Force assistance system for standing-up motion

Daisuke Chugo
Graduate School of Information Systems, University of Electro-Communications, Tokyo, Japan

Kuniaki Kawabata
Distributed Adaptive Robotics Research Unit, RIKEN (The Institute of Physical and Chemical Research), Saitama, Japan

Hiroyuki Okamoto
Ritecs, Inc., Tokyo, Japan

Hayato Kaetsu
Distributed Adaptive Robotics Research Unit, RIKEN (The Institute of Physical and Chemical Research), Saitama, Japan

Hajime Asama
Research into Artifacts, Center for Engineering, The University of Tokyo, Chiba, Japan

Norihisa Miyake
Product Department, Paramaount Bed Co., Ltd, Tokyo, Japan, and

Kazuhiro Kosuge
Department of Bioengineering and Robotics, Tohoku University, Miyagi, Japan

Abstract
Purpose – The aim is to develop a force assistance system for standing-up which prevents the decreasing of physical strength of the patient by using their remaining physical strength.
Design/methodology/approach – The system realizes the standing up motion using the support bar with two degrees of freedom and the bed system which can move up and down. For using the remaining physical strength, our system uses the motion pattern which is based on the typical standing up motion by nursing specialist as control reference.
Findings – The assistance system realizes the natural standing up motion by nursing specialist and it is effective to assist the aged person to stand up without reducing their muscular strength.
Originality/value – The first idea is distributed system which controls the support bar and the bed system with coordination among them. The second idea is the combination of force and position control.

Keywords Aids for the disabled, Motion, Control, Medical equipment

Paper type Technical paper

1. Introduction

In Japan, the population ratio of senior citizen who is 65 years old or more exceeds 20 percent at January 2004 and rapid aging in Japanese society will advance in the future (Statistics Bureau, Ministry of Internal Affairs and Communications, Japan, 2004). In aging society, many elderly people cannot perform normal daily household, work related and recreational activities because of decrease in force generating capacity of their body. Today, the 23.5 percent of elderly person who does not stay at the hospital cannot perform daily life without nursing by other people (Ministry of Health, Labour and Welfare, Japan, 2001). For their independent life, they need daily assistance system which enable them to perform daily life easily even if their physical strength reduces.

Standing up motion is the most serious and important operation in daily life for elderly person who does not have enough physical strength (Alexander *et al.*, 1991; Hughes and Schenkman, 1996). In typical bad case, elderly person who does not have enough physical strength will cannot operate standing up motion and will falls into the wheelchair life or bedridden life. Furthermore, if once elderly person falls into such life, the decrease of physical strength will be promoted

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0143-991X.htm

Industrial Robot: An International Journal
34/2 (2007) 128–134
© Emerald Group Publishing Limited [ISSN 0143-991X]
[DOI 10.1108/01439910710727478]

This paper was previously presented at the 9th International Conference on Climbing and Walking Robots (CLAWAR), September 12-14, 2006, Brussels, Belgium.

This study is supported in part by Organization for Small and Medium Enterprises and Regional Innovation, Japan.

because he will not use his own physical strength (Hirvensalo *et al.*, 2000). Therefore, we are developing the force assistance system for standing up motion which uses part of the remaining strength of the patient in order not to reduce their muscular strength.

In previous works, many researchers developed power assistance devices for standing up motion. However, these devices assist all necessary power for standing up and they do not discuss using the remaining physical strength of patients (Nagai *et al.*, 2003; Funakubo *et al.*, 2001). Therefore, there is a risk of promoting the decrease of their physical strength.

In our current research, we are developing a force assistance system which prevents the decreasing of physical strength of the patient by using their remaining physical strength. Our system realizes the standing up motion using the support bar with two degrees of freedom and the bed system which can move up and down. For using the remaining physical strength, our system uses the motion pattern which is based on the typical standing up motion by nursing specialist as control reference (Chugo *et al.*, 2006). In order to realize this motion pattern, the control system needs to operate the bar and the bed system keeping the coordination among them. Furthermore, the system is required to adapt them to change of the patient's posture during standing up motion.

Therefore, in this paper, we develop the novel control system for our force assistance device. Our key ideas are distributed controller which enables cooperative action and the combination of force and position control. Using our control scheme, the patients can stand up with fewer loads and can use their own remaining physical strength during the motion. We verify the performance of the proposed control scheme through the computer simulations and experiments using our prototype system.

This paper is organized as follows: we introduce the mechanical design and proposed controller of our assistance system in Section 2; we analyze the standing up motion by nursing specialist in Section 3; we propose the new control scheme and show the result of computer simulations and experiments using our prototype in Section 4; Section 5 is conclusion of this paper.

