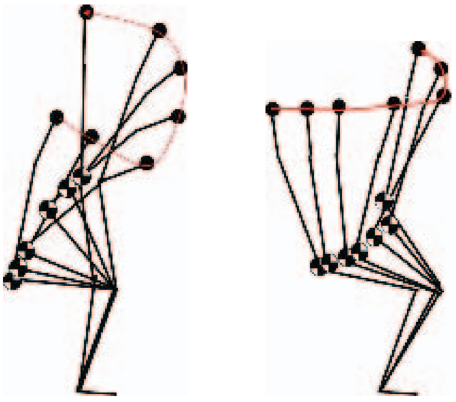
Without support With hip support



Without support With hip support

Fig. 3. Burden of Major Joints(above) and Muscles(below)

In addition, appropriate trajectory for assisting stand-up motion has also been studied. Fig.4 shows examples of the stand-up motion of (a) a young subject (male, age 30) and (b) an elderly subject (female, age 84), both without any assist. The figure also shows the trajectory of the great trochanter (approximately the Center of Gravity when stand-up), and the center of cephalic part (head). The comparison on the motion trajectory reveals that it is difficult for the elderly to take head forward posture, indispensable to reduce required power for stand-up by letting the center of gravity fall within the base of support, unlike for the young person. The reason for this is considered because of the impairment of balancing ability due to ageing.



(a) Young Subject (b) Elderly Subject

Fig. 4. Trajcetory of Stand-up Motion

It is also noted that the velocity of the motion is approximately 7 times slower in the case of the elderly, compared to that of a young person in this case. It means that a stand-up motion of an elderly is "quasi-static movement", rather than that of a young person, which is "dynamic movement" utilizing inertial force effectively.

C. *Prototype System*

A prototype system has then been developed. Fig.5 shows the overview of the system. The system has three degree of freedom, namely vertical lift-up (X) and horizontal traverse (Y), perpendicular to the bed's longitudinal direction, of a support pad, and vertical lift-up of the bed (Z) where the person to be assisted rests. The support pad is interchangeable, and a hand support handle or an elbow support pad can be attached, depending on the person's physical condition.

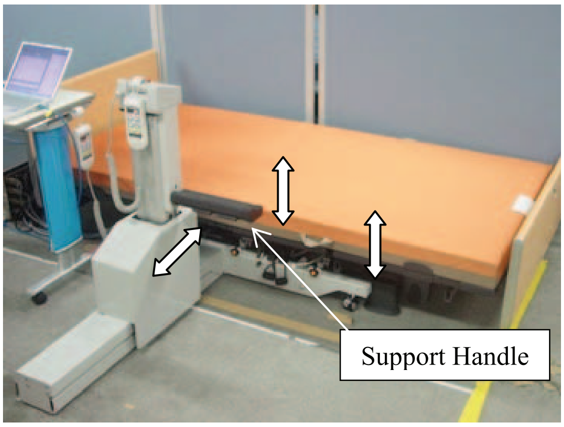


Fig. 5. Final Prototype System

The system is equipped with a force sensor at the bottom of the linear actuator for X axis, to detect applied vertical force at the support handle. The controller is a position based one, and issues position control command for the three axes to realize synchronized motion of the system. The motion trajectory of the system is determined in accordance with the person's physical dimension. The trajectory generation scheme is explained in the next Chapter.

III. TRAJECTORY FOR STAND-UP ASSIST

A. *Strategy to derive Assist Trajectory*

The result shown in Fig.4 indicates, as stated above, that an elderly person has decreased sense of balance which makes it difficult to take head forward posture. Such an elderly person needs even more muscle force or joint power to stand-up, because of the larger required torque, which is the product of body mass and horizontal distance between center of gravity and base of support of the person.

It is considered appropriate, from the above discussion, that the assisting movement of a skilled expert, such as a nurse or a physical therapist, guides the assisted person to take such head forward posture. The assist system, therefore, has to act as a skilled expert to let the elderly to move along the "natural" trajectory as if the person has a balancing ability of a young person. It can be assumed that the velocity of the end-effecter (such as a handle) of the system, along the trajectory, has to be controlled at the similar velocity as the movement of an elderly, not a young person's movement nor a skilled expert's movement, from the safety point of view. It is also noted that the required torque of the assisted person, stated above, does not increase much in spite of the limitation in the velocity, since the torque discussed here is determined with a static mechanics equation.

