Paper:

Realization and Safety Measures of Patient Transfer by Nursing-Care Assistant Robot RIBA with Tactile Sensors

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In aging societies, there is a strong demand for robotics to tackle with problems caused by the aging population. Patient transfer, such as lifting and moving a bedridden patient from a bed to a wheelchair and back, is one of the most physically challenging tasks in nursing care, the burden of which should be reduced by the introduction of robot technologies. To this end, we have developed a new prototype robot named RIBA having human-type arms with tactile sensors. RIBA succeeded in transferring a human from a bed to a wheelchair and back. The tactile sensors play important roles in sensor feedback and detection of instructions from the operator. In this paper, after outlining the concept and specifications of RIBA, we will explain the tactile information processing, its application to tactile feedback and instruction detection, and safety measures to realize patient transfer. The results of patient transfer experiments are also reported.

Keywords: nursing-care assistant robot, physical human-robot interaction, safety measures, tactile sensor

1. Introduction

With declining birthrate and the aging population, shortage of nursing caretaker has become a huge social problem, as such our expectations towards robotics are tremendous, and diverse nursing-care or welfare robots have been developed so far. Such robots include robots assisting those requiring nursing-care to take meals [1], mental commit robots designed to give mental comfort [2], myoelectric prosthetic arms [3], wearable power-assist devices that assist disabled people to move [4], and intelligent wheelchairs [5].

The most physically challenging task in nursing-care is patient transfer assistance, i.e., assisting those requiring nursing-care in lifting and moving between a bed and a wheelchair. As an equipment to assist patient transfer, nursing-care lifts have been released by several companies but they are not used on site so much. In Japan, only 14.8% of staffs in nursing-care facilities use floor traveling lifts due to the following reasons [6]: their use is time-consuming and troublesome, requiring a large floor area, and is a mental and physical burden to the patient due to suspension. In addition, it was reported in [7] that the physical burden of the caregiver is not reduced in many cases using patient lifts.

This raises our expectations towards robots that assist patient transfer. Such robots include Yurina (Japan Logic Machine), Melkong (Mechanical Engineering laboratory, Agency of Industrial Science and Technology) [8], Transfer Assist Robot (Panasonic) [9], and C-Pam (Daihen) [10]. However, all of these are time-consuming and cannot be used to transfer a patient to a non-reclining wheelchair, which is widely used on site. Although Panasonic released a bed-type dual-purpose robot which can be transformed into a bed and a wheelchair [11], only one patient can use it at a time and thus as many robots as patients requiring nursing-care are needed.

We developed and released a robot, RI-MAN [12], in 2006, aiming to use a pair of human-like arms to lift up a patient. Although RI-MAN successfully lifted up an 18.5 kg dummy sitting at a predetermined position relative to the robot, it failed to lift up an actual human because of lack of weight capacity, joint moving range, handling capability to situation change, and safety. We then developed a new prototype robot RIBA (Robot for Interactive Body Assistance), aiming to transfer real patients in nursing-care facilities, hospitals, etc. This is the first robot that actually succeeded in lifting up a patient from a bed or a wheelchair, moving, and lifting down, using human-type arms. The use of the human-type versatile arms enables patient transfer to a non-reclining wheelchair. RIBA is mounted with tactile sensors over a wide range of the arms, which are used to modify lifting trajectory, detect operator's instruction, and ensure safety.

This article first gives an overview of the RIBA design, next describes sensor output processing of the tactile sensors that play important roles in patient transfer, and then explains the arm angle modification by tactile feedback and tactile-based detection of operator's instruction. This article also reports the safety measures we took for transferring real humans and the results of transfer experiments with RIBA.

2. RIBA Overview

2.1. Design Concepts

1) Patient Transfer Assistance with Human-Type Arms: To transfer a human from a bed using a robot, the following methods have been proposed.

- Using human-type arms (this article).
- Attaching a simple bed to the end of robot arms, to which patients are transferred in some way from the bed they lay before lifted up (Yurina by Japan Logic Machine).
- Connecting a part of a bed with a robot, and lifting up the connected part together with the patient [8].
- Lifting up a human by plate-like support equipment with a belt to eliminate a friction [9].
- Transforming a part of a bed into a wheelchair [11].

An advantage of a robot with human-type arms is that it can be used in various ways of lifting up and other works. In fact, other methods failed to achieve patient transfer to non-reclining wheelchairs, which are often used in nursing-care. If a patient is not transferred to a wheelchair in a short time, the robot will be occupied by the patient during such activities as eating after having been lifted up. So, nursing-care facilities need to purchase as many robots as the patients.