2. System configuration

2.1 Assistance mechanism

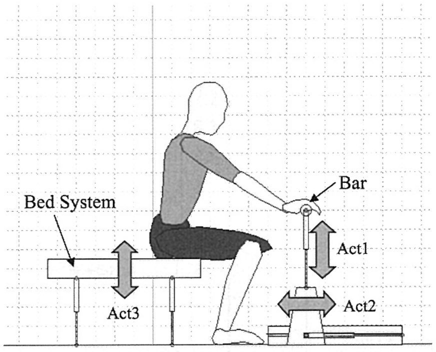
Figure 1 shows our proposed assistance system. The system consists of support bar with two degrees of freedom and the bed system which can move up and down. The support bar and the bed system are actuated by three linear actuators (ACT1 to ACT3 in Figure 1(a)) equipped on each degree of freedom as shown in Figure 2(a) (Sugihara *et al.*, 2004). We assume the patient sits down on the bed and grip the bar using his hand.

The support bar has our developed force sensor (Figure 2(b)) on ACT1. This sensor uses the elasticity element for measuring the applied force. Furthermore, the elasticity element reduces the impact when it contacts the other objects. The system can lift up the patient of 150 kg weight maximum.

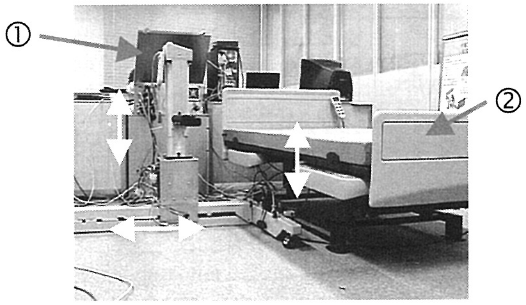
2.2 Controller

Our proposed controller is shown in Figure 3. We use a distributed system which consists of the integrated controller and three ACT controllers on each actuator. ACT controllers are small board computers and they are built in the actuator systems with motor driver. The integrated controller and three ACT controllers are connected by Ethernet.

Figure 1 Our assistant system



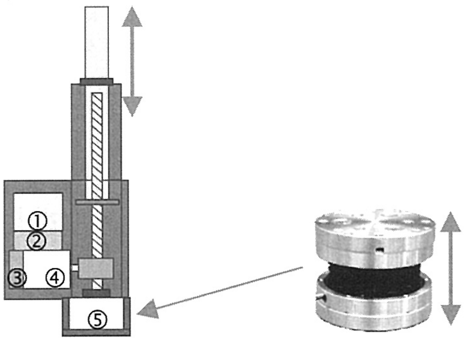
(a) Overview of our system



(b) Prototype system

Note: ① is bar (2DOF) and ② is bed system (1DOF)

Figure 2 Developed linear actuator



(a) Overview of our linear actuator **(b)** Force sensor

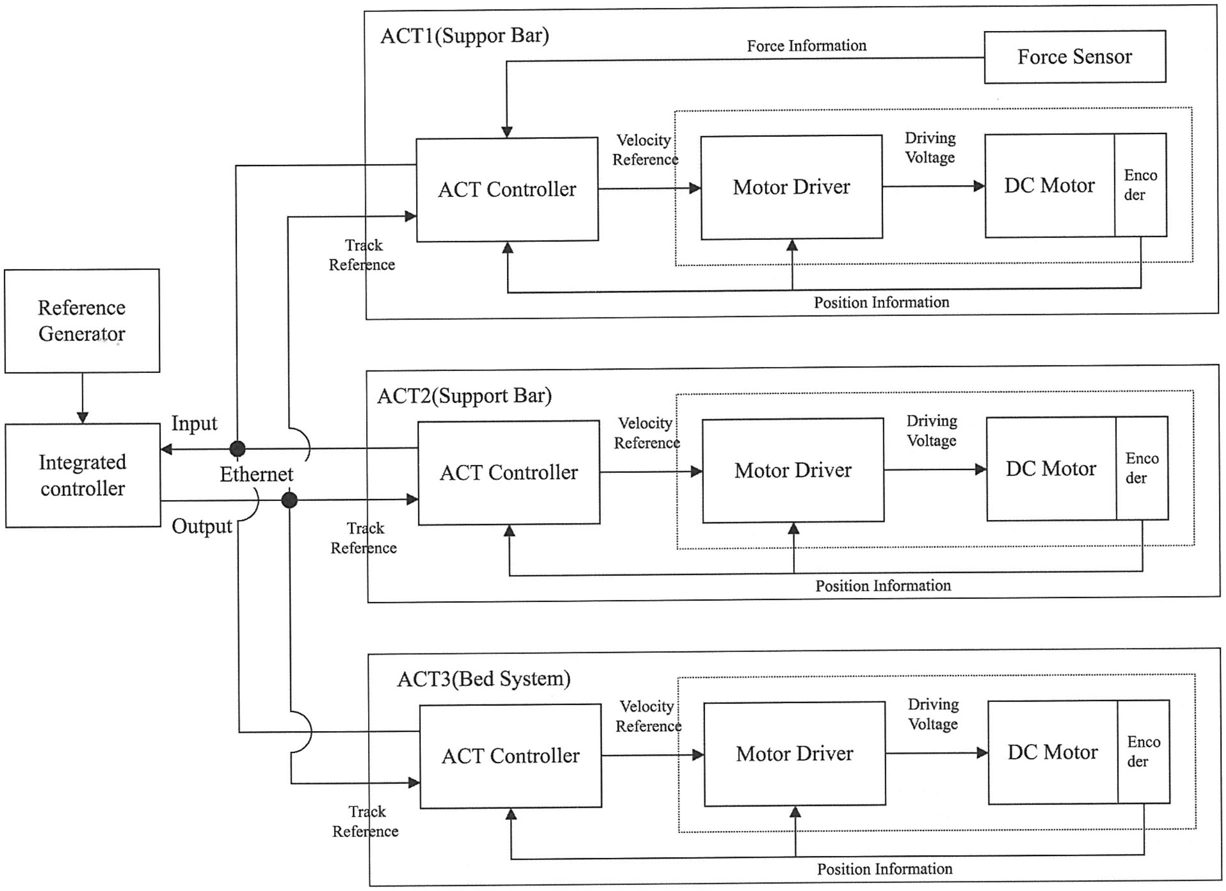
Note: ① is controller, ② is motor driver, ③ is encoder, ④ is DC motor and ⑤ is our developed force sensor. All devices are built in the actuator body

