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Letter:

Development of Transfer-Assisting Robot System Using Posture-Supporting Wear and Support Robot

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When assisting a care receiver to transfer from one plane to another, a caregiver needs to hold up and move him/her. As a caregiver has to support the weight of one person, transfer assistance imposes a heavy physical burden on the caregiver. Particularly, in Japan, with an increasing elderly population and a decreasing young population, there are a few caregivers to assist numerous care receivers to transfer. In this scenario, it is an extremely vital issue to develop methods to reduce the burden of the caregivers when assisting care receivers to transfer. In this study, by focusing on the clothes that care receivers wear, we developed a transfer-assisting robot system by combining a dedicated posture-supporting wear and a mobile robot based on a lift mechanism.

Keywords: wheelchair, transfer, functional wear, lift, omni-wheel

1. Introduction

Transferring refers to the motions of transferring from one plane to another in sitting or supine postures without changing the basic body posture, as in the case of moving sideways on a bench or moving from a bed to a chair [a]. In transferring a care receiver in a wheelchair, a caregiver needs to hold him/her up in a sitting posture, support his/her weight, and transfer him/her to a destination while maintaining the sitting posture at the destination also. Therefore, transfer assistance imposes the heaviest physical burden in caregiving work on caregivers, and can cause them to suffer from chronic low back pain.

Concurrently, in Japan, with an increasingly aging population with a few children, the burden on caregivers or care persons is expected to increase accordingly. The Cabinet Office, Government of Japan estimates that in 2040, the elderly will account for approximately 35.3% of the total population in Japan [b]. Specifically, in Japan, one in three persons will become elderly, increasing the burden on the caregivers or the care persons at care sites. In this view, transfer assistance is considered one of the most critical caregiving issues to solve. In response to the need for assisting devices to reduce the physical burden in future transfer assistance, the Ministry of Health, Labour, and Welfare recommends simultaneously using a lift, a sliding board, and other devices in care work to prevent low back pain in caregivers [c]. In addition, various approaches for supporting nursing care services using robotics have already been launched. A robotic care equipment development and introduction support project was launched by the Ministry of Economy, Trade, and Industry in 2013 [d]. It specified transfer-assisting devices as a priority area in 2014 [e], on which research and development of transfer-assisting robots have been undertaken.

Transfer-assisting robots, which are specified as a priority area by the Ministry of Health, Labour, and Welfare and the Ministry of Economy, Trade, and Industry, are classified into the following two types. These are mounting type to power assist caregivers in transferring care receivers, and nonmounting type to power assist the motions of a caregiver in holding up a care receiver when transferring him/her [f]. An example of a mounting-type transfer-assisting robot is HAL of Cyberdyne Inc. [g], whose effectiveness has already been proven [1] and which has already been productized [h]. As another example, Borisoff et al. proposed a detachable exoskeleton-wheelchair, which is intended for rehabilitation purposes with power assist functions to assist the standing up and walking motions of a user and is mountable as well as deformable [2]. Nonmounting-type transfer-assisting robots that have previously been proposed include RATD [3, 4] with an arm-type lift installed on an electric wheelchair. It achieved better scores than the conventional lift type in transfer evaluations using a mannequin by the Usability Survey of Assisted Technology (USAT) and NASA-TLX, and has also been better accepted by users [5]. Mukai et al. proposed realizing transfer assistance using RIBA [6], a nursing care support robot having double arms and a force sensor, and proved its effectiveness. In another study, a transfer-assisting robot with a large hand as an end effector to assist a care receiver to transfer to a wheelchair in supine postures was developed [7]. In addition to the abovementioned examples, numerous companies have proposed nonmounting-type care support robots, which are expected to be productionized shortly [h]. LTAR [8], a wheelchair-type transfer-assisting robot has a seat that can be moved up and down to slide a user in the horizontal direction. It has high scores in terms of the functional independence measure, proving its capability to transfer a user more rapidly than ordinary wheelchairs [9]. A robotic bed, a part of which is separated and deformed into an electric wheelchair unit, which can move a user by changing him/her from a supine to sitting posture [10], is being aggressively developed. The development is based on its behavior and risk evaluation in moving from a bed unit to an indoor table [11]. Ichinotani et al. proposed a similar nursing care bed system in which a part of the bed is separated and deformed to act as an electric wheelchair unit [12].