Another advantage of the arms of the same size as human is that they can be put into/out of a small space. If the helper makes a small space below a bedridden patient, the robot can put its arms into the space. More specifically, to lift the bedridden patient, the robot puts its arms into a space under the knees made by bending the patient's legs and a space under the back made by slightly raising the patient's head. In patient transfer, most time is spent for placing a support under the patients, so capability of putting arms into/out saves the time.

For this reason, we use a robot with human-type arms to transfer a patient. Disadvantages of the robot with human-type arms include problems caused by a complicated system such as increase in cost and failure rate and a risk of the patient slipping through the arms and falling off. We intend to develop a useful robot with a sophisticated design and skillful control to overcome disadvantages.

2) Trade-Off of Size, Speed, and Weight Capacity: Those robots used in nursing-care facilities and hospitals have to have similar size to humans to get in a door and a narrow bedside space. At the same time, such robots have to lift up and down the weight of a human and act at an acceptable speed for the user. These are in a trade-off relationship but they have to be all satisfied at an acceptable level if the robot is to be practically used. When designing RIBA, we gave priorities to (1) weight capacity (over 60 kg) to lift up a human, (2) size (below 80 cm wide) to get into a narrow space, and (3) joint speed made available through the above two priorities.

3) Whole-Body Manipulation: To handle weight and size of a human, we adopted a whole-body manipulation to hold a human with the entire body of the robot [13]. Since RIBA handles a human, whole-body manipulation means that most part of the body may touch a human, thereby requiring measures for safety and comfort.

4) Cooperative Patient Transfer by Helper and Robot: In nursing-care facilities and hospitals the environments of which are not prepared for the robot to work, the current information technology is insufficient to determine, using sensor information, what kind of lifting action should be made according to the position and posture of a patient, whether the patient is mentally ready to be lifted, and whether or not an accident might occur or has occurred. In addition, to clarify where responsibility lies, the final decision to lift should be made by a human. For this reason, we selected the usage of RIBA as follows: the helper operates the robot to transfer the patient in cooperation with the robot so that human is in charge of recognition and decision. While working autonomously within a range where safety is ensured, the robot works under human instructions in delicate situations where it is difficult for the robot to determine its motion.

Instructions from the helper to the robot are preferably simple and conveyed without any additional device. We developed a method named tactile guidance, in which the helper touches the robot and operates by guiding it to directions in which the helper wants the robot to move. The tactile guidance allows the helper to be in charge of recognition and determination by operating the robot with one hand and to be in charge of delicate works such as lifting up the patient's head, at which the robot is not good, with the other hand. Since the helper can operate the robot while touching the patient, the helper can give the patient a sense of safety, thereby achieving warm nursing-care.

In actual nursing-care facilities, a bedridden patient is usually transferred by two or more helpers. If the most physically burdened helper among them is replaced with the robot, shortage of helpers can be solved, and helpers can be relieved from heavy works and thus their physical safety can be ensured.

2.2. Basic Specifications

The robot RIBA and its joint configuration are shown in **Fig. 1** and its basic specifications are shown in **Table 1**. We adopted a coupled drive mechanism [14] for thin, lightweight arms to handle heavy weight with higher motor utilization ratio. The mechanism is used for pairs of joints in the arms.

The width of 750 mm shown in **Table 1** is of the shoulder, the greatest width of the entire robot when the arms are folded. The width of the robot becomes 1200 mm when the arms are stretched as in **Fig. 1**. The cart is 740 mm wide. The cart is provided with omni-wheels for use in small spaces, allowing the cart to move in any directions without switching back.

RIBA is operated on voice commands for each action such as "lift up from bed" and "say hello." RIBA is provided in advance with the joint angles' and cart's basic

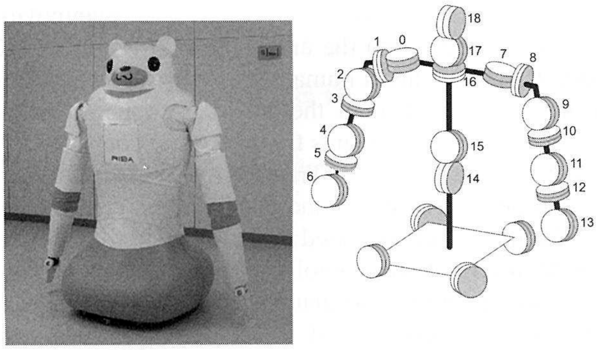
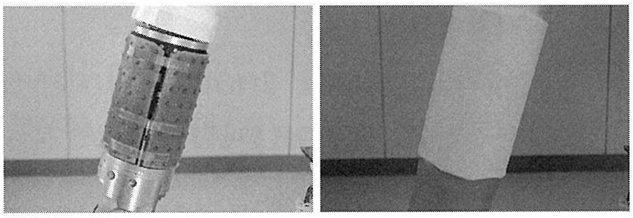


Fig. 1. RIBA (Robot for Interactive Body Assistance) and its joint configuration.