B. *Phases of Stand-up*

Phases of the Stand-up motion of a person having no disability can be divided into three or four phases [10][11][12][13]. Here, a three phase method, described as follows, is considered. Phase-1 is a flexion-momentum phase to generate the initial momentum for rising. Phase-2 is a rising phase, beginning at the release from the seating surface and ending at maximal ankle dorsiflexion. Phase-3 is an extension phase during which the body rises to its full upright position. It is pointed out that the trade-off between muscle strength of lower limbs and stability of posture appears during Phase-2, where forward momentum of the upper body is transferred to forward and upward momentum of the whole body.

It is difficult, however, to generate the initial momentum for rising in Phase-1, as a skilled caregiver or a young person does, when the strategy taken for the proposed assist system is based on quasi-static motion. Still, guiding to take a head forward posture, which is difficult for an elderly, even with a quasi-static motion, is effective in reducing the required power for stand-up. Observing the trajectory, especially of the acromion shown in fig.4, guiding the upper body of an elderly, toward forward and downward direction is considered as an effective strategy to take as Phase-1. Once the Center of Gravity of the person is located vertically above the plantar, i.e. base of support, thighs are lifted up from the surface of a mattress spread on the bed as Phase-2. In Phase-2, body of the person is supported only by planters and support handle of the assist system. Lastly, the body of the person moves upward, as Phase-3, to take an upright position.

C. *Fitting for an Individual*

The assist trajectory of the system has to be adapted to the physical size of the person. A human body is generally modeled as a planer 7 link mechanism, under the assumption that the length of each corresponding (right and left) link is equal, as shown in Fig.6 (a).

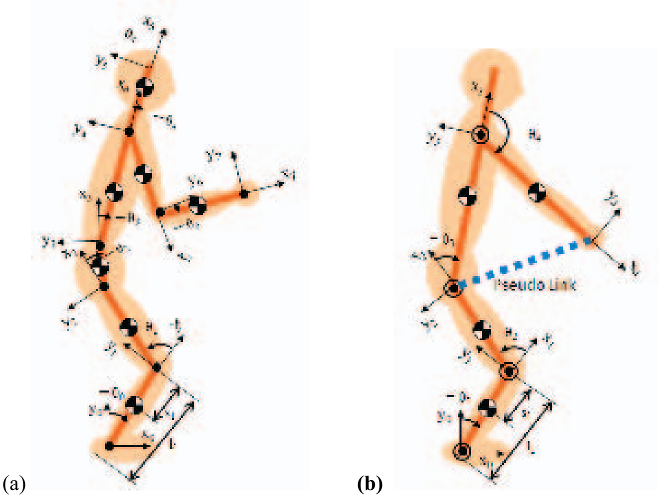


Fig. 6. Multi Link Human Model

The posture of a person to be assisted cannot be uniquely determined with this 7 link model because of redundancy. Thus, a human body is modeled with a simplified planer 4 link mechanism, namely lower legs, thighs, trunk and upper arms as shown in Fig.6 (b). Furthermore, an artificial constraint similar to the one proposed previously [6] is applied, and the location of the contact point with the person to be assisted is kept constant with respect to the trunk during this phase of the motion. This assumption can be restated that the contact point of the support device is kept at a same distance from the great trochanter of the person. A human body can be considered to be a three link structure, as a result of this abbreviation.

In Phase-1, the end-effector of the system, namely the handrail or the pad, initially located at the position where the person is sitting-square posture, is driven forward and downward, while the height of the bed moves upward. The rotation of the upper body around the ankles, while the knee angle is kept constant, enables further to bend, letting the body to take head forward posture, as the end-effector moves.