For our proposed system, we design the control algorism as follows. The first, the integrated controller calculates the track control reference of each actuator during the standing up motion as equation (1) and transmits these references to each ACT controller completely:

$$v_i^{\mathrm{ref}} = [v_i^{\mathrm{ref}}(0), \ldots, v_i^{\mathrm{ref}}(\hat{s}), \ldots, v_i^{\mathrm{ref}}(1)]^T \tag{1}$$

$$\hat{s} = \frac{t}{t_s} \tag{2}$$

Figure 3 The structure of our controller



where v_i^{ref} is control reference and it is function of the movement pattern $\hat{s}$ (Hughes and Schenkman, 1996) as equation (2). t_s is required time to the standing up operation and t is present time. i means sub-number for identification of the actuator.

The second, after the receiving all track control reference, ACT controller derives the velocity reference from them and drives the DC motors using PID-based control. During the lifting motion, ACT controller sends the measuring value of force sensor and the integrated controller re-calculates the control reference using it.

The integrated controller sends the difference value as equation (3).

$$e_i^{\text{ref}} = v_i^{\text{ref}}(\hat{s}) - v_i^{\text{newref}}(\hat{s}) \qquad (3)$$

where $v_i^{\text{newref}}(\hat{s})$ is new control reference.

ACT controller derives the new reference using the received value and drives its actuator. The integrated controller can send the difference value every 20 ms and ACT controller can control each actuator with 1 ms feedback loop.

With our algorism, the ACT controller can work using the previous control reference even if network trouble occurs and this means our proposed system realizes the robustness. Using these ideas, our proposed distributed system realizes the real-time control function on each actuator and the control function with coordination among these actuators with low costs.

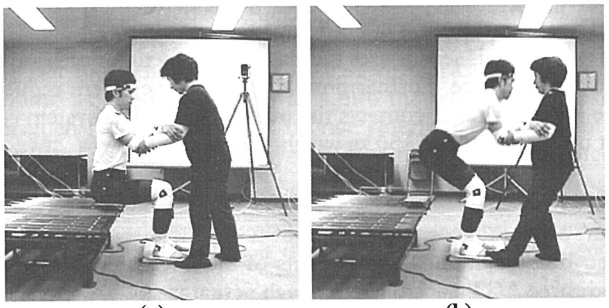
3. Standing up motion

3.1 Motion by nursing specialist

In previous study, a lot of standing up motions for assistance are proposed. Kamiya (2005) proposed the standing up motion which uses remaining physical strength of the patients maximum based on her experience as nursing specialist. Figure 4 shows the standing up motion which Kamiya proposes.

In our previous work, we analyze this standing up motion and find that Kamiya scheme is effective to enable standing up motion with smaller load (Chugo *et al.*, 2006). We assume the standing up motion is symmetrical and we discuss the motion as movement of the linkages model on 2D plane

Figure 4 Standing-up motion with Kamiya scheme


(a) (b)

(Nuzik *et al.*, 1986). We measure the angular values among the linkages, which reflect the relationship of body segments. The angular value is derived using the body landmark as shown in Figure 5(a).

In order to realize the Kamiya scheme, the trunk needs to incline to forward direction during lifting up from chair as shown in Figure 5(b). *Y*-axis shows the angular value (pelvis and trunk, knee, ankle) and *X*-axis shows the movement pattern which means the ratio of standing up operation as equation (2).