Although the previously proposed transfer-assisting devices have achieved significant outcomes, a mounting type is difficult to mount, and in many cases, the nonmounting-type ones require the introduction of large-sized devices such as a dedicated wheelchair and a bed. In addition, this introduction is highly time-consuming.

Therefore, we studied building a robot system with a simple structure using wheelchairs and beds that have been used in caregiving sites with additional limited number of assisting devices. Particularly, in transferring a wheelchair user, because the user is in sitting postures at the start and end points of the transfer, a robot system should be able to hold up his/her weight as well as to place him/her in a sitting posture. If a wheelchair user could remain in a sitting posture from the start to end points of a transfer, any problem of placing him/her in a sitting posture at the transfer destination could be avoided. To maintain a care receiver in a sitting posture during a transfer, a robot system must employ belts for harnessing the receiver, e.g., in the case of transferring a care receiver using a lift. We considered that a marionette can adopt any arbitrary posture under an applied force by the threads connected to its limbs and that in breaking down the postures of an opponent in judo or aikido, forces are applied to his/her clothes, e.g., uniforms. Accordingly, we regarded clothes as a member to fix and support the weight and postures of a care receiver and added functions to enable the lifting device to be mounted and dismounted easily to solve the problems with lift-type devices. Moreover, fixing and supporting the postures of a care receiver with his/her clothes is considered effective for patients with paralyzed upper limbs. Therefore, in this study, we proposed a transfer-assisting method as well as developed a transfer-assisting system combining a dedicated wear to support the postures and weight of a care receiver and an omnidirectional mobile robot.

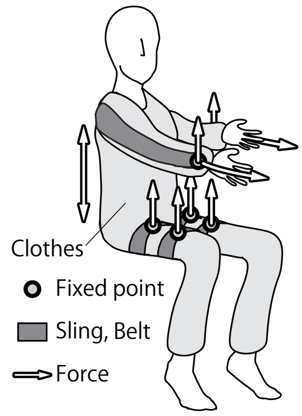


Fig. 1. Overview of posture-supporting functional wear.

2. Proposed Transfer Method

In this paper, considering that a care receiver is kept in his/her sitting posture from the start to end points of a transfer, we propose a method for a care receiver to maintain his/her sitting posture using dedicated clothes he/she wears. We assumed that arranging several fixed points on the surface of these clothes a care receiver wears enables him/her to maintain his/her sitting posture in air like a marionette. Therefore, in this study, we arranged the fixed points to apply pulling forces to the belts and slings on the four limbs of the connected care pajamas that covers his/her entire body (**Fig. 1**). The proposed transfer method using such a dedicated wear is assumed to be used for those who find it difficult to maintain their standing or sitting postures because of body muscle weakness due to neural malignant diseases or because of their severe paralysis due to cerebrovascular disorders.

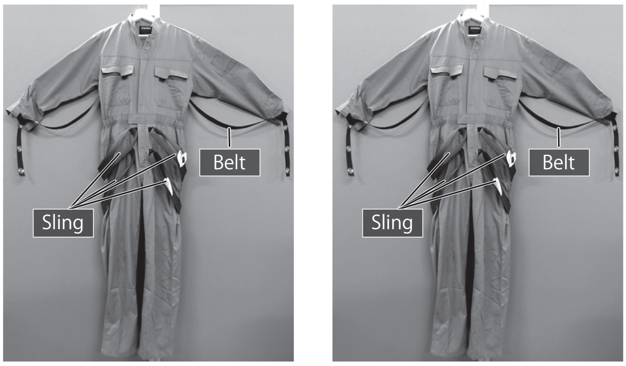
The dedicated clothes are modeled as a connected nightwear covering the entire body, which may not be highly common in caregiving sites. Because the upper and lower limbs are connected to each other by the fabric of the clothes, the postures of the upper limb can be maintained by the lower limb part pulling the upper limb part. Moreover, the designed dedicated clothes that cover the entire body, as shown in **Fig. 1**, have large areas in contact with the body surface. Therefore, it can disperse the forces to be applied in holding up a care receiver as well as reduce any pressing feelings or pains in holding up a care receiver.

