Robot Patient Design to Simulate Various Patients for Transfer Training

Zhifeng Huang, Chingszu Lin, Masako Kanai-Pak, Jukai Maeda, Yasuko Kitajima, Mitsuhiro Nakamura, Noriaki Kuwahara, Taiki Ogata, and Jun Ota

***Abstract*—To improve the patient transfer skill of nursing education students, we developed a robot patient that can simulate three categories of patients: 1) patients whose movements are affected by paralysis; 2) patients whose movements are sensitive to pain with painful expression; and 3) patients whose movements are constrained by medical devices. By practicing with the robot patient, nursing students can learn the skills required for interacting with various patients. To simulate trunk movements of these different patients, novel waist and hip joints with hardware-inherent compliance and force-sensing capability were proposed. In addition, control methods were developed and the parameters were tuned based on actual patient videos. To evaluate the developed robot, nursing teachers performed trials of transferring the robot patient as they would transfer an actual patient. The nursing teachers scored the robot patients based on a checklist. Moreover, subjective evaluations of a questionnaire were performed by the nursing teachers. The results showed that the nursing teachers performed most of the required skills of the checklist and agreed regarding the learning effectiveness of the robot. They recommended training nursing students using the robot patient in the questionnaire. Finally, hugging speed comparison showed that the nurses slow down the speed when dealing with a robot patient with painful expression.**

***Index Terms*—Compliant joint, patient transfer, robot patient, various patients.**

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Z. Huang is with the School of Automation, Guangdong University of Technology, Guangzhou 510006, China (e-mail: zhifeng@gdut.edu.cn).

C. Lin, T. Ogata, and J. Ota are with Research into Artifacts, Center for Engineering, University of Tokyo, Chiba 277-8568, Japan (e-mail: lin@race.u-tokyo.ac.jp; ogata@race.u-tokyo.ac.jp; ota@race.u-tokyo.ac.jp).

M. Kanai-Pak is with Kanto Gakuin University, Yokohama 236-8501, Japan (e-mail: m-nakamura@tau.ac.jp).

J. Maeda, Y. Kitajima, M. Nakamura are with the Faculty of Nursing, Tokyo Ariake University of Medical and Health Sciences, Tokyo 135-0063, Japan (e-mail: jukai@tau.ac.jp; kitajima@tau.ac.jp; m-nakamura@tau.ac.jp).

N. Kuwahara is with the Department of Advanced Fibro-Science, Kyoto Institute of Technology, Kyoto 606-8585, Japan (e-mail: nku-wahar@kit.ac.jp).

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I. Introduction

A. Motivation

A ROBOT patient that can simulate the conditions of various patients is an important tool for training nursing students in correctly transferring patients. Through such simulations, nursing students can learn the appropriate way to handle patients with different ailments. In addition, practicing with a robot enables avoiding injuries and damages to an actual patient or a healthy person acting as a patient during training.

B. Background

However, current training methods in nursing education do not consider this. Nursing students generally practice the transfer skill on classmates or teachers acting as the patient [1]. Moreover, most of the time, the various symptoms of actual patients (e.g., paralysis) cannot be accurately imitated. Consequently, nursing education programs do not enable students to practice with different patients, and therefore, nursing students lack practical and clinical experience with various patients [2]. This increases the possibility of injuries in both patients and nurses in the hospital [3]–[6].

During patient transfer, the nurses must pay attention to the patient's trunk as well as the physical interactions between the nurse and patient. When transferring a patient, the trunk should be supported so that it is stable and straight in order to avoid it from accidentally falling down. Moreover, the weight of the trunk accounts for more than 50% of the patient's weight [7], which makes it difficult for the nurses to assist in movements involving the trunk. Hence, handling the trunk during the transfer requires essential skills.

C. Previous Studies

The recent developments in robotics have enabled building various medical training robots [8]–[22]. The upper limb robots described in [8]–[10] can simulate the behaviors of arms afflicted by spasticity and rigidity and are used to train physical therapists. In addition, the hand robot with fingers enables imitating contractures for neurological examination training [11]. Moreover, other limb robots, such as the knee joint robot, can simulate movement trouble, contractures, rigidity, and spasticity for training therapists [12]. In addition, some robots are used in diagnosis training for medical students, such as the prostate simulator robot imitating four different conditions:

normal state, prostatitis, symmetric inflammation, and carcinoma [13]. Another robot used for diagnosis training can reproduce 31 cardiac conditions with abnormal heart beats [14]. Other researchers have introduced robots for simulating patients with airway difficulties [15] and swallowing disorders to enable rehabilitation [16]. Kitagawa *et al*. constructed a robot with a humanlike structure that could imitate chaotic emotions for injection training [17] as well as a robot that simulates the oral cavity for clinical training for dentistry students [18]. In addition, both WABIAN-2R [19] and HRP-2 [20] are utilized to emulate walking disabilities in order to understand human disabilities. However, these robots still have some difficulties as regards their application in transfer training. Robots [8]–[16] without whole body structures are unable to reproduce the movements of a full body, such as mutual hugging and standing. The robots developed in [17]–[20] had four limbs and torso. However, they did not simulate the movements of the patient's trunk and the physical interactions between the trainee and the robot. Furthermore, the robots in [15]–[20] did not simulate the variability of the patients and the symptoms, which made it difficult for trainees to obtain the corresponding skills for handling different patients and made them inefficient in training.

In our previous work, we developed a robot patient that was only able to reproduce the movements of elderly people with weak muscle force [21]. However, the motion of the patient's trunk was not taken into account. The joints of robot's waist and hip were simplified as passive joints. Therefore, previous robot only can simulate one type of patient and cannot enable the nursing students to learn skills corresponding to patients with different symptoms.

D. Objective

Therefore, a robot that can imitate various patients for transfer training is an urgent need. This study used three categories of patients as imitation targets: patients with movements of paralysis, painful sensations and expression, and constraint of medical devices. The patients are described in detail in Section II.

The robot for training nurses in patient transfer must be able to do the following.

1) Reproduce the movements of various patients suffering from different symptoms during the transfer.
2) Simulate the movements of the patient's trunk including falling down and physical interactions between the patient and nurse.

Developing simpler mechanisms with diversification of functions and control methods, which enables simulating different patients and symptoms, is a challenge. Moreover, designing waist and hip joints equipped with compliance and force-sensing function is a challenge in simulating the patient's trunk and physical interactions. The physical interactions include the support provided by the nurse; therefore, a rigid joint cannot reproduce a human's flexibility, and the stiffness, support, and strength of the nurse will vary. Moreover, force sensing is required to detect the supporting force from the nurse.

To simulate the movements of the trunk and physical interactions, we aimed to develop waist and hip joints with a compliant unit. In addition, we proposed control methods to reproduce three categories of patients using only one robot patient. For controlling movements of paralysis, the parameters were tuned based on the clinic videos of patients.

In accordance with the previous studies [10], [16], [21], which aimed to reproduce the movements of an actual patient, the robot patient evaluation in this study focused on how the robot can simulate the actual patient's actions and whether the robot can be used in nursing education. Ensuring such applicability is essential before employing the robot in this field.