Table 1. Basic specifications of RIBA.

Dimensions	Width	750 mm (when arms are folded)
	Depth	840 mm
	Height	1,400 mm
Weight inc. batteries		180 kg
D.O.F.	Head	3 (2 are not used now)
	Arm	7 each
	Waist	2
	Cart	3 (with 4 motored wheels)
Base movement		Omni-directional
Actuator type		DC motor
Payload		63 kg (tested value)
Operation time		2 hour in standard use
Power		NiMH batteries
Sensors	Vision	2 cameras
	Audition	2 microphones
	Tactile	Upper arm (128 pts. each) Forearm (94 pts. each) Hand (4 pts. each) Shoulder pad (8 pts. each)



(a) Without cover (b) With cover

Fig. 2. Tactile sensors on the upper arm.

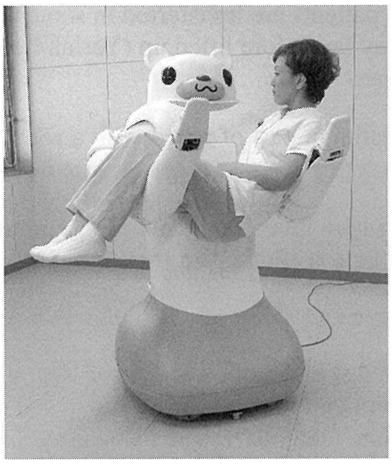


Fig. 3. RIBA lifting a human in its arms.

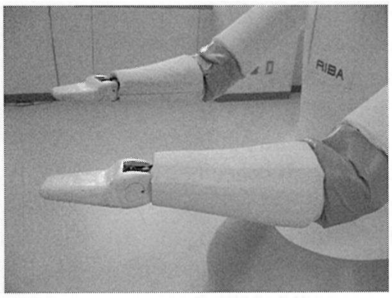


Fig. 4. Forearms the shape of which fits the human back.

trajectory for each action corresponding to voice commands. However, the trajectories are modified using tactile information in actions such as patient transfer because predefined trajectories cannot keep up with the situation change.

RIBA is provided with voice recognition ability so that instructions are given with voice commands. It is also provided with face recognition ability for the visual sense and sound source localization ability for the hearing sense, so that it can find the operator. As tactile sensors, we developed a flexible tactile sensor sheet with semiconductor pressure sensors and a readout circuit embedded in an elastic material [15]. This type of tactile sensor is mounted on the upper arms and forearms. **Fig. 2(a)** shows the upper arms covered with the tactile sensor sheets, which are, as shown in **Fig. 2(b)**, further covered as the robot's tactile sensor. The number of pressure-sensitive elements is 128 on each of the upper arms and 94 on each of the forearms. We call the body side of the arm inside and the other side outside when the robot is in the posture shown in **Fig. 1**. In lifting shown in **Fig. 3**, human weight is applied to the inside of the upper arms and the forearms. Since the forearms mainly support the patient's weight in lifting, we adopted a slightly recessed shape that comfortably fits the patient's back (**Fig. 4**). In addition to the above semiconductor-based tactile sensors, hands and shoulder pads are embedded with pressure-sensitive conductive rubber sensors.

The power source and the information processing system are all housed in the robot so that the robot can be stand-alone. We adopted a distributed information processing by a network consisting of a main PC (CPU: Intel CoreDuo, 2 GHz) and 20 or more small controllers (CPU: Microchip dsPIC33F) so that the computational load on the main PC to actuate many sensors and motors is reduced. Placing small controllers near the sensors or motors also contributes to reduce the number of cables and analog sections which are susceptible to noise. Each joint is position-controlled by the small controller placed near

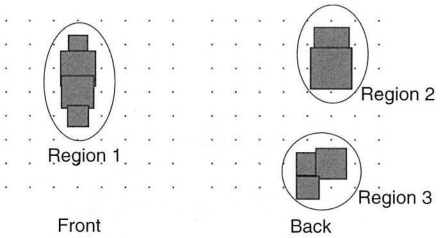


Fig. 5. Regions are detected from the tactile sensor output and features are calculated for each region.

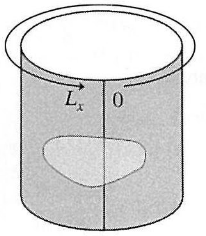


Fig. 6. Coordinates on a circular surface.

the motor to achieve target trajectories given by the main PC. The control periods of the tactile sensor controller, the motor controller, and the main PC are 4 ms, 1 ms, and 10 ms, respectively. While RIBA is basically stand-alone, it can be connected with an external computer through wireless LAN for monitoring.