In this study, we propose the following transfer procedure using a dedicated wear, as shown in **Fig. 1**, and a care robot with a moving mechanism.

(1) The caregiver operates the care robot to approach a wheelchair user wearing the dedicated wear in his/her sitting posture.

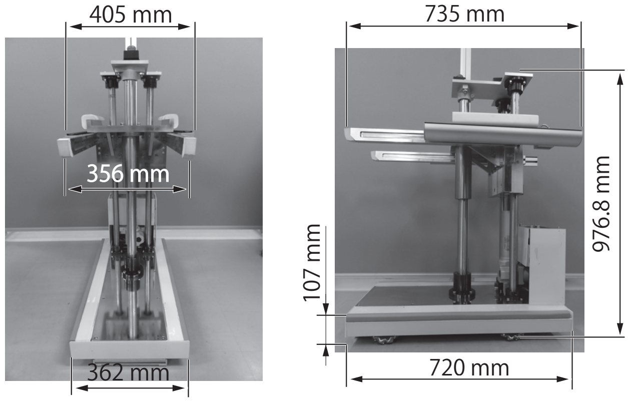
(2) The caregiver connects the lift of the care robot with the slings and belts attached to the dedicated wear of the care receiver.

(3) The caregiver raises the lift of the robot together with the wheelchair user wearing the dedicated wear.



(a) Front view (b) Rear view

Fig. 2. Posture-supporting functional wear.



(a) Front view (b) Side view

Fig. 3. Transfer-assisting robot.

(4) The caregiver operates the care robot to move it to a destination.

(5) The caregiver operates the care robot to lower the lift and seat the wheelchair user at the destination.

(6) The caregiver detaches the belts and slings of the dedicated wear worn by the care receiver fixed to the care robot.

(7) The caregiver operates the care robot to travel to move it away from the care receiver.

In this study, we developed a dedicated wear and a care robot to realize the above-mentioned transfer procedures.

3. Transfer-Assisting Robot System

3.1. Posture-Supporting Functional Wear

Figure 2 shows the posture-supporting functional wear developed in this study. The dedicated wear, similar in shape to a connected caregiving nightwear, is a cotton-blended connected wear (mixing rate: polyester 65%, cotton 35%; size: M; adaptive height: 160–168 cm; adaptive waist: 84–92 cm) with slings and belts arranged at fixed points to maintain the posture of the wearer. We adopted wide soft slings (withstanding load: 0.5 t) and sewed them directly on the femoral region of the connected lower limb part. This enabled the femoral region of the connected lower limb part to support the weight of a wheelchair user when the care support robot holds him/her up in a sitting posture. We used belts (withstanding load: 90 kg) for the upper limb part to support the upper limb postures of the user without excessively constraining him/her. The belts were passed through belt loops arranged on both arms and on the back of the connected upper limb part. We fitted brass grommets (inner diameter: 14.8 mm; outer diameter: 28 mm), three each at both ends of the belt near both arm wrists. The grommets arranged on the belt were used to fix the belt to the robot using hook-eye nuts.

3.2. Transfer-Assisting Robot

In this study, we developed a care support robot to transfer a care receiver wearing the developed posture-supporting functional wear (**Fig. 3**). Assuming that the care robot holds up a care receiver and transports him/her, we have adopted a forklift-type mechanism for a simple structure.