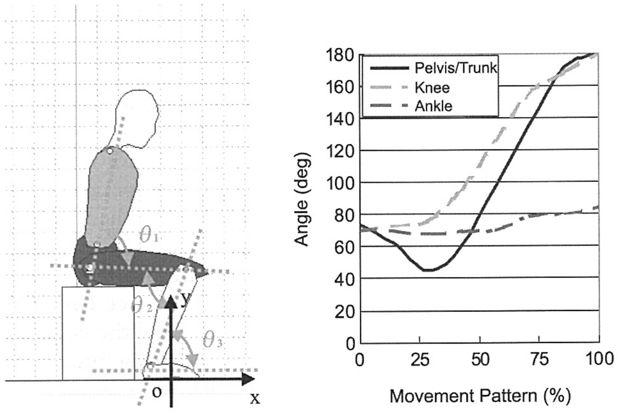
θ_1 shows the angular of the pelvis and the trunk. θ_2 and θ_3 shows the angular of the knee and the ankle, respectively.

Generally, inclining the trunk reduces the load of knee during standing up (Fisher *et al.*, 1990) and this motion is useful for elderly person who does not have enough physical strength. Therefore, in the next section, we derived the control reference for our assistance system which realizes this motion using computer simulations.

3.2 Derivation of control reference

In this section, we derive the control reference of our assistance system which can realize the standing up motion proposed by Kamiya using a computer simulation. Figure 6 shows the simulation setup. The parameters are chosen from a standard body data of adult male (Digital Human Research Center, AIST, 2006; Omori *et al.*, 2001) as shown in Table I.

Figure 5 Standing-up motion with Kamiya scheme



(a) Coordination **(b)** Angular value

Figure 6 Simulation setup

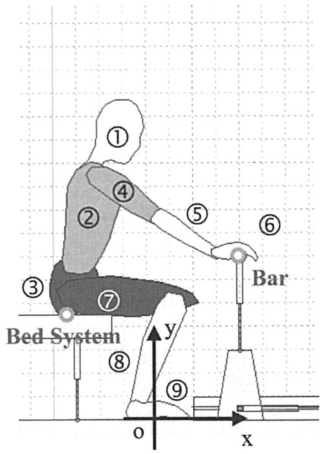


Table I Human parameters

Number	Link name	Mass (kg)	Length (m)	Width (m)
1	Head	5.9	0.28	0.21
2	Trunk	27.2	0.48	0.23
3	Hip	18.1	0.23	0.23
4	Humerus	4.5	0.39	0.12
5	Arm	2.7	0.35	0.08
6	Hand	0.5	0.2	0.07
7	Femur	9.1	0.61	0.17
8	Leg	4.5	0.56	0.16
9	Foot	0.8	0.26	0.11

In derivation of the references using the simulation, we assume the following points:

- the human model moves each joints as Figure 5(b);
- the human model does not bend its arm;
- the human model does not put out the power on its arm (the joint of shoulder is free);
- the human model grasps the bar using its hand with enough force; and
- we assume the height of human model is 170 cm.

We use the Working Model 2D as a physical simulator and MATLAB as a controller. Both applications are linked by Dynamic Data Exchange function on Windows OS.

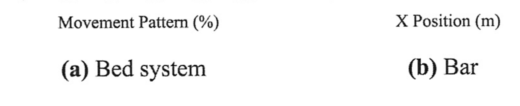
From the simulation results, Figure 7(a) shows the tracks of the bed system and Figure 7(b) shows the tracks of the support bar. The coordination of Figure 7(a) and (b) is defined as shown in Figure 6. In Figure 7(b), the start point is lower right and the end point is upper left. Using these tracks as the position control reference, our assistance system can realize the standing up motion which Kamiya proposes.

3.3 Discussion

In standing up motion of Kamiya scheme, we can divide the standing up motion into four phases as Table II (Chugo *et al.*, 2006). In the first phase, the patient still sits and inclines his trunk to forward direction. In the second phase, he lifts off from the chair and in the third phase (as shown in Figure 4(b)), he lifts the body. In the fourth phase, he extends his knee joint completely and ends the standing up motion.