Because of individual differences among patients suffering from the same symptom, no individual can represent the standard patient. Therefore, it is difficult to evaluate the robot patient through direct comparison with patients. Thus, we examined whether the robot patient enables the trainees to practice the required transfer skills in the correct manner and simulates an actual patient. Accordingly, in the experiment, nursing teachers performed transfer trials with the developed robot patient and then evaluated the robot patients based on a checklist including the required skills and specific considerations during transfer.

In addition, the nursing teachers performed subjective evaluations of the robot's performance, learning effectiveness for trainee, and recommendations for training using the robot. Finally, hugging speed comparison evaluated whether the robot allows the nurse to reduce the assistance speed when transferring patients with painful sensations and expression.

The contributions of this study are summarized as follows.

1) The DoFs of patient were simplified and the robot was developed to simulate six different target patients.
2) The novel structure of compliant units were proposed pioneer to reproduce the trunk stiffnesses, paralysis falling down, and physical interaction with nurse.
3) The experiment was conducted with nurses and approved the training applicability of robot.

The remainder of this paper is organized as follows. The target patients are described in Section II, and the requirements of mechanisms are presented in Section III. Sections IV and V discuss the mechanical design and control methods. Section VI presents the experiments and results. Section VII discusses the findings of the study, and finally, Section VIII concludes this paper.

II. Target Patients

A. Actions in Patient Transfer

The main actions during patient transfer follow the same steps, although different patients have different behaviors. The steps of transfer are sitting on the bed, mutual hugging, standing up, pivot turning, sitting down, and sitting on the wheelchair, as shown in Fig. 1.

B. Target Patients

Based on a discussion with nursing teachers, three categories of patients were selected: 1) patients with movements of paral-

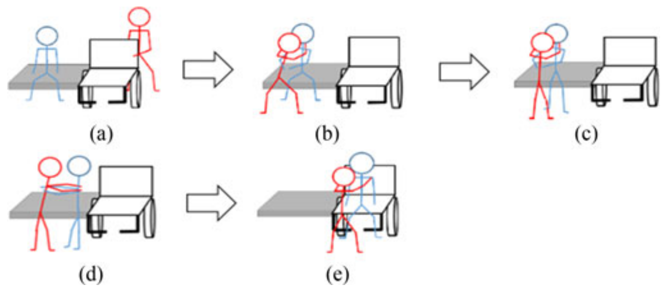

Fig. 1. Actions while transferring patients (a) sitting on the bed, (b) mutual hugging, (c) standing up, (d) pivot turning, and (e) sitting down on the wheelchair.

ysis; 2) painful sensations and expression; and 3) constraint of medical devices. Such patients are particularly challenging to transfer and nurses need extensive training to transfer such patients. However, current training methods that employ healthy people to act as patients are ineffective because the symptoms of patients cannot be simulated.

1) Movements of Paralysis: The first category of patients includes those suffering from paralysis, including hemiplegia and quadriplegia. Patients with hemiplegia are paralyzed in one side of the body [22], [23]. On the other hand, patients with quadriplegia lose control of all four limbs as well as the waist and the hip [22].

Patients with hemiplegia and quadriplegia exhibit distinctive behavior movements of the trunk falling down. Patients with hemiplegia fall toward the paralyzed side because they subconsciously place their weight in that direction [24]. Patients with quadriplegia fall forward/backward as well as in lateral directions owing to trunk instability. Most patients with hemiplegia can still properly sit despite being slanted, whereas patients with quadriplegia cannot maintain the sitting posture. Therefore, when transferring patients with quadriplegia, the nurse must first support the patient from the lying position to the sitting position, and then perform the transfer. In addition, the nurses must prevent the patient's trunk from falling down and keep the trunk balanced and stable during patient transfer.

The unstable movements of paralysis are difficult to simulate with healthy individuals because healthy individuals unconsciously exert force on the muscle in order to support and maintain the balance of postures, while these voluntary movements are different with paralysis that loses muscle control.

2) Painful Sensations and Expression of Injury: The patients in this category feel pain and express it when the movements involving the injured body part are too fast. In addition, verbal expression of the pain warns the nurse to slow down the assistance actions. Under this category, the target patient feels pain and verbally expresses regarding an injured arm. When dealing with patients with painful sensations, the nurse must be cautious regarding the injured body part and slow down the supporting and auxiliary actions.

The painful sensations are also challenging to simulate using healthy individuals because of difficulty in measuring the rotation speed of injured joints via muscles and nerves.

3) Constraint of Medical Devices: The patients in the third category are equipped with medical devices. Three specific devices are selected as our targets for imitation: 1) intravenous line; 2) arm sling; and 3) leg support brace. The patients' behaviors are restricted by the devices installed directly on their body; therefore, some movements cannot be performed. In addition, the patients with an arm sling or leg support brace also have painful sensations and express discomfort when the injured parts are moved too fast. These patients also cannot be imitated by healthy individuals for the same reasons as the previous two categories of patients.

III. Requirements and Specifications

A. Proposed System of the Robot Patient

The system represented a general process of behaviors. The behavior input can be a verbal phrase (e.g., command of "please sit down") or sensations of supporting force from nurses. The corresponding output was a verbal reply (e.g., painful expression) or a robot movement.

B. Height and Weight of Robot Patient

In developing the robot, the statistics of the Japanese adult female were referred to. The data showed that adult females in Japan have an average height of 158.7 cm and a weight of 50.7 kg [25]. In Japan, a patient with body size out of this range will be transferred by two nurses. The weight of the robot in this study was reduced to 60% of the adult female's average weight to avoid injuries, considering that the trainees might perform inappropriate operations during the transfer training.

C. Trunk With Waist and Hip Joints

1) Function Diversification: The hip and waist joints must be developed to reproduce the movements of the trunk. With the different target patients, the hip and waist joints should be able to simulate both abnormal and normal conditions. For example, the waist and hip joints simulate the unstable movements of paralysis, but when simulating patients with an arm sling, the waist joint reproduces the movement maintaining a healthy sitting posture.

2) Degree of Freedom (DoFs) and Range of Movement (ROM): Reproducing hundreds of human DoFs through mechanisms is difficult and complicated. Therefore, the first step should be to simplify the DoFs. For educational purposes, the DoFs were determined by the patient's behaviors, which enables the nurses to learn the required skills during transfers.

Following [26], the pivot turning of the transfer takes place on the nurse's foot while assisting the patient to turn from the bed to the wheelchair. However, the yaw rotation of the patient's waist is not possible during the turning because the nurses are mutually hugging with the patient and holding their pants, whose trunk leans upon the nurse.