As the maximum moving speed of the transfer-assisting robot, 0.2 m/s was chosen from the traveling speeds of 0.2 m/s and 0.4 m/s used in [13]. Considering human emotions of fear for moving care robots, the chosen traveling speed would alleviate the fear and be safe in case of collisions or in its overturns. For easiness of handling in small Japanese houses, the moving mechanism of the robot is such that its carriage has mecanum wheels (manufactured by Chengdu Hangfa Robotics Co., Ltd.; maximum load: 30 kg; outer diameter: 101.6 mm) driven by four motors (rated voltage: 12 V; torque: 44.8 Nm) to realize its omnidirectional movements. Given that the distance between the bottom of the footrest of the wheelchair used in this study and the floor is 113 mm, we set the height of the top plate of the robot carriage above the floor at 107 mm to ensure the carriage could intrude under the wheelchair without needing to raise the foot pedals of the wheelchair.

We set the maximum loading capacity as 100 kg, which is approximately 1.5 times the average weight (approximately 65 kg) of the Japanese elderly aged 65 years and older. We selected the fork dimensions and lifting range of the robot by seating on the wheelchair (manufactured by Miki Corp.) 16 healthy adults (14 males; 2 females; average age: 23 years, SD 4.7; average height: 167 cm, SD 7.0). Subsequently, we measured the distance obtained by subtracting the buttock/abdominal thickness in the sitting posture from the buttock-knee length in the sitting posture. In addition, we measured the femoral height in the sitting posture. Based on the measurements, the maximum length of the femoral region was 460 mm, and the fork length was set as 500 mm. The fork, made of aluminum, has an I-type cross-sectional shape, as shown in **Fig. 4**. We selected the cross-sectional dimensions of

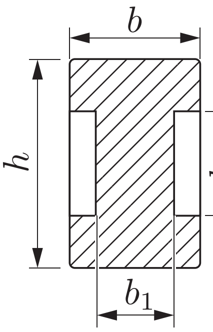


Fig. 4. Cross-section of fork.

Table 1. Design specifications of transfer-assisting robot.

Principal particulars	Numerical values
Maximum load capacity	100 kg
Maximum load to hold up	200 kg
Lifting height (lifting range)	150 mm (590–740 mm)
Maximum moving speed	0.2 m/s
Fork length	500 mm
Fork width (b)	25 mm
Fork height (h)	40 mm
Fork web thickness (b_1)	15 mm
Fork web height (h_1)	20 mm
Carriage height	107 mm

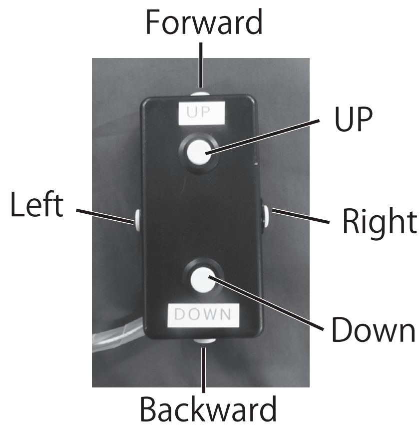


Fig. 5. Support robot controller.

Fig. 6. Formation of sitting posture using system.

the fork to be such that the maximum stress when a load of 100 kgf is applied to the fork tip is below the tensile strength of aluminum. Accordingly, the selected dimensions were top and bottom flange width (b): 25 mm, height (h): 40 mm, web thickness (b_1): 15 mm, and web height (h_1): 20 mm. We determined the dimensions of the other structural members similarly to ensure that the maximum stress on each structural member when a maximum load of 100 kgf is applied to the fork tip is below the yield stress or yield strength of that member. Regarding the lifting range of the fork, given that the minimum dimension between the sole of a foot and the anterior region of a knee is 580 mm, the minimum height of the fork was set as 590 mm and its lifting range as 150 mm (590 mm–740 mm). In this study, we adopted an electric cylinder (rated thrust: 2.00 kN; rated speed: 18 mm/s; voltage: DC 12 V) as the lifting device of the fork. The representative dimensions of the body were 735 mm (L) $\times$ 405 mm (W) $\times$ 976.8 mm (H), and its gross weight was approximately 71.8 kg. **Table 1** lists the design specifications of the proposed transfer-assisting robot.