Now, we show the output torque of each joint in Figure 8(a) and the force applied to the force sensor of ACT1 in Figure 8(b) from computer simulations. The knee load

Figure 7 Derived control references

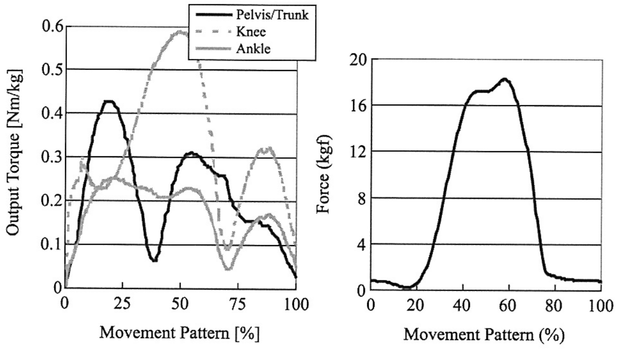


(a) Bed system **(b)** Bar

Table II Four phases of standing up motion

Phase	Priority	Action
1:Flexion momentum	Stability	Sitting
2:Momentum transfer	Stability	Lift-off
3:Extension	Traction	Max dorsiflexion
4:Stabilization	Stability	End hip extension

Figure 8 Required force for the standing up motion



(a) Output torque of each joint **(b)** Applied force

becomes heavy from 25 to 70 percent of movement pattern. During this period, the body is lifted up from the bed and we can consider that this period is third phase. In general, if the applied load to each joint is heavier than 0.5 Nm/kg, it is difficult to stand up for the elderly person (Schenkman *et al.*, 1990).

From the simulation result as Figure 8(a), the output torque of knee joint exceeds 0.5 Nm/kg in the third phase. Therefore, it is required to reduce the load of knee joint in the third phase. On the other hand, in the first, second and fourth phases, the load of each joint does not exceed 0.5 Nm/kg. Therefore, in these phases, it is required to maintain the motion of Kamiya scheme.

4. Force control

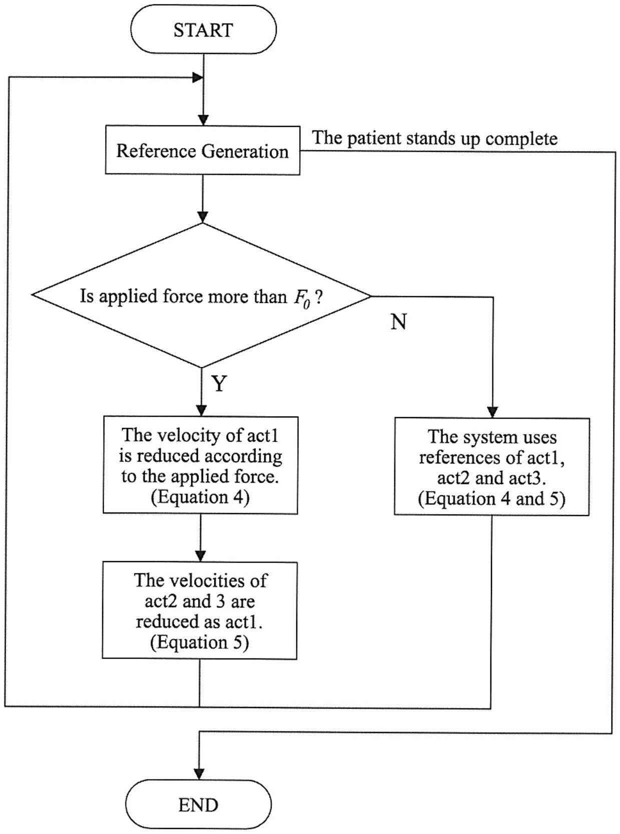
4.1 Proposed control scheme

In Section 3, the control references for our assistance system are derived. Using the derived tracks of the bar and the bed system, our assistance system is required to realize the standing up motion which Kamiya proposed. For realizing the motion of Kamiya scheme, the conditions are discussed as follows:

- in the third phase, it is required to reduce the load of knee joint; and
- in other phases, it is required to maintain the standing up motion.

Therefore, we propose new control scheme as shown in Figure 9. Proposed control scheme combines dumping and position controls. The dumping control is suitable for the control of the objects with contact (Sugihara *et al.*, 2004). When the required torque of each joint is small enough in the first, second and fourth phases, the controller uses the position control. On the other hand, when required torque of knee joint is heavy in the third phase, the controller uses the dumping control.

Figure 9 Flow chart of our proposed control scheme



We use force sensor attached on ACT1 for switching condition between the position and the dumping controls. Comparing with Figure 8(a) and (b), the applied force to force sensor shows the same tendency to the applied load of knee joint. Therefore, we can divide the third phase and the other phases using the measuring value of the force sensor as a threshold. Using our proposed control scheme, the controller can select more appropriate control method using force sensor on ACT1 as shown in Figure 8(b).

Now, we explain our proposed control scheme closely. The reference generator derives the tracks of each actuator and its velocity. The output of ACT1 is derived from equation (4):

$$\begin{cases} v_1 = v_1^{\mathrm{ref}} - B(F - F_0) - K\left(x_1 - x_1^{\mathrm{ref}}\right) & \cdots \quad (\text{if } F > F_0) \\ v_1 = v_1^{\mathrm{ref}} & \cdots \quad (\text{if } F \le F_0) \end{cases} \tag{4}$$

The velocities of ACT2 and ACT3 are derived from equation (5):

$$v_i = \frac{v_1}{v_1^{\mathrm{ref}}} v_i^{\mathrm{ref}} \tag{5}$$

where F is the applied force on ACT1 and F_0 is the threshold which selects force or position control. v_i^{ref} is the velocity reference and x_i^{ref} is the position reference derived by the integrated controller before the system starts. v_i is the updated reference which the integrated controller send to ACT controller during the assistance motion. B and K are constants.