In Phase-2, the end-effector is driven forward and upward, while extending the knee angle, to let thighs of the person slides along the surface of a mattress on the bed where the person sits, while keeping the Center of Gravity of the person located directly above the plantar surface to maintain stability. Next equation holds if the upper body of the person is assumed to move along the thighs during the phase.

$$\phi = \tan^{-1} \mu \tag{1}$$

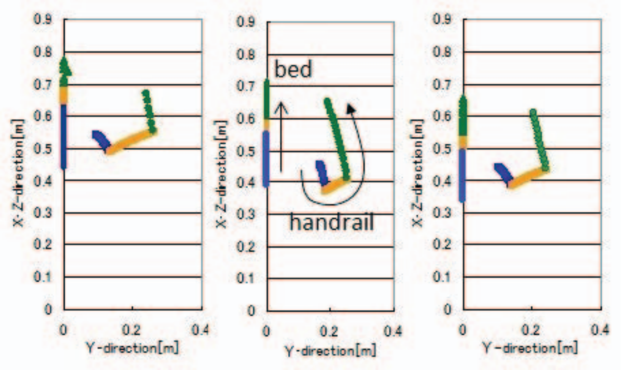
where μ is the dynamic friction coefficient depending on the mattress material and ϕ is the inclination angle of the thighs. This value for the thighs' angle is utilized as a switching parameter from Phase-1 to Phase-2 of the assist motion. Naturally, the flexibility or the elasticity of the mattress is indispensable for the strategy to work, although it is fair to assume that a mattress is equipped with when a bed is in use.

In Phase-3, both the end-effector and the bed are driven upward to guide extension of lower limbs and trunk to let the person fully stand-up steadily.

It should be noted that the trajectory generated by the above mentioned strategy (Phase-1 through Phase-3) is dependent on the physical size of the person to be assisted. An example of the end-effector trajectories, when a handrail is equipped with, generated by using bodily dimensions of three persons, indicated in Table.1, is shown in Fig.7.

TABLE I. PHYSICAL SIZE OF THE SUBJECTS

	Subject 1	Subject 2	Subject 3
Height	1750mm	1700mm	1480mm
Weight	92kg	62kg	42kg
Link1 length	383mm	364mm	344mm
Link2 length	429mm	391mm	352mm
Link3 length	440mm	417mm	395mm
Link4 length	515mm	497mm	478mm



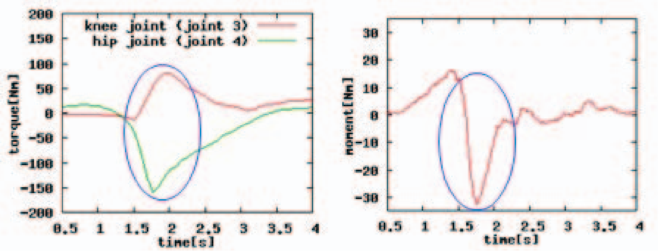
Subject 1 Subject 2 Subject 3

Fig. 7. Trajectories for Individuals with Different Physical Size

It is understood that different bodily dimensions resulted in different motion trajectories, both for the end-effector (X, Y) and for the bed height (Z).

D. Utilizing the Force Information

The force sensor, described earlier, is prepared to measure applied force in vertical direction at the end-effector. The most unstable period during the stand-up process is when hip of the person is disengaged from the mattress, since number of support points is decreased from three (hand/elbow, feet, hip) to two at that instant. This can be seen from the study on required knee joint torque and the risk of fall, during stand-up process, as shown in Fig.8 [8].



(a) Joint Burden (b) degree of fall risk

Fig. 8. Trajectories for Individuals with Different Physical Size

This is interpreted that the area of base of support is discontinuously reduced at the time of disengagement of hip from the mattress, which is the timing when the switching from Phase-2 to Phase-3 takes place. Thus, the force information can be effectively used to determine the timing for control phase change of the stand-up process adaptively, as well as to modify the stand-up trajectory to realize more stable posture. Additionally, the force sensor can also be used to determine the required assist force for lift-up, in case of damping control [7].

IV. EVALUATION

The effectiveness of the developed system is studied from various points of view. Motion and interacting force of the person, without and with the system's assist are measured, and motion load of major muscles and joints are calculated by using the 7 link human model. Stability measure of the person during stand-up process is also introduced and calculated.

A. Human Model

Human body is modeled as links having masses and joints in kinaesthetics [14], one of the skills that nurses and physical therapists use when caring patients. A link represents a body member with a length and weight. A joint represents a revolute pair connecting two body members. Legs, pelvis, trunk, head and arms are modeled as links. Legs are divided into lower legs and thighs at knee joints. Arms are also divided into upper arms and forearms at elbow joints. Thus, a human body is modeled as a 7 masses structure as shown in Fig.6 (a). Each link having a mass is given a coordinate system fixed to the link, which is defined by using Denavit-Hartenberg notation as shown in the Figure.