The traveling operations of the robot and the lifting operations of the fork were performed using a cable controller (**Fig. 5**) installed on the robot body. In the controller, as shown in **Fig. 5**, six momentary-type button switches are installed. Pushing a combination of the four buttons arranged on the sides of the controller enables the robot to travel forward or backward, turn right or left, and translate on the right or left side. Moreover, pushing the up and down buttons arranged on the top of the controller enables the fork to be lifted up and down, respectively.

When transferring a care receiver, the robot can lift him/her up and down and move him/her in a sitting posture. This is achieved by fixing the slings arranged on the lower limbs of the worn dedicated wear to the fork and by fixing the grommets of the belts arranged on the upper limbs to the lifting machine of the fork (**Fig. 6**). To prevent the entire robot body from overturning while transferring a care receiver, the lower limb slings are made to contact with the fork at multiple points to disperse the load due to his/her weight and to ensure the center of gravity of the load is inside the four wheels.

Figure 7 shows the system configuration of the care support robot. The control computer of this robot is Arduino Due (CPU: ARM 84 MHz; operating voltage: 3.3 V; GPIO: 54; analog inputs: 12). The control computer decides the drive motors corresponding to the on/off conditions and number of switches installed on the controller. It drives the motors by generating PWD signals and rotation direction command signals and by inputting them to the driver circuits (manufactured by Tosa Elec-

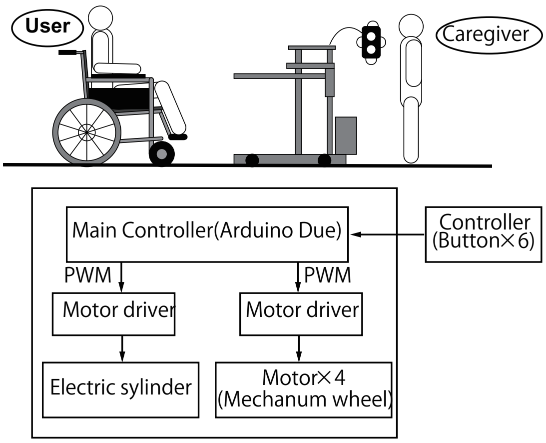


Fig. 7. System configuration.

tronics Inc.; rated voltage: 9–12 V; maximum output current: 80 A; continuous output current: 30 A).

4. Verification Tests of Transfer-Assisting System

To examine whether the developed transfer-assisting system can hold up and transfer a care receiver in his/her sitting posture, we conducted verification tests, in which two 22-year-old male adults participated as a care receiver and a caregiver, respectively. In the verification tests, the care receiver wears the posture-supporting wear and sits on a wheelchair. The care support robot is arranged 50 cm away from the care receiver, and the caregiver is assigned the task of controlling the robot and moving it near the care receiver, who is in a sitting posture. While the caregiver performs his task, the care receiver remains relaxed to the maximum extent in a resting state. **Fig. 8** shows the caregiver performing the assigned task. The experiment requires approximately 90 s from the start to the end. After the start of his task, the caregiver first moves the care support robot forward to approach the wheelchair. At 11 s after the start of the task, the caregiver finds the front wheel caster of the wheelchair obstructing the care support robot from moving forward and corrects the wheel direction. Subsequently, at 29 s after the start of the task, the caregiver completes the forward movement of the care support robot. Following this, the caregiver hooks the slings to the fork of the robot, completing this step at 42 s after the start of his task. Subsequently, the caregiver connects the belts arranged on the upper limbs of the dedicated wear to the hook-eye nuts of the robot, completing this step at 56 s after the start of his task. On fixing the care receiver to the care support robot, the caregiver lifts the fork up at 73 s after the start of the task. Subsequently, at 90 s after the start of his task, the caregiver moves the robot backward until it reaches the position where the robot and the wheelchair do not interfere with each other when viewed from the sides of the wheelchair. **Fig. 8** shows the feasibility of transfer-