4.2 Computer simulation

We verify the performance of our control scheme by the computer simulation. In this experiment, the human model stands up with Kamiya motion as shown in Figure 5(a) and our assistance system assists him using our proposed control scheme. Furthermore, we compare the result by our proposed scheme with the result using only the position control reference.

We use the control references as shown in Figure 10 which is derived from standing up motion with Kamiya scheme in the previous section. The simulation parameters are chosen from Table I. The coordination is shown in Figure 6.

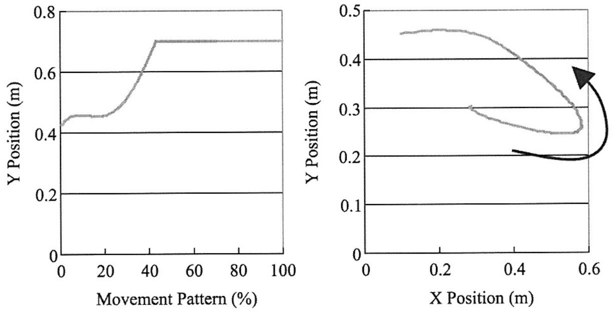
Furthermore, we set $F_0 = 12\,\mathrm{N}$ as a threshold which is derived experimentally. Red lines in Figure 10 show that the control system uses the dumping control.

Figure 11 shows the simulation results. Figure 11 is standing up motion using our proposed assistance control. Allows in Figure 11 shows the applied assistance force to the patient. The bed system applies the force vertically to the hip and the bar applies the force to the hand which grasps it. Using our proposed control scheme, we verified that our assistance system realizes the natural standing up motion.

Table III shows the maximum output and output power of each joint. From these results, our proposed control scheme reduces maximum output into 0.5 Nm/kg comparing with the result by the position control. Therefore, the patient can adapt this motion using his remaining physical strength. Furthermore, with our proposed control scheme, the workload of each joint is maintained comparing with the result by the position control. During standing up motion, the patient is required to use his 92 percent of physical strength comparing with physical strength without the force assistance control. This means our assistance system can use part of his remaining strength in order not to reduce muscular strength.

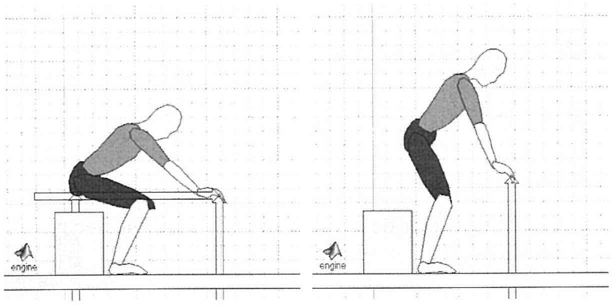
Therefore, we can verify that the system selects more appropriate control method and our proposed control scheme is effective.

Figure 10 Control references



(a) Bed system **(b)** Bar

Figure 11 Simulation result



(a) **(b)**
Allows show the applied force

Table III Simulation results

		Pelvis/trunk	Knee	Ankle
Only position control	Peak (Nm/kg)	0.48	0.59	0.38
	Workload (Ws)	29.0	39.3	31.0
Proposed control	Peak (Nm/kg)	0.49	0.50	0.38
	Workload (Ws)	26.9	36.3	28.8

4.3 Experiment

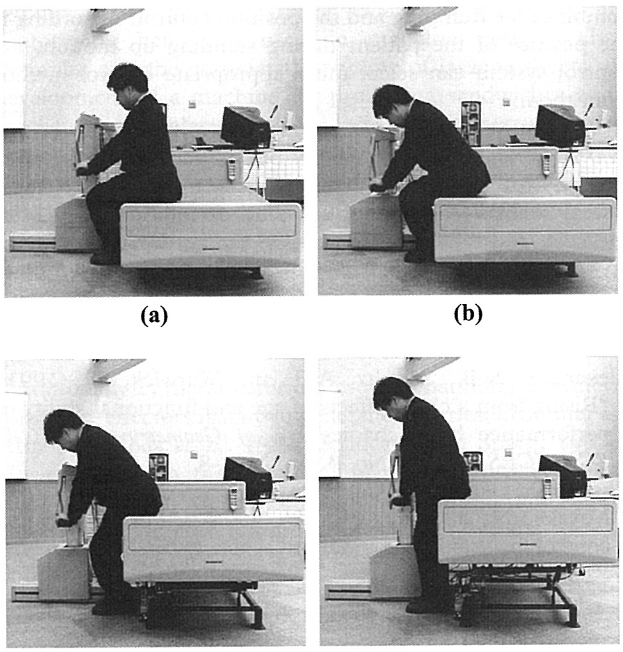
Here, we verify the performance of our prototype system by the experiment. In this experiment, our prototype system assists the patient with our proposed control scheme.