The instability movements of the trunk caused by falling down are crucial behaviors that facilitate the trainees' learning of the supporting skill for paralysis patients. Clinic videos [27]–[29] showed that the falling down directions of the patient's trunk

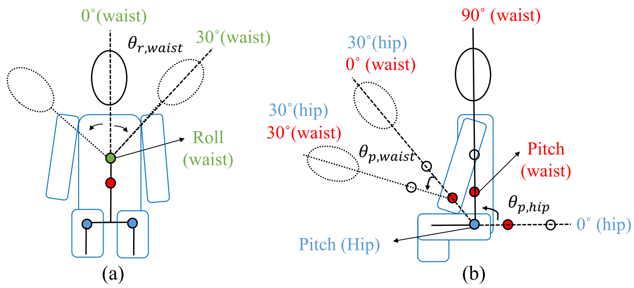

Fig. 2. ROM of waist and hip joints: (a) front view; and (b) side view.

are mainly pitch and roll rotations. The yaw rotation may also take place, but it does not lead to the falling down of the trunk. Therefore, this study did not consider yaw rotation.

In terms of the ROM, studies on the spine and orthopedics [30], [31] were referred to. Healthy people and paralysis patients have the same ROM with active and passive movements, respectively. Fig. 2(a) and (b) shows the ROM of the falling down movements toward the lateral, front, and back sides. In addition, during the falling down, the waist joint can passively bend forward, not backward, because of the loss of muscle control and the structure of spine.

3) Required Torque and Speed: The required torques were calculated based on the robot mass and ROM. The mass of the upper body was 12 kg for roll rotation, 14 kg for pitch rotation in the waist joint, and 16 kg for pitch rotation in the two hip joints. Accordingly, we obtained maximum required torques of 11.76 N·m at (±30°) for the roll rotation, 16.46 N·m at (+30°) for pitch rotation in the waist joint, and 47 N·m at (0°) for pitch rotation in the two hip joints.

The angular speed at which the lateral bending and forward/backward bending movements occurred was determined by referring to videos of paralyzed patients. The average angular speed of falling down was approximated at 10°/s in the roll axis of the waist joint, 10°/s in the pitch axis, and 20°/s in the hip joint.

4) Location of Rotation Center: The locations of the rotation center were designed based on the human anatomy [32]. The waist joint is located higher than the hip joint. In addition, there are five vertebrae in the lumbar, numbered from L5 to L1 from the bottom to top. The lower vertebrae, L4 and L5, have the largest ROM for flexion and extension bending, whereas L1 has the largest ROM for lateral bending [33]. As a result, the roll rotation was located higher than the pitch rotation in the waist joint, as shown in Fig. 3.

5) Stiffness of Inherent Compliance: As described before, the flexibility of the robot patient's trunk must be similar to that of humans. Therefore, the stiffnesses of the compliance of the hip and waist joints were determined based on previous research works [34], [35]. It has been shown that the passive stiffness is 120–150 N·m/rad for the bending of the waist and 100–110 N·m/rad for each hip joint. In addition, to simulate the instability during the sitting position of the trunk, the deflection angle of the compliant unit was determined to be 8°. The deflection angle allows 10-cm displacement of robot's head for lateral and forward/backward.

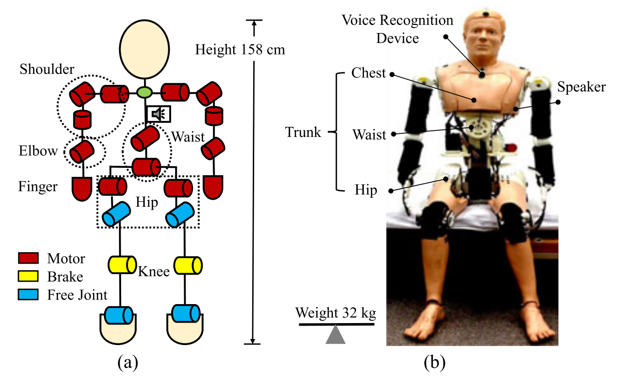

Fig. 3. Configuration of robot: (a) schematic drawing; and (b) actual picture.

6) Minimum Sensitivity Range of Torque Sensing: The nurses must support the patient's trunk to handle its paralysis movements, thereby leading to the gradual realignment of the truck to be straight. Based on clinical experience, the minimum supporting force of a nurse was approximately 0.5 kg on the trunk base, which the joints must be capable to detect. The distances from the robot's trunk to the roll and pitch of the waist were 0.5 and 0.56 m, respectively. The distance to the hip joints was 0.7 m. The calculation showed that the minimum range of sensitivity in the waist joint was 2.5 and 2.8 N·m for the roll and pitch rotations, respectively, and 3.5 N·m for the hip joints.

D. Upper and Lower Limbs

To reproduce the actions described in transfer, the robot must have fours limbs. The two arms enable to reproduce the mutual hugging with nurses, which are the robot's arms placed on nurses' shoulder. Whereas the two legs allow the nurses to learn how to adjust the lower body posture and assist patient to stand and sit. Moreover, the simulations of patients with medical devices require the fours limbs to equip. In addition, each joint of the four limbs must have speed-sensing functions in order to simulate painful sensations when the injured parts are moved too quickly.

IV. Mechanical Design

A. Weight and Configuration of Robot Patient

Fig. 3(a) and (b) shows the robot's weight and height according to the requirements. Some cavities were left on the robot's chest and limbs, such that the robot's weight could be adjusted in the future by placing weight units.

The joints configuration of the robot patient is shown in Fig. 3(a). The robot had shoulder, elbow, finger joints, hip, and knee joint. Moreover, a speaker to express painful sensations was installed on the chest. The used components are listed in Table I.

B. Trunk Design

Fig. 3(b) shows the developed trunk comprising a chest and waist and hip joints. In the waist joint, roll rotation was 60-mm

TABLE I
COMPONENTS LIST OF ROBOT

Components (Make, Model)	Location	Number
RC Motor (Futaba, RC405CB)	Arm joints	10
Servomotor (Moog Animatics, SM23165DT)	Hip/Waist joints	4
Harmonic driver (Harmonic, CSG-17-50-2UH/ CSD-20-100-2UP)	Hip/Waist joints	2/2
Electromagnetic brakes (Miki, 111-08-11)	Knee joints	2
Angular sensor (compliant unit) (Alps Electric, RDC506002A)	Arms/Hip/Waist joints	12
Speaker	Chest	1

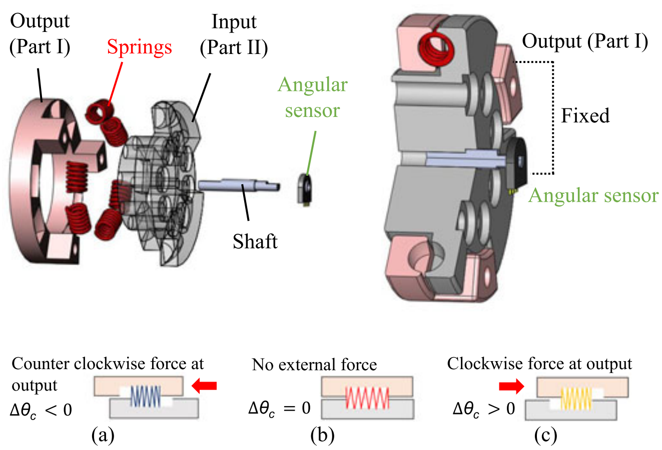

Fig. 4. Compliant unit: (a) explored view; (b) cross-sectional view; (c) spring with counter clockwise force; (d) without force; and (e) with clockwise force.

higher than the pitch rotation base on the ROM of the lumbar, and the hip joint was located below the waist joint. There are two DoFs of pitch and roll in the hip and waist joints. The compliant units were installed in the joints to achieve the requirements of compliance and force sensing.