Here, the ankle joint is regarded as the contact point of lower legs and the floor, at the time of stand-up process, and the center point of the ankle joint is set to the origin of inertial coordinate system $\Sigma \mathbf{O_0}\text{-}\mathbf{x_0y_0}$. Joint-i coordinate system is defined as $\Sigma \mathbf{O_i}\text{-}\mathbf{x_iy_i}$ consecutively.

B. Evaluation Indexes

Physical burden of a person can be evaluated by the moment around each joint. The force and moment around each joint is given by the following equations.

$$m_i \mathrm{d}^2(\mathbf{T_i p_i})/\mathrm{d}t^2 = \mathbf{T_i f_i} - \mathbf{T_{i-1} f_{i-1}} + m_i \mathbf{g} \qquad (2)$$

$$(I_i + m_i \mathrm{p_i}^2)\,\ddot{\theta}_{i-1} = \tau_i - \tau_{i-1} + |(\mathbf{A_i f_i}) \times \mathbf{r_i}| + |(\mathbf{T_i}^{-1} m_i \mathbf{g}) \times \mathbf{p_i}| \qquad (3)$$

where the center of mass of Link-i is expressed as a position vector $\mathbf{p_i}$, and the origin of Link (i-1) is expressed as a position vector $\mathbf{r_i}$, both with respect to the joint-i coordinate system. And m_i and I_i are the mass and the moment of inertia of Link-i, fi and τ i are the applied force and moment around the Link-i's origin, respectively, $\mathbf{A_i}$ is the transformation matrix from $\Sigma \mathbf{O_i}\text{-}\mathbf{x_iy_i}$ to $\Sigma \mathbf{O_{i-1}}\text{-}\mathbf{x_{i-1}y_{i-1}}$, and $\mathbf{T_i}$ is the transformation matrix from $\Sigma \mathbf{O_i}\text{-}\mathbf{x_iy_i}$ to $\Sigma \mathbf{O_0}\text{-}\mathbf{x_0y_0}$ ($=\mathbf{A_i A_{i-1}} \cdot \cdot \cdot \mathbf{A_i}$) [15].

The moment around a joint given from these equations is considered as a burden of a person's respective joint, and has been used to evaluate bodily burden of person including elderly in various researches [16][17][18]. Here, the maximum value for each joint moment during the stand-up motion is evaluated as the maximum burden of the joint.

It is also important to evaluate a person's stability during the stand-up assist process, from the safety point of view, in addition to the joint burden. Several indexes to evaluate a person's stability, such as the range of projected center of gravity [9], the moment value to maintain a person's posture counter balancing the environmental applied force [6][7], are proposed. The latter index, introduced here, is defined as the following equation.

$$\tau_{PH} = \Sigma (\mathbf{P_g}(t) - \mathbf{P_j}(t)) \times \mathbf{F_j}(t) \qquad (4)$$

where $\mathbf{P_j}$ is the position vector of each contact point, $\mathbf{P_g}$ is the position vector of the center of gravity, both with respect to the $\Sigma \mathbf{O_0}\text{-}\mathbf{x_0y_0}$ coordinate system, and $\mathbf{F_j}$ is the applied force vector at the contact point $\mathbf{P_j}$. This definition means, with the assumptions that acceleration of the person's motion is negligibly small, and human body is approximated as a rigid body at the instant, the value of the counter moment to balance with the moment generated by the external force applied to the person being assisted, around the center of gravity of the person, during stand-up process. The maximum and the average values of this index τ_{PH} are therefore considered to be equivalent to the maximum and average required moments for the person to maintain his/her posture during stand-up process, and thus named as "Posture Holding Moment: PHM". The posture is more stable when the value is smaller, since the person is required to generate less torque to secure balance against the external force.