As the result of the experiment, our system can assist the patient as shown in Figure 12. The height of the patient is 170 cm and the system lifts him at 30 s. Figure 13 shows the tracks of the position of the patient's waist, knee and ankle joint and their control references. From Figure 13, both tracks are almost same line and this means our assistance system realizes the natural standing up motion by nursing specialist.

5. Conclusion

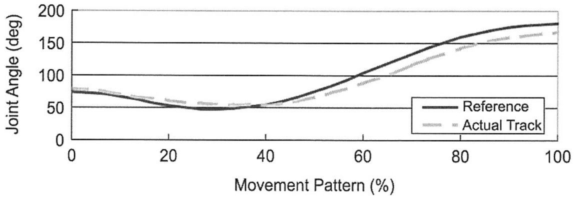
In this paper, we develop the novel assistance system for the standing up motion. Our system focuses on the need the elderly person to use part of their remaining strength, in order not to reduce muscular strength.

Figure 12 Experimental results

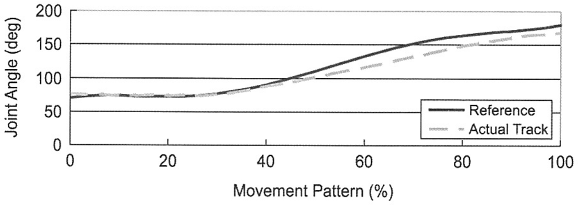


(a) **(b)**
(c) **(d)**

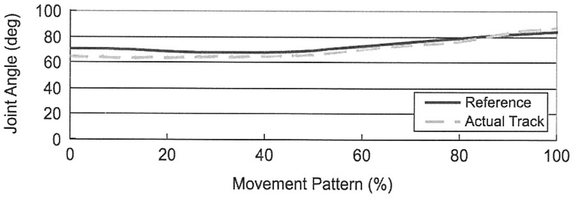
Figure 13 Angular value of each joint



(a) Pelvis/Trunk



(b) Knee



(c) Ankle

We discuss the condition for realizing the effective standing up motion by analyzing the motion of the nursing specialist. In order to fulfill this condition, we design the distributed control system which operates the support bar and the bed system. Our developed distributed controller enables both the real-time control function on each actuator and the coordination function among all actuators with low costs. Furthermore, we design the novel control scheme which combines the dumping and the position control. According to the posture of the patient during standing up motion, our control system can select more appropriate control method from them.

Using our assistance system, the load of knee joint reduces to 0.5 Nm/kg, which the elderly person can adapt with their own physical strength, generally. Furthermore, our assistance system realizes the natural standing up motion by nursing specialist and it is effective to assist the aged person to stand up without reducing their muscular strength.

References

Alexander, N.B., Schultz, A.B. and Warwick, N. (1991), "Rising from a chair: effects of age and functional ability on performance biomechanics", *J. of Geometry: MEDICAL SCIENCES*, Vol. 46 No. 3, pp. M91-8.

Chugo, D., Okada, E., Kawabata, K., Kaetsu, H., Asama, H., Miyake, N. and Kosuge, K. (2006), "Force assistance control for standing-up motion", *Proc. of IEEE/RAS-EMBS Int. Conf. on Biomedical Robotics and Biomechatoronics*, p. F132.

Digital Human Research Center, AIST (2006), "Human body properties database", available at: www.dh.aist.go.jp/bodyDB/index-e.html (accessed March 2006).

Fisher, N.M., Pendergast, D.R. and Calkins, E.C. (1990), "Maximal isometric torque of knee extension as a function of muscle length in subjects of advancing age", *Arch. Phys. Med. Rehabil.*, Vol. 71 No. 10, pp. 729-34.

Funakubo, A., Tanishiro, H. and Fukui, Y. (2001), "Power assist system for transfer aid", *J. of the Society of Instrument and Control Engineers*, Vol. 40 No. 5, pp. 391-5.

Hirvensalo, M., Rantanen, T. and Heikkinen, E. (2000), "Mobility difficulties and physical activity as predictors of morality and loss of independence in the community-living older population", *J. of the American Geriatric Society*, Vol. 48, pp. 493-8.

Hughes, M.A. and Schenkman, M.L. (1996), "Chair rise strategy in the functionally impaired elderly", *J. of Rehabilitation Research and Development*, Vol. 33 No. 4, pp. 409-12.