C. Compliant Unit

Fig. 4(a) and (b) shows the proposed novel structure of the compliant unit used to reproduce the trunk stiffnesses and the interaction between the nurses and the patient. Each compliant unit has 8° deflection angle, which allowed the robot head to tilt forward and backward to 10 cm.

Compared to the proposed compliant unit with a conspicuous prior art [36], the novelty and difference of the old design were the spring installation. The previous design required the precompression of the spring with half-length while assembling into the compliant unit. The precompression decreased the compressible spring length. In contrast to that in the proposed compliant unit, the springs were directly placed into the six recesses, thereby enabling the springs to have more length for compression and providing the compliant unit with a larger deflection angle. In addition, no matter in which deflecting direction, all the springs were compressed to provide torque [see Fig. 4(c) and (e)], whereas in the former structure, only half of spring can be contracted in single direction. Accordingly, under the same condition of deflection angle and springs, the resistance torque of the proposed compliant unit can be about four times than the former one. In other words, the new structure makes it possible to apply much smaller spring and make the compliant unit be more compact.

The compliant unit was installed in the roll/pitch rotations in the waist and in the pitch rotation in the hip joints. It comprised springs, circle parts I and II, a shaft, and an angular sensor. Part I is the output and part II is the input of the compliant unit. The springs were placed on the recesses of parts I and II. An angular sensor was fixed on part I. A shaft was inserted into part II and the other side was fitted into the angular sensor, enabling the sensor to measure the difference between the angles of the input and output of the compliant unit.

If there is no external force on the output, the deflection angle will remain at zero, indicating that there is no spring compression [see Fig. 4(d)]. On the contrary, if external force exists on the output, then the springs will be compressed and deflection angle will not be zero anymore, as shown in Fig. 4(c) and (e). With the data of deflection angle, the external force can be computed by the following equation:

$$T_c = \theta_c \cdot k_c. \tag{1}$$

Here, T_c is the torque computed by the compliant unit, θ_c is the difference between the angles of the input and output, and k_c is the coefficient of elasticity.

The stiffness of the compliant unit was determined from the number of springs, elasticity coefficient of springs, and the distance from the rotation center to the spring. Consequently, the stiffnesses of the pitch and roll of the waist were 146.1 N·m/rad, comprising six constant springs (29.008 N/mm) 7.55 mm in diameter and 11.6 mm in length. The pitch of the hip was 111.72 N·m/rad, comprising eight constant springs (19.11 N/mm) 11.6 mm in diameter and 18.5 mm in length.

The stiffness was confirmed through an experiment. The experimental method involved exerting a variable torque that ranged from 0 to 30 N·m on the compliant unit. The detected stiffnesses were 130.96 N·m/rad for the pitch/roll of the waist and 103.57 N·m/rad for the pitch of the hip. The results were slightly less than the theoretical values because of the friction inside the compliant joint. However, the values still satisfied the stiffness requirement.

D. Mechanical Design of Waist Joint

The mechanical design of the waist joint is shown in Fig. 5. Two DoFs of the waist joint were developed to simulate the trunk's lateral movements and forward/backward bending.

A servomotor (Moog, Animatics Company Ltd.) was combined with a harmonic driver (ratio 100:1) to achieve the required torque. In addition, a supporting shaft was installed to decrease the shear force on the motors caused by the weight of the robot's upper body.

The motor for roll rotation was installed in the middle owing to the lack of space in the waist joint, whereas the motor for pitch

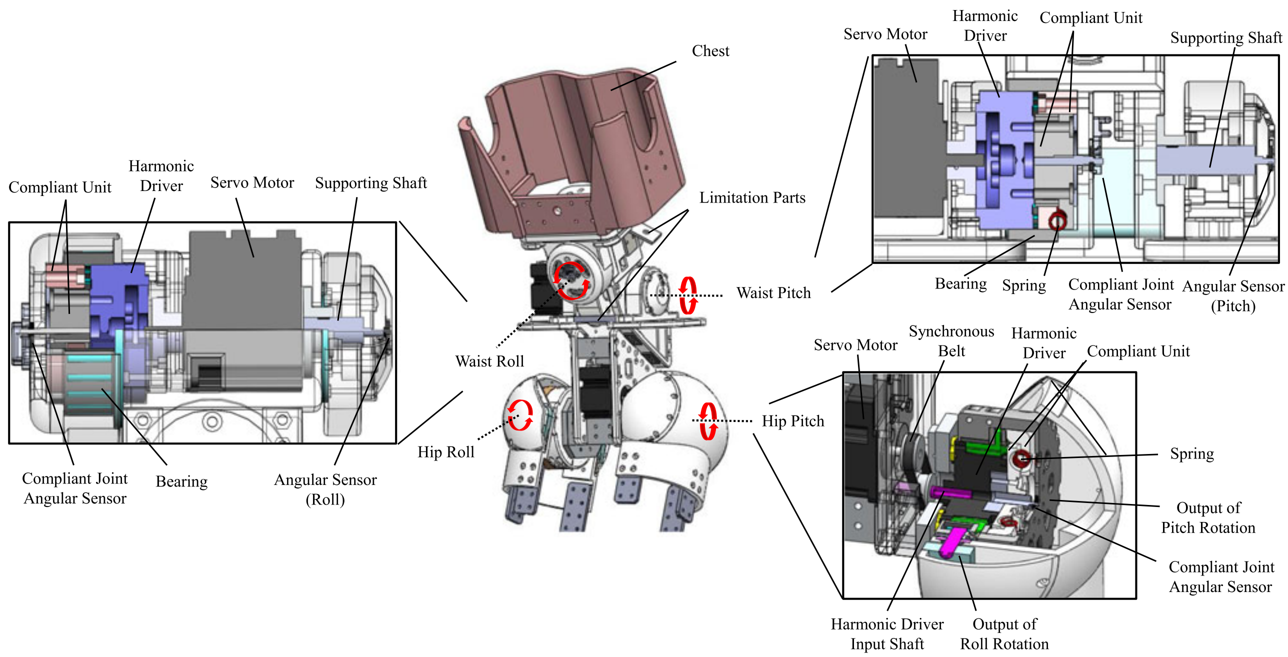

Fig. 5. Three-dimensional drawing of proposed mechanical design of trunk with waist and hip joints.

TABLE II
SPECIFICATIONS OF WAIST AND HIP JOINTS

Items	Descriptions
Range of movement	Waist: Roll (−30°, +30°); Pitch (−25°, +30°) Hip: Pitch (0°,+120°)
Required torque	Waist: Roll 50 N·m; Pitch 50 N·m Hip: Pitch 25 N·m (each joint)
Rotation speed	Waist: Roll/Pitch 52 r/min Hip: Pitch 104 r/min
Location of rotation center	Roll rotation higher than pitch 60 mm (waist)
Minimum sensitivity range of torque sensing	Waist: Pitch 2.01 N·m; Roll 2.01 N·m Hip: 1.595 N·m (each hip joint)
Stiffness	Waist: Pitch 146.1 N·m/rad; Roll 146.1 Nm/rad Hip: 111.72 N·m/rad (each joint)

rotation was placed on the right side to decrease the distance between the centers of the pitch and the roll rotations.