To improve safety, lifting stability and comfort, all the components such as cables are housed inside to make the arms and bodies free from projections, and the whole body including the joints is covered with soft materials such as polyurethane foam and silicon rubber. In addition, since a mechanical robot appearance is unsuitable for nursing-care sites and an imperfectly human-like appearance is eerie, the robot is provided with an appearance like a stuffed polar bear for friendliness and cleanness.

Thus, RIBA has successfully achieved actions for patient transfer such as "lifting up from the bed," "lifting down to the bed," "lifting up from the wheelchair," "lifting down to the wheelchair," and "moving while lifting the patient."

3. Pattern Processing of Tactile Sensor Outputs

In lifting, the RIBA's tactile sensors have to distinguish contact between the patient and the operator. Contact by the patient is used for sensor feedback of the lifting actions and contact by the operator is used for detection of the operator's intention. The tactile sensors output two-dimensional pattern information on surface pressure distributions of the upper arms and the forearms. The information undergoes pattern processing to distinguish those contacts.

In the processing, contact regions are first extracted. An example of the pressure pattern detected from the upper arm is shown in **Fig. 5**. Log scales of pressure which are outputs of the pressure-sensitive elements are represented by the size of squares. Based on 4-connectivity of elements, contact regions containing reacting elements are determined. Then, features such as the size, pressure center, pressure sum, and maximum pressure are calculated for each region. The current RIBA distinguishes contact regions of the patient from those of the operator based on two conditions of the pressure center position and the pressure sum. The whole tactile pattern processing is performed by the small controllers near the sensors, and extracted features are sent to the main PC through the network.

Basically, region detection and feature calculations can be performed through the same algorithm as those developed for image processing (e.g., [16]). However, since the robot surface is not a flat plane but has complex shape, the following modifications are required.

First, it should be noted that the tactile sensors make a closed surface encircling the arms. For instance, we will now discuss the case where the x axis is circular and assigned with a coordinate value from 0 to L_x. Let (x,y) denote the position of the pressure-sensitive elements and $p(x,y)$ the pressure detected at the position. With the contact region lying on the line of discontinuity of the x coordinate as in **Fig. 6**, let us first consider the x coordinate of the pressure center simply calculated by

$$x_{\text{cop}} = \frac{1}{S} \sum_{(x,y)\in A} x p(x,y) \quad \dots\dots\dots \quad (1)$$

where $S = \Sigma_{(x,y)\in A} p(x,y)$ and A represents an intended region. Here, the resultant x_{cop} is close to $L_x/2$, which is not correct. Then, an alternative coordinate system is defined as follows:

$$\tilde{x} = x + nL_x \quad \dots\dots\dots\dots\dots \quad (2)$$

where n is an integer appropriately selected so that the coordinate value is continuous in the intended region. Geometric features such as the pressure center are calculated with this $\tilde{x}$ coordinate and the end result is mapped onto $[0, L_x)$, so that this problem is solved.

Another problem is caused in defining neighboring elements if the surface has a free-curved shape which cannot be expanded into a two-dimensional plane. In RIBA, the shape of the forearms falls into it. Contact regions are calculated using 4-connectivity used in image processing as described earlier but, when the surface cannot be expanded into a plane, neighboring elements in a normal sense may not be found. We will now discuss an example as **Fig. 7** in which a three-dimensional surface is expanded into two tactile sensor sheets. The tactile sensor sheets are originally a square but their corners are cut off to fit the three-dimensional shape, therefore some parts have no elements for 4-connectivity. On the other hand, elements positioned separately in the expanded plane may be positioned adjacently in the original three-dimensional shape. So, we use alternative definitions of 4-connectivity for such parts. **Fig. 7** is an example of redefinition of neighbors. We defined the encircled elements' neighbors as parts bound by line segments.

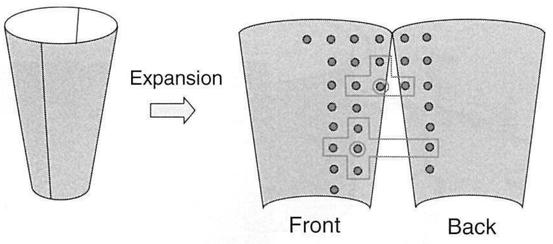


Fig. 7. Alternative definitions of 4-neighborhood elements on expanded planes.

4. Patient Transfer Using Tactile Information

4.1. Trajectory Modification by Tactile Feedback

Detecting information on contact with the lifted patient enables actions to be modified as appropriate to the situation. In lifting shown in **Fig. 3**, the patient contacts the inside of both the forearms and the upper arms. So, based on the result of the tactile pattern processing, we determine a contact region which has the pressure center in those areas and applies force greater than a predetermined threshold as contact derived from the patient. Since, in a preliminary experiment, patients pointed out the necessity to fit the angles of the patients' back and the recessed surface of the forearm in lifting action, we achieve this by tactile feedback in this article. Although we prepare appropriate lifting trajectories in advance, each attempt has slightly different patient's position and posture, thereby requiring sensor feedback-based modification.