Kamiya, K. (2005), "Development and evaluation of life support technology in nursing", *Proc. of 7th RACE Symp., Research into Intelligent Artifacts for the Generalization of Engineering, The University of Tokyo*, pp. 116-21.

Ministry of Health, Labour and Welfare, Japan (2001) Annual Reports on Health and Welfare 2001 Social Security and National Life, available at: www.mhlw.go.jp/toukei/saikin/hw/k-tyosa/k-tyosa01/4-3.html (accessed August 2006).

Nagai, K., Nakanishi, I. and Hanabusa, H. (2003), "Assistance of self-transfer of patients using a power-assisting device", *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 4008-15.

Nuzik, S., Lamb, R., Vansant, A. and Hirt, S. (1986), "Sit-to-stand movement pattern, a kinematic study", *Physical Therapy*, Vol. 66 No. 11, pp. 1708-13.

Omori, K., Yamazaki, Y., Yokoyama, H., Aoki, U., Kasahara, M. and Hiraki, K. (2001), "The relationship between strength in the lower extremity and the ability to stand up from a chair in elderly inpatients", *Sogo Rehabilitation*, Vol. 30 No. 2, pp. 167-71.

Schenkman, M., Berger, R.A., Riley, P.O., Mann, R.W. and Hodge, A. (1990), "Whole-body movements during rising to standing from sitting", *Physical Therapy*, Vol. 70 No. 10, pp. 638-48.

Statistics Bureau, Ministry of Internal Affairs and Communications, Japan (2004), "Current population estimates as of October 1, 2004", available at: www.stat.go.jp/english/data/jinsui/2004np/index.htm (accessed August 2006).

Sugihara, T., Kawabata, K., Kaetsu, H., Asama, H., Kosuge, K. and Mishima, T. (2004), "Development of a reasonable force sensor for a standing-up and sitting motion support system", *Proc. of Robotics and Mechatronics Conf. 2004, 1P1-H-11.*

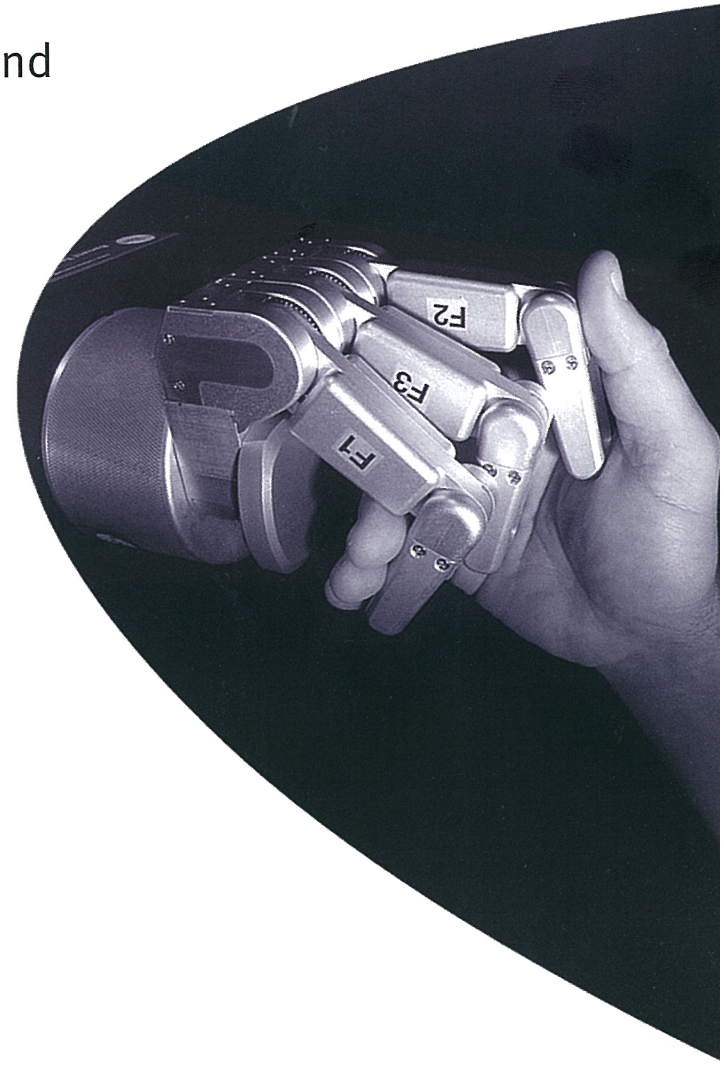
Corresponding author

Daisuke Chugo can be contacted at: chugo@is.uec.ac.jp

ISSN 0143-991X
Volume **34** Number **2** 2007

Industrial Robot

The international journal of industrial and service robotics



IFR International Federation of Robotics

www.emeraldinsight.com

40 Emerald Years in Publishing 1967-2007

Emerald