To reproduce the inherent compliance as human flexibility, the compliant units were installed. Part II of the compliant joint was connected to the harmonic driver, and part I was connected to the output of the joint. To eliminate the effect of friction, the compliant unit was fitted into a bearing, as shown in Fig. 5.

Angular sensors were installed at the end of the joints to detect the trunk position. Based on the angular data, we can control the motions and postures. Furthermore, limitation parts were designed with a specific angle to restrict the ROM and were assembled with the joints, as shown in Fig. 5. The final specifications are presented in Table II.

E. Mechanical Design of Hip Joint

The hip joint's hardware components are shown in Fig. 5. To simulate the actions of the trunk and lower limbs described in Section II, each hip joint of the robot consisted of two DoFs, a pitch, and a roll. Pitch rotation enabled the robot patient to simulate healthy movements of maintaining the sitting position and the paralysis movements of the trunk falling forward/backward when acting as a patient with quadriplegia sitting on the bed. Moreover, the pitch rotation allows the robot patient's lower limbs to simulate the standing up and sitting down actions with the assistance of the nurse.

In the mechanical design of the pitch rotation, the synchronous belt transits the rotation from the motor to the input shaft connected to the harmonic driver. A combination of the servomotor and harmonic driver (ratio 50:1) was employed to meet the requirements. The compliant unit was also installed with the same assembly method as the waist joint in order to reproduce the flexibility of a human. In addition, the roll rotation was designed orthogonal to the pitch rotation. Roll rotation reproduced the passive adjustments of the sitting posture by the nurses; thus, a free rotation joint without a motor was developed.

V. CONTROL METHOD

A. Control Method for Hemiplegia Instability

The movements of falling down to the paralyzed side (left side) were reproduced through the roll rotation of the waist joint, and the control algorithm is presented in Fig. 6. The first step of the algorithm is force sensing through the compliant unit.

Because of the friction caused by the harmonic driver, if the motor itself does not rotate, the trunk cannot smoothly follow the force despite the nurses supporting the trunk, as in the case of patients with paralysis who lose muscle control. Therefore, if the force is detected, the motor will rotate, making the trunk gradually follow the force. In addition, the rotation speed and relative position of the motor are proportional to the deflection

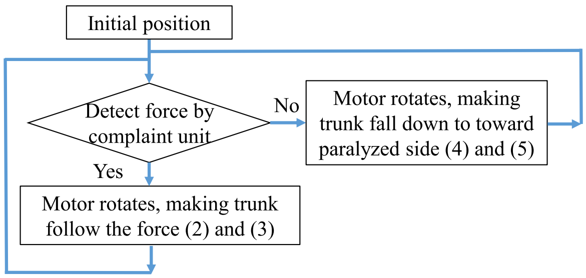

Fig. 6. Algorithm of roll rotation in the waist joint simulating the unstable movements of a hemiplegic trunk.

angle, as shown in the following equations:

$$\dot{\theta}_{\text{motor}} = \theta_c \cdot k_v \tag{2}$$

$$\theta_{\text{rp,motor}} = \theta_c \cdot k_{\text{rp}} \tag{3}$$

where θ_c is the deflection angle of the compliant unit caused by the external force, $\dot{\theta}_{\text{motor}}$ and $\theta_{\text{rp,motor}}$ are the rotation speed and the relative position of the motor, respectively, and k_v and k_{rp} are constants. Therefore, a larger θ_c caused by a larger supporting force leads to a faster motor rotation. Moreover, the rotation direction depends on the force direction.

In contrast, the trunk should fall down toward the paralyzed side if no force is detected by the compliant unit. Therefore, the motor was given an initial falling down command in (4) and (5), causing the trunk to start falling down toward the paralyzed side

$$\dot{\theta}_{\text{motor}} = kp_v \tag{4}$$

$$\theta_{\text{rp,motor}} = kp_{\text{rp}}. \tag{5}$$

Here, kp_v and kp_{rp} are the constants to control the falling down speed and relative position of the motor, respectively.

For free-falling objects, the falling down speed will increase along with time because of gravity. The same situation of the trunk's falling down movements can be reproduced using (2) and (3). The torque on the hip will increase when the trunk falls down, thereby causing θ_c to become larger. Consequently, the falling down velocity (2) and the relative position (3) increase with the falling down process.

B. Control Method for Quadriplegia

Since the action of the trunk falling forward/backward comprises the movement of the pitch rotations in the waist and hip joints, the rotation speed and position of both joints should be controlled. The roll rotation in the waist joint reproduced falling down in the lateral direction. Therefore, the control method was divided into two parts: pitch and roll rotations in hip joints, and roll rotation in waist joint.

The control method for pitch rotation is shown in Fig. 7. If the force is detected, the hip joint will rotate following the force, as in (2) and (3). In contrast, if there is no force detected by the compliant unit, the motor will rotate depending on the trunk's position. For example, if the trunk is slanting toward the front side (hip > 90°), the motors of the hip joint will rotate, leading the trunk to fall toward the front side as in (4) and (5).

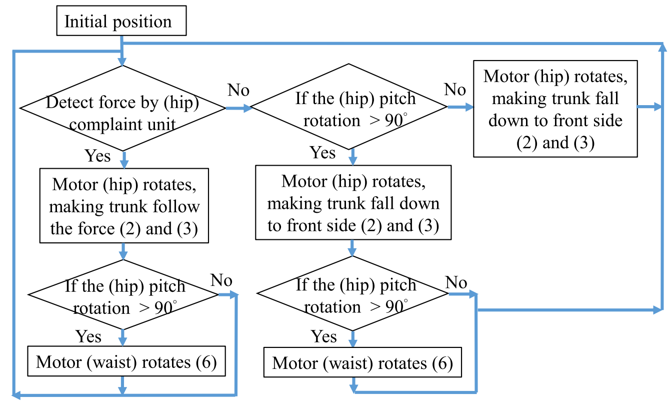

Fig. 7. Algorithm of pitch rotation in waist and hip joints simulating the unstable movements of a quadriplegic trunk.

The analysis results of the lumbar spine and the hip during forward bending [37] showed that the ratio of the lumbar to the hip (L/H) was variable, depending on the bending angle. The L/H flexion ratio range during the last period of bending was 0.37. With regard to the individual difference and control method simplification, the relation of the hip and the waist joint was determined to show an interlocking given as follows:

$$\theta_{p,\text{waist}} = (\theta_{p,\text{hip}} - 90^\circ) \cdot 1/3. \tag{6}$$

The second part of the control method is roll rotation in the waist joint, and it follows the same algorithm as pitch rotation in the hip joint. If the compliant unit does not detect the force, the motor will rotate depending on the waist angle (i.e., if the trunk slants toward left side, the motor will rotate, making the trunk fall down toward the left side). In contrast, if the force exists, the motor will rotate, leading the trunk to follow the force.