We assume here that the patient's back is mounted on the left arm of RIBA and the angle representing the rotation of the left forearm (the axis 12 of **Fig. 1**) is ϕ as shown in **Fig. 8**. We define surface coordinates (ξ, η) as shown in the figure to represent a contact position on the forearm. Here, ξ is a circumferential coordinate value. The angle of the left forearm rotation in the predetermined trajectory is denoted by $\phi_0(t)$. A modification value $\Delta\phi(t)$, with which the surface of the forearm fits the back, is obtained by the tactile sensor feedback, and let

$$\phi_0(t) + \Delta\phi(t) \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

be an alternative target value. We calculate $\Delta\phi(t)$ so that the pressure center $(\xi_{\mathrm{cop}}, \eta_{\mathrm{cop}})$ of a contact region caused by the load of the back falls in the center of the recessed surface with respect to the ξ direction. More specifically, let ξ_d be a ξ-coordinate value representing the center of the recessed surface, and

$$M\Delta\ddot{\phi}(t) + D\Delta\dot{\phi}(t) + K\Delta\phi = C(\xi_d - \xi_{\mathrm{cop}}) \quad . . \quad (4)$$

where M, D, and K are virtual inertia, viscosity, and stiffness, respectively, to suppress radical angle change, and C is a constant for dimensional transformation from position into torque. The parameter values used in this article are shown in **Table 2**.

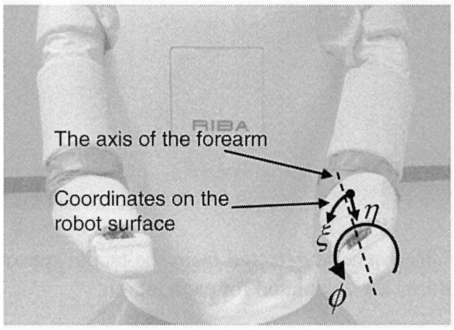


Fig. 8. Rotation angle ϕ of the forearm that supports the patient's back.

Table 2. Parameter values.

Symbol	Value	Unit
M	53.3	kg·m^2
D	266	kg·m^2/s
K	133	kg·m^2/s^2
C	1	kg·m/s^2

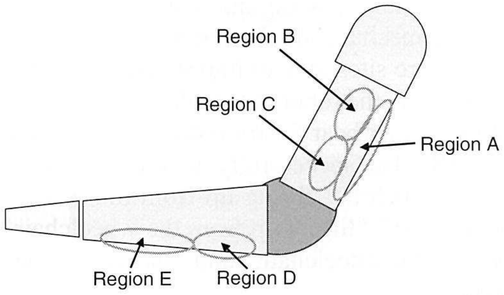


Fig. 9. Regions on an arm for tactile guidance.

4.2. Patient Transfer Instructions by Tactile Guidance

When transferring a patient, the operator makes a decision on the situation and uses the tactile guidance to instruct action modification. Based on the result of tactile pattern processing, a contact region which applies force less than a predetermined value on the outside of the arms is determined as contact derived from the operator. As minimum instruction required for patient transfer, in this article, we apply the tactile guidance to cart moving operation to eliminate differences between initial positions of the patient and to action progression control.

The instruction to move the cart is made on the outside of the upper arm (the side on which the patient is not mounted when lifting) so that the operation is possible even while lifting. When moving, the arms basically take a posture as **Fig. 9**. The operator contacts somewhere in the Region A, slides the contact point back and forth, thereby moving the robot back and forth. The movement speed is designated by the sliding distance. Pushing the Region B causes lateral translational movement and pushing the Region C causes rotation. In those movements, selection of the left or right side of the arm to push determines the direction of the movement, and the strength of force to push determines the movement speed. The operation is possible on either of the left and right arms. Seeing the status of the robot and the patient, the operator can intuitively operate the robot by sliding the contact point or applying force to the desired direction. When the operator takes his hands off and releases the contact, the movement ends.

Also in the tactile guidance which controls the process of lifting up and down actions, tactile outputs of parts which are unaffected by the patient's mounting are used. Suppose that $\theta(\tau)$ is an action trajectory of joints given in advance. Then, the change in τ is operated by contact with the outside of the forearms. Selection of the tip side (Region E of **Fig. 9**) or the base side (Region D) determines forward/backward of the time τ, and the total sum of pressure in the contact region determines the time rate of change.