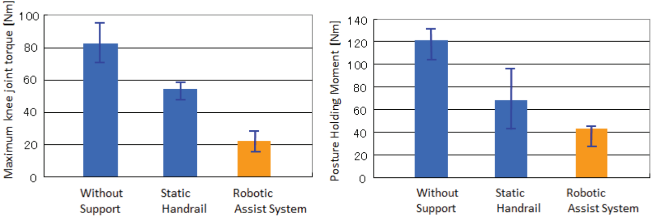
C. Experiments

Maximum moment for each joint and the value of PHM are obtained through experiments by using equations (2)(3)(4). Motion of each link of a subject, and force applied to the subject, are measured to obtain values of these evaluation indexes. The following equipments, i) three dimensional motion capture system (Qualisys ProReflex) to measure each joint trajectory, ii) force plate (Kistler 9286AA) to measure the load against the subject's feet, iii) force sensor (Nitta 100M40A) to measure the load against the subject's hip, are introduced for the measurement.

Stand-up i) without using any assist, ii) with a handrail placed in front of the bed, iii) with the developed robotic assist system, are compared through the experiment. Position of the handrail in the case of ii) is chosen to the start point of Phase-1 of the robotic assist system. Height of the bed or a hip support at the beginning of stand-up motion is set to 330mm. The subject for the experiment is 170cm tall, 63kg weight, male, 30 years old, and have no physical disabilities, and the measurement are conducted three times on each of three experimental conditions.

D. Results

It is known that the heaviest burden is generated at knee joint at the time of stand-up motion, and is generated in the direction of extension [16]. Therefore, a knee joint moment is picked up, as an example, for the joint burden evaluation. The results, where direction of extension is chosen to have positive value, are shown in Fig.9 (a).



(a) Knee joint moment (b) PHM

Fig. 9. Experimental results

This means that reduction of the positive value of knee joint moment has an effect to decrease human burden at the time of stand-up. The wide columns in the Figure indicate the maximum values, and the lines indicate the standard deviations.

The average values, and minimum and maximum values of PHM index are shown in Fig.9 (b). Positive value means forward bending moment, and negative gives upward extension. Reduction in absolute value of PHM indicates that the person requires less balancing effort, and thus maintains more stability, when stand-up.

Required knee joint moment, approximately 80Nm without any support, is reduced to nearly 70% with the fixed handrail, and is reduced to almost 25% of its original value with the developed robotic assist system, in combination with a bed, to prove that the system is effective in decreasing human bodily burden.

PHM, a stability measure, or required moment to maintain posture, approximately 120Nm without any support, is reduced to nearly 50% of its original value, with the fixed handrail, and is reduced to about 35% with the robotic assist system. It is clearly understood that the stability measure is improved by using some support to stabilize a person's body, although the effectiveness of using the robotic assist system is much greater than the fixed handrail.

Several field trials, through ethical review, have also been conducted at a nursing-care facility to study the acceptability and effectiveness of the developed system, and it is found to be usable for persons who are daily assisted by caregivers when stand-up.

V. CONCLUSION

A robotic self-help stand-up assist system from a bed, based on quasi-static motion control method, has been developed.

Firstly, a vertical lift-up system based on power assist strategy is developed and found to be not satisfactory in motion trajectory. Effect of the differences in various support portion of a body is then studied. Motion trajectories of a young person, an elderly, and a person assisted by a caregiver, during stand-up motion, are next studied to determine appropriate motion skill, such as the three phases and their switch timing, for the robotic assist system to take. Here, a method to generate stand-up motion trajectory, including a bed with up and down capability, and fitted to the person to be assisted, is also proposed. It is noted that the trajectory for each person is determined by the body dimension, such as height, arm and leg lengths, of the person. Finally, effectiveness of the system is evaluated through experiments with the actual stand-up assist task, to confirm the reduction in joint moment and improvement in a proposed stability measure.

The developed system has a capability to assist stand-up motion, and a person generally stands-up to do some activities of daily living, such as to go to the toilet. If the person uses a walker or a wheelchair, transfer from the developed system to the walker or the wheelchair, or return transfer from such devices is required, and such transfer motion is also a problem for a person with disabilities. A system combining the stand-up assist and a function of a walker, for instance, is therefore desired once the effective stand-up assist technology is developed. This can be achieved by adding a lift-up mechanism to a wheel-type walker, and by controlling coordinated motion of lift-up mechanism (X) and wheels (Y), similarly to the developed robotic system. The authors believe that the technology, not only the robotic system itself, developed here can be effectively applied to such novel systems to contribute in helping daily living activities of elderly and people with disabilities in the near future [19].

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