C. Parameter Tuning and Setting

The velocities of k_v and kp_v, were tuned by the falling down speed in the videos. As regards the relative position of k_{rp} and kp_{rp}, the larger values increased the responding time of force sensing and caused trunk vibration, whereas the smaller values led the trunk to follow the external force slower than usual. The k_{rp} and kp_{rp} parameters were determined before the experiment by the nursing teachers' clinical experience. The robot patient simulations were then recorded and compared with the actual patient's videos after the tuning. The experimental pictures and results are shown in Fig. 8.(a)–(d). However, in the videos, actual patient was not allowed to completely fall down due to safety concern. Therefore, the nurse starts to support them once their bodies tilt to a dangerous position. Thus, only the partial video without the nurse's support of the patient was compared.

Accordingly, pictures were extracted from the videos per 0.5 s. The "IC measure" software was employed to compute the angle of the hip and waist joints with tolerance at approximately 1°.

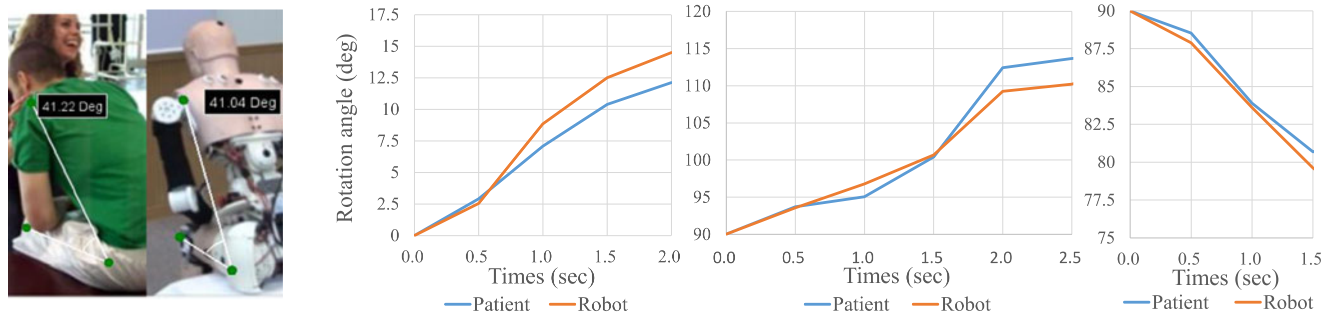

Fig. 8. (a) Comparison between patient and robot (b) falling down toward the left side as a result of hemiplegia with roll rotation in the waist joint, and (c) falling down toward the front side owing to quadriplegia, and (d) pitch rotation angle of hip joint while falling backward.

D. Painful Sensations and Expression

Painful sensations and expression are required for patients with an injured arm, an arm sling, or a support brace leg. The first step of the algorithm is detecting the speeds of the joints. If the speed is greater than the threshold, the speaker will say "it hurts." For the patients with an injured arm and an arm sling, the rotation speed of the shoulder and elbow joints were measured. The threshold was $\dot{\theta} > 10°/s$ for an injured arm and $\dot{\theta} > 0°/s$ for an arm sling. In the patient with a leg support brace, the rotation speed of the hip and knee joints were detected with thresholds of $\dot{\theta} > 15°/s$ and $\dot{\theta} > 0°/s$, respectively. Due to individual difference of patients, the pains may cause by different directions and speeds of movements. However, in this study, the pains of injured leg were defined as pitch rotation of hip, which potentially occurs with large ROM during the transfer and cause pain frequently.

E. Control Method of the Upper and Lower Limbs

The arm and knee joints were set in "torque off" mode to simulate the loss of muscle function due to paralysis. In this mode, the motors were turned off and can be freely rotated by external force. Accordingly, the injured arms and legs were unable to perform any active behavior with painful sensation and expression. Hence, the motors for the joints representing the injuries were set to the "sensing mode," which detected the angular speed.

As for the healthy limbs (e.g., limbs of nonparalyzed side of hemiplegia) that were not affected by the abovementioned symptoms, both arms moved to the designated postures controlled by the motor position and performed the hugging posture with the nurses. Furthermore, the electromagnetic brakes of the knee joints were turned on after the leg completely strengthened, thereby reproducing the standing movement.

VI. Experiment

A. Purpose

For a robot patient simulating different patients and being applied to transfer training, there are two important points.

1) Can the robot patient enable the nurse to practice the skills required to transfer an actual patient?

Fig. 9. Patient transfer trial.

2) Subjective evaluation of the robot patient by nursing teachers, including reproducibility of the robot, learning effectiveness of the trainee, and recommendation of the robot for training.

B. Participants

The sample size of the experiment was determined by referring to several former studies [10], [21] related to the robots in nursing training. Four nursing teachers with up to ten years of experience in nursing education were invited. Three of them participated in the transfer trials and one of them participated an evaluation of checklist. The protocol was approved by the local ethics committee. All subjects were informed about the purpose of the study and written informed consent was obtained prior to the study.

C. Procedure

First, the nurses were informed in advance of the type of patients and the painful limb. This situation is the same as that in hospitals, where the nurses have preknowledge about their patients. Then three nursing teachers were requested to perform at least one trial of transferring the robot patients from a bed to a wheelchair [see Fig. 9]; the trials were shot by cameras. After performing the trials, the three nursing teachers answered a questionnaire about their experience and their suggestions based on the trials. The fourth teacher, who did not perform the

TABLE III
CHECKLIST RESULTS

Checkpoints and description	Ratios
Intravenous line	
Move the drip infusion to the wheelchair in advance	(6/6)
When moving the drip infusion, prevent accidental removal	(6/6)
Clear obstacles between the bed and wheelchair and avoid any interferences	(6/6)
Move the drip infusion to the wheelchair; it should be placed on the side where the patient is equipped with the drip infusion	(6/6)
Painful sensations and expression of injured arm	
Slowly assist and support the patient when hugging mutually	(3/5)
Avoid putting too much strain on the arm	(5/5)
Avoid quick actions that will hurt the patient	(3/5)
Arm sling	
Do not try to straighten the injured arm	(6/6)
Avoid moving the injured part tied with the sling	(6/6)
Avoid pushing and suppressing the nurse's chest on the sling tied to the patient's injured arm	(6/6)
Leg support brace	
Place the wheelchair on the side of the patient's healthy leg	(6/6)
Pivot turn using the healthy leg of the patient	(6/6)
Do not strain or put stress on injured leg	(2/6)
Hemiplegia	
Place the wheelchair on the nonparalyzed side	(5/5)
Keep supporting the patient's trunk to prevent it from falling down	$*$(5/5)
Assist the patient to stand and turn using the nonparalyzed leg	(5/5)
Ensure the nonparalyzed leg stretches correctly and avoid spraining the knee during pivot turning	(5/5)
Quadriplegia	
Support the patient from the lying on the bed position to the sitting position	(3/3)
Keep supporting the patient's trunk and prevent it from falling down	$*$(3/3)
Support the entire weight of the patient during the transfer	(3/3)

"$*$" The nursing teachers performed the action but did not support the correct area.