5. Safety Measures for Experiments to Transfer Human Patients

5.1. Stopping Method

Robots stop their operations when an abnormality is detected, and the way to stop is a problem for, in particular, robots that lift up a human such as RIBA. The robot has to hold a human so as to avoid a fall even if it stops during a lift up; on the other hand, it has to release the patient when appropriate. We prepared the following three stopping states for RIBA.

S1: By stopping time progression of the action trajectory, the target value of each joint is held at what it is when the robot is stopped.

S2: Output of each joint angle sensor is read when the robot is stopped and designated as a target joint angle to keep.

S3: Servo itself of each joint is stopped.

S1 is used in situations where the robot's system itself is perfect but its operations are inappropriate, for example, contacting with something unexpected while operating. With S2, the posture when the robot is stopped can be held even if a joint angle sensor (potentiometer) has a failure and outputs a different value from the actual joint angle. Since the servo is on in S1 and S2, the robot will avoid a fall of a human during a lift up. On the other hand, since the servo itself is stopped in S3, the joints move in the direction to release the patient although slowly when holding a human. For this reason, the robot automatically switches to S1 or S2, and by the operator's further determination the robot switches to S3. With an emergency stop switch, the robot switches to S3.

5.2. Hardware Safety Measures

Since the entire body of RIBA is covered with an elastic material such as polyurethane foam or silicon rubber, collision impact is reduced. In particular, the joints are covered with an elastic material to separate operating sections such as gears from the outside, thereby preventing fingers or hair from being caught. For protection against electric shock, the exterior is made of non-conductive material.

The arm joints are provided with worm gears to self-lock when the servo is off due to power cut off. If a heavy weight of over 25 kg is applied to one arm in lifting up of a human when the servo is off, the arm drops slowly due to the gear friction (though the amount of load to make the arm drop significantly depends on the posture of the robot). When the arm moves only by the weight of the lifted human, the operator can maintain the lifting state by putting his hand to support the human. When the weight is not enough, on the other hand, the lifted human is released when the operator applies additional force. If the waist moves, even though slowly, due to the load and the robot inclines beyond its limit, there is a risk of falling down. For this reason, the current angles of the waist are held by off brakes when the servo is stopped. The waist angles are limited also by mechanical stoppers.

The motor driver of RIBA consists of an amplifier and a local controller. For safety, we designed the amplifier not to be operated, if outputs from the local controller cannot be obtained due to abnormality, even though the amplifier power is on.

5.3. Software Safety Measures

Since RIBA has a power sufficient to lift up a weight of over 60 kg, there is a limit in design based on intrinsic safety. So, it is important to introduce functional safety to detect potentially dangerous states and protect and correct them. Software monitors values from various sensors and, if there is any input value or time change of input value deviating from normal actions which are considered to be safe, the action is stopped. The robot switches to S1 when the system is in a normal state and the robot switches to S2 when the system is in an abnormal state. A warning tone is sent out when the robot switches to S2, and, if S2 is not enough, the operator operates an emergency stop switch or an external monitor computer to switch the robot to S3.

Among software-based safety measures, the following examples are those to be switched to S1 or those basically in a state of S1 but operate only when there is a certain input.

(S1-1) When the robot is in operation, a voice command "stop" is input to stop the robot.

(S1-2) A target value exceeding a certain joint angle range is not accepted and a current target value is retained (software limit of joint angle).

(S1-3) In lifting up/down operations, a stopping state is maintained when there is no input of a command to progress actions by tactile guidance.

(S1-4) The operation is stopped if there is any response in tactile sensors during actions that should not cause any contact.

(S1-5) When in operation, if the difference between a target joint angle and its actual angle is greater than a certain threshold, the operation is not further progressed until the difference is reduced to an acceptable range.

(S1-6) In tactile guidance, if the difference between a target joint angle and its actual angle is greater than an acceptable range, inputs are not accepted until the difference is reduced to an acceptable range.

In (S1-5) and (S1-6), when the actual joint angle keeps up with the target value and falls below the threshold, the robot is back to the normal state where actions can be progressed. This prevents an unexpected posture of the robot, when the target trajectory has parts the joint speed of which is faster than the actually possible speed, causing some joints to achieve the target value while others to fall behind the target value.

Next, those to be switched to S2 are presented.

(S2-1) Stop if a node that is supposed to exist is not found in the information processing network in the robot.

(S2-2) Stop if the difference between the target joint angle and its actual angle exceeds the threshold at which the robot switches to S1 and gets larger.

(S2-3) Stop if the actual joint angle changes over an acceptable range in one sampling period.

(S2-4) Stop if the total sum of pressure on a tactile sensor changes over an acceptable range in one sampling period.

(S2-5) Stop if the load of each arm detected by the tactile sensors is less than expected when a human weight is supposed to be applied to the arms.