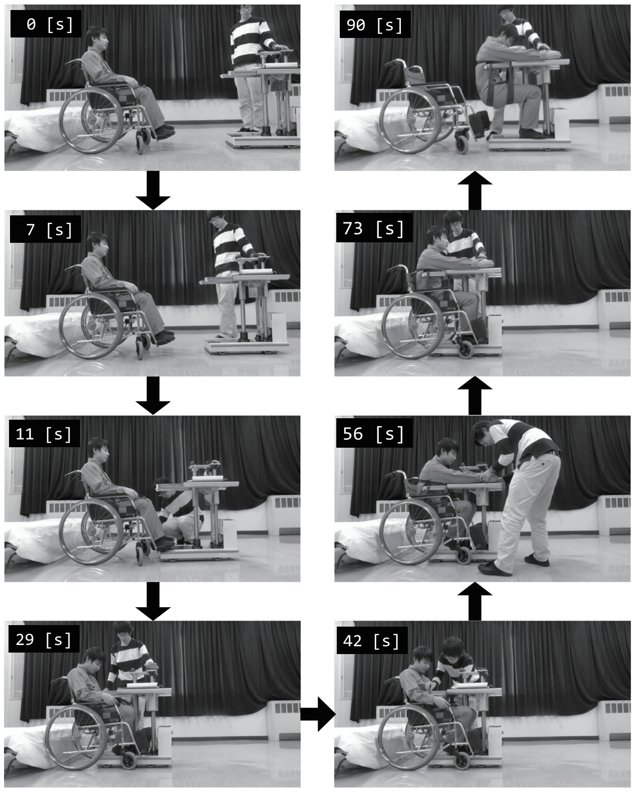


Fig. 8. Transfer from bed to wheelchair using developed transfer robot system.

ring a care receiver from a wheelchair using the transfer-assisting system developed in this study. The abovementioned transfer processes represent only half of the actual transfer operations; therefore, the total operations are estimated to take 180 s, which is 20 times longer than the time (8 s or less) required by the LTAR, as described in [5]. The time required by the developed system is also longer than the time (52.1 s, excluding preparation) required to transfer a care receiver from a wheelchair to a bed using a ceiling-type lift, as reported by Alamgir et al. [14]. Moreover, it is longer than the transferring time (104.6 s) using a floor lift. We prioritized the safety of the developed transfer-assisting robot and set its maximum moving speed at 0.2 m/s; therefore, it moves slowly when it is not engaged in any transferring operations. The transferring time of the developed care support robot could be made shorter than that of the conventional lift system by reviewing its maximum moving speed and control algorithm. Concurrently, this would increase the risks of collisions or overturns of the transfer assisting robot; therefore, some countermeasures would need to be adopted, such as additional installation of collision preventing sensors and an overturn prevention mechanism.

The care receiver, who participated in the experiments as shown in **Fig. 8**, reported that while he felt no uneasiness when the robot moved, under the conditions in which he was held up or his postures were maintained at the time of transfer, the slings fitted on the femoral region gave him large oppressive feelings or a burden. This is probably attributable to the prioritization of holding up a care receiver. Therefore, we believe that his burden could be eased by fitting the slings at more optimum positions of the dedicated wear in his sitting posture. The abovementioned verification tests of the developed transfer-assisting system showed that its belt arrangement and sling installation method need to be further addressed in the future.

5. Conclusion

In this study, we developed a transfer-assisting support system combining a dedicated wear with posture-supporting functions and a care support robot. We realized the posture-maintaining and holding up functions of the dedicated wear by fitting slings and belts to the connected clothes for operation. The slings and belts fitted to the clothes can also be used to move and change the body postures of the care receiver on a bed. The method proposed in this study can easily fit slings to a fork when it is positioned above the femoral region of the care receiver, which obviates the need for the robot to strictly position the slings, which is an advantage of the developed robot system.

In the future, we plan to evaluate the safety risks of the developed robot system, such as overturns or collisions at the time of movement, and to implement countermeasures for them as necessary. For shortening the transferring time, we plan to review the motion control of the robot to ensure it can approach a wheelchair more smoothly. In addition, we will examine the method for fitting slings and belts to the care support robot using fewer operations than those in this study. We also intend to further study functional designs of the dedicated wear based on the actual clothes of a care receiver.

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