TABLE IV
QUESTIONNAIRE RESULTS

Question and Description	Average/SD
Intravenous line	
Reproducibility of patient with intravenous line	3.67/1.52
Learning effectiveness for the nurse	4.00/1.00
Recommended for training students with robot patient	3.67/1.15
Painful sensations in injured arm	
Painful expression of injured arm at the proper timing	3.67/1.15
Learning effectiveness for the nurse	4.33/0.58
Recommended for training students with robot patient	4.66/0.58
Injured arm sling	
Reproducibility of patient with sling	4.66/0.58
Painful expression of injured arm at the proper timing	4.00/0.00
Learning effectiveness for the nurse	4.00/1.00
Recommended for training the students with robot patient	4.00/1.00
Leg support brace	
Reproducibility of pivot turning by using healthy leg	3.33/0.58
Painful expression of injured leg at the proper timing	4.33/0.58
Learning effectiveness for the nurse	4.33/0.58
Recommended for training students with robot patient	4.33/0.58
Hemiplegia	
Reproducibility of paralyzed trunk falling toward paralyzed side	4.66/0.58
Reproducibility of paralysis arm during mutual hugging	3.67/1.15
Reproducibility of paralysis leg during standing	3.00/1.00
Learning effectiveness for the nurse	5.00/0.00
Recommended for training students with robot patient	5.00/0.00
Quadriplegia	
Reproducibility of patient being supported from the lying position to the sitting position	3.00/1.73
Reproducibility of paralyzed trunk falling down	4.00/1.00
Reproducibility of paralyzed arms during mutual hugging	3.67/1.52
Reproducibility of paralyzed legs while standing	3.00/2.00
Learning effectiveness for the nurse	4.33/1.15
Recommended for training students with robot patient	3.33/1.52

transfer trial, reviewed the videos of the trials performed by the other three teachers and evaluated these trials on the basis of a checklist.

D. Evaluation Methods

1) Nurse Checklist: Because of individual differences among patients, an evaluation by directly comparing with patients would be ambiguous due to no specific patient can be taken as standard to be compared. Accordingly, based on the developed checklist, we verified whether the robot allowed the nursing teachers to utilize the correct method to transfer the robot patient, as they would transfer an actual patient. The checklist was developed based on previous studies [38]–[48] and the clinical experience of the nursing teachers. Consequently, there are 20 important checkpoints, as presented in Table III. Each type of patient has three to five checkpoints that represent correct ways to handle the corresponding symptoms during transfer.

2) Questionnaire: To assess the reproducibility of the robot patient, we referred to the questionnaire evaluation method in a previous study [9]. The nursing teacher evaluated the reproducibility, learning effectiveness for trainee, and recommendation for training, as shown in Table IV. Reproducibility was evaluated based on whether the specific behaviors or symptoms were appropriately simulated. All questions were answered using a five-point Likert scale, in which the items were ranked from 1 (strongly disagree) to 5 (strongly agree).

3) Hugging Speed Comparison: To evaluate whether the painful sensations and expression (i.e., speaking "I am hurt") can make the nurses slow down the assistance speed, we compared the hugging action in the trials using the injured arm with painful sensations and expression and those without painful expression. Therefore, we selected a patient with a leg support brace as the control subject because this type of patient has a healthy arm without painful expression. The angular speed of the pitch rotation in the robot's shoulder was measured during the hugging action because this rotation involves the largest ROM of the hugging action.

E. Results

Table III shows the checklist ratios. The numerator represents the number of trials that completed the checkpoint, whereas the denominator denotes the number of total trials. In addition, different types of patients have different numbers of total trials. The nursing teachers conducted fewer trials (at least one trial) for

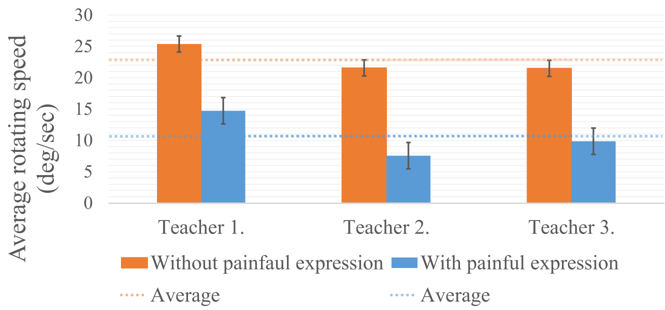

Fig. 10. Average rotation speed of robot's shoulder during mutual hugging.

the types of patients with heavy physical loading and demand a longer time for transfer. In Table IV, the results of the questionnaire with the average scores of the three nursing teachers are presented. The results of speed comparison during the mutual hugging are shown in Fig. 10.

VII. Discussion

The results of the checklist shows that the required skills can be carried out with an 85% achievement rate (among 20 checkpoints, 17 points were completed). This reveals that the robot patient can be employed in training nurses because during the experiment, the test subjects transferred the robot in the correct manner, just as they would transfer actual patients.

The checkpoints "slowly assist and support the patient when hugging mutually" and "avoid quick actions that will hurt the patient" were completed with a ratio of only 3/5. However, the first teacher see Fig. 10] performed both these trials. The first teacher assisted the robot patient in rotating the shoulder joint to perform the hugging action at a speed at 15°/s, whereas the other two teachers performed this at a speed lower than 15°/s. Although the degrees of decreasing the speeds varied among the teachers, the results in Fig. 10 still show that the expression of hurt facilitated the nurses in reducing the assistance speed.

The checkpoint "do not strain or put stress on the injured leg" was completed in only a few trials. This may be explained by the fact that it is difficult to avoid putting stress on the injured leg because this leg was fixed with the supporting brace, which makes the leg straight and easier to touch with the ground.

The other checkpoint "keep supporting the patient's trunk to prevent it from falling down" was performed but not in the appropriate way. The reviewer mentioned that "ideally, a nurse usually supports the patient's trunk, but the robot's trunk was only built with mechanisms and lacked the original shape of a human trunk; therefore, the three nursing teachers were supporting more like a scapula area." This could be a constructive suggestion for improving the hardware.

The item "reproducibility of patient being supported from lying position to the sitting position" obtained comparatively low points. The first step in correctly handling a paralysis patient who is lying in bed is to support the patient from the lying to the sitting position, then turning the patient 90°, which allows him/her to sit on the edge of the bed with his/her legs bended. However, this experiment skipped the step of turning the patient's direction because this skill was beyond the scope of this study, thereby causing the difference between the stander operating processes.

The questionnaire results revealed that the nursing teachers approved the robot patient's performance. Hence, the simplified design, DoFs, and control method of the robot patient were properly considered. Here, we first focused on the items related to the main contributions of the hip and waist joints. The unstable movements of the trunk of patients with hemiplegia and quadriplegia obtained scores of 4.66 and 4.0 points, respectively. Some comments were given to explain the consent of simulations as follows. First, the trunk smoothly following the supporting force reproduced the reaction of a trunk being supported, and second, the following speed of the trunk varied according to the supporting force magnitude. Those two points make the teacher consider the robot react more like actual patient and also reveals that the mechanical design and control method enable appropriately reproducing the symptom. Moreover, the checklist results showed that the robot enabled the nursing teachers to perform the required skills even if the yaw rotation was not reproduced.