(S2-3) and (S2-4) use the fact that physical amounts do not change significantly in a short period of time. If there is such change, the operation is stopped because a sensor circuit may have electrical failure.

5.4. Safety Measures in Experiment Procedures and Operation

Before targeting at human, we conducted experiments using dynamic simulator and a lifesize dummy to confirm safety. We applied to the RIKEN Research Ethics Committee and obtained permission to conduct experiments involving human.

In experiments targeting at human, safety in operation is ensured by the following measures.

- In order to stop the robot safely just in case of an abnormality occurrence, we prepare one person in charge of the emergency stop switch, one person to prevent the lifted person from falling off, one person to support the robot from falling down, and one person to operate and monitor the wirelessly connected in-robot computer, in addition to the robot operator, i.e., the helper.
- At first the robot only lifts up and down the patient on a bed, and, after safety is confirmed, the robot moves away from the bed.
- In an initial stage of the experiment, the patient wears a helmet and protectors on elbows and knees. Before the robot cart moves while lifting the patient, a mat is prepared on the floor in case of a fall.

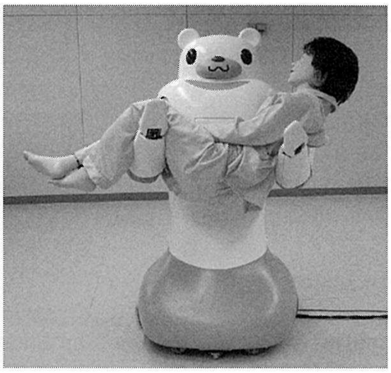


Fig. 10. Lifting a lifesize dummy.

6. Experiment

6.1. Forearm Angle Modification

We conducted an experiment to confirm rotation angle modification of the back side forearm by tactile sensor feedback. We set a forearm rotation angle which did not fit the back in lifting and recorded the angle modification value $\Delta\phi$ and the pressure center position when the modification function by the sensor feedback was turned on/off. However, since this experiment included an inappropriate lifting state, we used a dummy (148 cm tall and weighs 18.5 kg) as shown in **Fig. 10** in place of a human from the research ethics perspective. The use of a dummy had also the advantage of improving objectivity and reproducibility.

In the surface coordinate system, we designated the center of the recessed surface of the forearm as the origin, so that the pressure center fell in the center of the surface with respect to the ξ direction when $\xi = 0$. When the sensor feedback was activated, the value of $\Delta\phi$ changed and accordingly ξ got close to zero (**Fig. 11**). This indicates that the sensor feedback worked effectively for the forearm angle modification.

6.2. Human Patient Transfer

We have conducted patient transfer tests using 10 adults (one male and nine females). The robot lifting up the patient from the bed is shown in **Fig. 12** and that from the wheelchair is shown in **Fig. 13**. The robot has successfully lifted down the patient to the bed and the wheelchair in the reverse process.

In each case, the operator sends instructions to RIBA through the tactile sensor and transfers the patient while

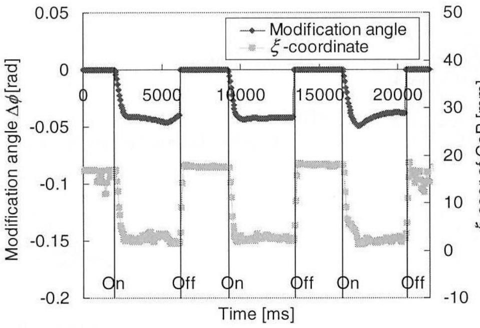


Fig. 11. Modification angle $\Delta\phi$ and the ξ coordinate of the pressure center when holding a lifesize dummy and adjustment was turned on and off.

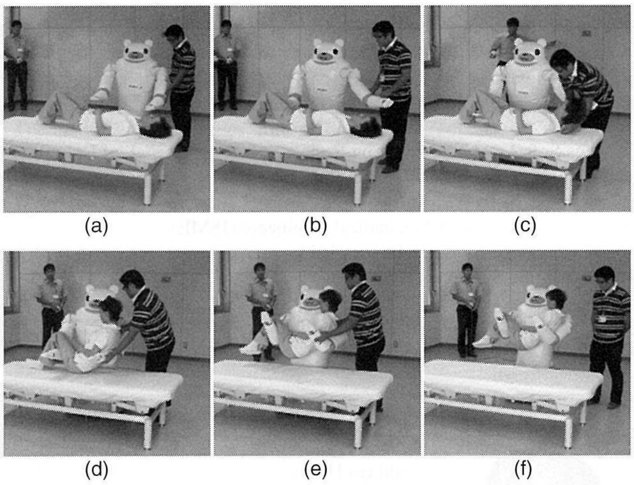


Fig. 12. Lifting up from a bed.

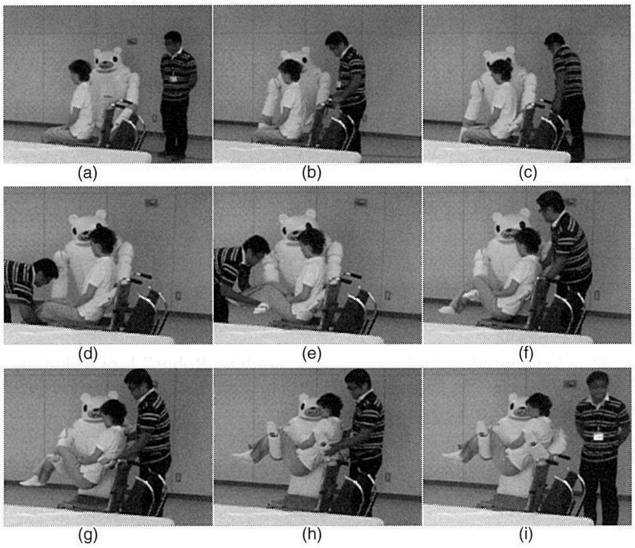
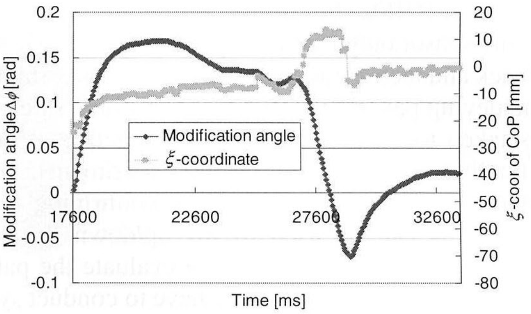
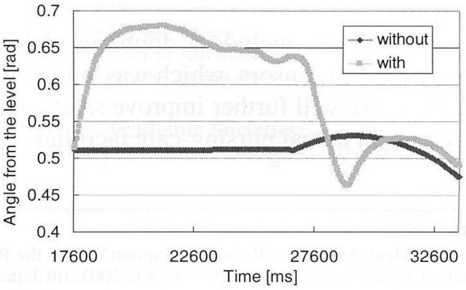


Fig. 13. Lifting up from a wheelchair.

fine tuning the position where the arms will be inserted. In lifting up the patient from the bed, as seen in **Fig. 12(c)**, the operator operates RIBA with his one hand while lifting up the patient's head with his other hand. Similarly, in lifting up the patient from the wheelchair, as in **Figs. 13(d)** and **(e)**, the operator operates RIBA while lifting up the patient's legs.



(a) Modification value $\Delta\phi(t)$ and the ξ-coordinate of the center of pressure on the forearm.



(b) The angle between the tangential plane at the contact point and the horizontal plane with and without the modification value $\Delta\phi(t)$.

Fig. 14. Angle adjustment results of the forearm that supports the human's back.

Figure 14(a) shows time change of the modification value $\Delta\phi$ of the rotation angle of the back side forearm and the ξ-coordinate value of the pressure center in lifting. **Fig. 14(b)** shows the result, obtained by forward kinematics, of the angle of the tangent plane on the back side forearm at the contacting point with the lifted patient from the horizontal plane, realized by $\phi_0(t)$ (without modification) and $\phi_0(t)+\Delta\phi(t)$ (with modification). In this figure the x axis represents time lapsed from the start of the lifting action and the range indicated in the graph substantially corresponds to the process from **Figs. 12(d)** to **(f)**. The angle of the tangent plane achieved with the modification changed significantly from that without the modification. This is considered to have resulted from modification performed in accordance with the lifted human's posture which was not constant during the lifting.

The lifting is stable and the patient has never faced a danger of falling off. The maximum weight of the lifted patient is 63 kg and time required for one of the actions was about 40 s. The operator has operated slowly for safety so far but, once he is skilled, time may be further reduced.

7. Conclusions

We have developed RIBA as a prototype of robots that transfer patients, and have successfully transferred a human between a bed and a wheelchair. After taking an overview of RIBA, this article first described processing of tactile sensor output and its application to tactile sensor feedback and tactile guidance, which play important roles for achieving patient transfer, then explained safety measures taken to conduct experiments targeting at human, and finally reported patient transfer experiments.

At present, we are at a stage of confirming that the robot's arms can be used to lift up/down the patient from/to a bed or a wheelchair. To evaluate the patient's physical and mental burdens, we have to conduct systematic experiments such as myoelectric measurements and questionnaire survey to a number of patients, which are future challenges.

Future improvements include a doubling of joint angle sensors and tactile sensors, which was skipped due to space limitation. We will further improve safety and conduct experiments in actual nursing-care facilities.

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