In addition, the reproducibility of "painful expression at the proper timing" received 3.66 for the injured arm, 4.0 for the arm sling, and 4.33 for the leg support brace. The comparatively lower score of 3.66 may be because the arms with four DoFs formed a wide range of postures; therefore, we should also consider the posture with a specific angle that would cause pain to the patient. However, according to the comments of the nursing teachers, the painful expression makes the robot patient more similar to an actual patient.

In the teachers' subjective evaluation of the learning effectiveness for the student, all six patients were scored with above four points. Moreover, the teachers recommended training the students using the robot patient and scored it with more than four points, except for intravenous line and quadriplegia marked at 3.66 and 3.33, respectively. The teachers explained that when handling patients with quadriplegia, they usually transfer the patient using an apparatus such as a lift or the cooperation of two nurses because of concerns regarding the disability and safety of the patient. For the intravenous line, care must be taken to not remove the needle from the patient's vein. However, the robot patient was fixed with the intravenous line via tapes and hence could not simulate the conditions of an actual patient.

Reviewing the proposed robot with a small scale (i.e., 32 kg), it is difficult to say that the weight was optimal for training. However, the questionnaire results revealed that the nursing teachers approved the learning effectiveness and intend to recommend the robot to the students. Hence, implicating the robot weight was considered acceptable for training.

VIII. Conclusion

A robot that can reproduce three patient categories was developed herein to provide student assessment toward different patients. This robot enabled the students to learn the corresponding transfer skills. The categories included patients with movements of paralysis, painful sensations and expression, and constraint of medical devices. Experienced nursing teachers performed trials using the developed robot patient. Evaluations were performed based on a checklist questionnaire and hugging speed comparison. The results are summarized as follows.

1) The checklist results revealed that during the transfer involving the robot patient, the test subjects could perform the skills required for transferring an actual patient with 85% achievement rate.
2) The questionnaire results showed that the proposed method that used compliant unit to simulate the trunk instability of paralysis patients obtained approval from nursing teachers.
3) The hugging speed comparison showed that the painful expression enabled the slowing down of the nurses' assistance speed.

The training effectiveness of a nursing student by practicing with the robot patient will be examined in future work. We also aim to increase the types of patients, different affectation or symptom levels, and variations of weight and height in our future studies. Moreover, we intend to extend the range of applications in the manual handling of patients, such as changing dressing.

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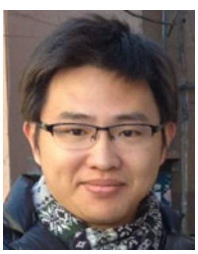

Zhifeng Huang received the B.Eng. degree in mechatronics engineering from the South China University of Technology, Guangzhou, China, in 2007; the M.Eng. degree in mechatronics engineering from the Harbin Institute of Technology, Harbin, China, in 2010; and the Ph.D. degree in precision engineering from the Department of Precision Engineering, University of Tokyo, Tokyo, Japan, in 2014.

He is currently a Lecturer with the School of Automation, Guangdong University of Technology, Guangzhou, China. His research interests include nursing engineering, skill acquisition, and healthcare robotics.

Chingszu Lin received the B.Eng. degree in mechanical and electromechanical engineering from National Sun Yat-sen University, Kaohsiung, Taiwan, in 2012. He is currently working toward the M.E. degree in precision engineering with the Department of Precision Engineering, University of Tokyo, Tokyo, Japan.

His research interests include robot patients and humanoid robots.

Masako Kanai-Pak received the B.S.N. degree from Southern Oregon State College, Ashland, OR, USA; the M.S.N. degree from the University of Hawaii, Honolulu, HI, USA; and the Ph.D. degree from the University of Arizona, Tucson, AZ, USA, in 1985, 1988, and 2009, respectively, all in nursing.

She is currently the first Vice President of the International Council of Nurses, Geneva, Switzerland. Her research interests include work empowerment and leadership.

Jukai Maeda received the Ph.D. degree in nursing from the Nagano College of Nursing, Komagane, Japan, in 2004, and the Registered Nurse license from the University of Tokyo, Tokyo, Japan. After graduation, he was at Sony Corporation, Tokyo for five years as an Accountant and thereafter returned to the nursing world. He was at the Nagano College of Nursing for 14 years as an Educator. Since 2009, he has been a Professor with the Tokyo Ariake University of Medical and Health Sciences, Tokyo. His research current research focuses on information processing in nursing.

Yasuko Kitajima received the bachelor’s degree from Senshu University, Tokyo, Japan; the master’s degree from Saitama University, Saitama, Japan; and the doctoral degree from the Graduate School of Economic Science, Saitama University, in 1999, 2002, and 2013, respectively, all in economics. She also holds a nursing qualification.

She teaches adult nursing with the Tokyo Ariake University of Medical and Health Sciences, Tokyo.

Dr. Kitajima is licensed as an Emergency Life-Saving Technician in Japan.

Mitsuhiro Nakamura received the B.S.N. and M.S.N. degrees in nursing from the Nagano College of Nursing, Komagane, Japan, in 2000 and 2006, respectively.

He is currently a Faculty Member with the Tokyo Ariake University of Medical and Health Sciences, Tokyo, Japan . His research interests include nursing ethics and fundamental nursing.

Noriaki Kuwahara received the Ph.D. degree in engineering from the University of Tokyo, Tokyo, Japan, in 1997.

In 1987, he joined Sumitomo Electric Industry, Ltd., Osaka, Japan, and, in 1993, ATR Communication System Labs., Kyoto, Japan. Since 2007, he has been an Associate Professor with the Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto, Japan.

Prof. Kuwahara is a member of the Human Interface Society of Japan, the Japan Ergonomics Society, and the Institute of Image Information and Television Engineers.

Taiki Ogata received the B.Eng. and M.Eng. degrees in precision engineering, and the Ph.D. degree in psychology from the University of Tokyo, Tokyo, Japan, in 2004, 2006, and 2009, respectively.

He is currently a Research Associate with Research into Artifacts, Center for Engineering, University of Tokyo. From 2009 to 2011, he was a Project Researcher in the Intelligent Modeling Laboratory, University of Tokyo. His research interests include temporal cocreation between people, human communication, human interface, and human cognition.

Dr. Ogata is a member of the Society of Instrument and Control Engineers and the Japan Society for Precision Engineering.

Jun Ota received the B.Eng., M.Eng., and Ph.D. degrees in precision engineering from the Faculty of Engineering, University of Tokyo, Tokyo, Japan, in 1987, 1989, and 1994, respectively.

Since 2009, has been a Professor with Research into Artifacts, Center for Engineering, University of Tokyo. From 1989 to 1991, he was at Nippon Steel Corporation, Tokyo. In 1991, he became a Research Associate at the University of Tokyo, and became an Associate Professor in 1996. His research interests include multiagent robot systems, design support for large-scale production/material handling systems, embodied-brain systems science, human behavior analysis, and support.