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Development of a Nursing Skill Training System Based on Manipulator Variable Admittance Control

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Abstract— **The use of robot-based skill training systems is an emerging topic in nursing education, as many innovative robotic systems have been developed to simulate real patients, offering a safe and self-directed platform for nursing students to learn and practice their skills. Among these training systems, several human patient simulators (HPS) have been proposed to simulate the patients performance during patient transfer; however, without an entire motion model and control strategy, most HPS show limited effectiveness in simulating actual patient behavior. Herein, this work presents a novel patient transfer training system that has the potential of improving the practical skills of nursing students. First, we propose a simplified force model for patient transfer motion to estimate the contact force in the absence of wearable sensors. We then reveal the correlation between the nurses force and patients motion during the transfer through the utilization of the variable admittance model. Finally, we demonstrate the feasibility of the proposed patient transfer training system by performing several experiments on a UR10e robot. To the best of our knowledge, this system is the first patient transfer skills training system that simulates force interaction between nurse and patient using a collaborative robot.**

I. INTRODUCTION

There is a growing demand for nursing healthcare, as we now face many social issues such as an aging population and epidemics [1]. Given the pressing need for qualified nurses, today's nursing education is expected to offer effective and efficient methods for imparting fundamental nursing skills to students. Nevertheless, conventional nursing training in patient handling usually requires students to practice with mock rather than real patients due to safety and ethical concerns. At the same time, nursing education resources appear to be limited where factors like high student-educator ratios may hinder students from acquiring nursing skills due to inadequate individual supervision and feedback from traditional teaching methods [2].


(a) Assist to stand up (b) Assist to turn around (c) Assist to sit down

Fig. 1. Complete patient transfer motion

Nursing activities often involve complex and arduous physical tasks. Among them, patient transfer is one of the most critical and frequently used skills that nurses must master [3]. The fundamental procedure of transferring a patient comprises three sequential steps: 1) aiding the patient to rise; 2) rotating the patient's body; and 3) helping to sit down, as illustrated in Fig. 1. Throughout each stage, the nurse must apply appropriate body mechanics, while also assisting the patient in the transfer process. Additionally, the nurse is required to support most of the patient's weight. Incorrect techniques or postures may result in harm to both the patient and the nurse [3]. Therefore, developing a patient transfer training system that can efficiently exercise and assess student's nursing skills would be beneficial and is of vital importance.

In relation to addressing the problem above, many methods were proposed where the human patient simulator (HPS) was introduced [4], [5]. According to these studies, humanoid robot is substantiated to be effective in training patient transfer skills by simulating patients with different symptoms. Some research evaluated the phase of nurses assist patients transfer from a sitting to a standing posture, referred as sit-to-stand (STS) (Fig. 1(a)) [6], [7]. However, most of previous studies focused only on the STS part, and no former research has proposed a force-motion correlation model during the complete patient transfer, leading to the robots low similarity with real patient behavior.

There are some studies that have investigated the use of compliant control in robotic manipulators to train motor skills. Tugal *et al.* developed a robotic manipulator system capable of performing hand impedance measurements during active manipulation tasks and demonstrated its effectiveness in laparoscopic training [8]. Yang *et al.* developed a

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dual-arm robotic interface for human-robot-human writing skill transfer [9]. Ye *et al.* proposed a remote motor skill training system that utilizes an impedance controller-based manipulator to provide a high-fidelity welding experience for trainees [10]. These studies demonstrate the possibility of using manipulators to establish a mutual mapping of forces and motion, allowing trainees to comprehend the magnitude and direction of force during tasks.

Based on these methods, this work presents a manipulator-based nursing skills training system. We first proposed a simplified force model of patient transfer. This allows us to estimate the support force applied by the nurse to the patient without the need for complex and expensive wearable sensors. In addition, we innovatively model the complete patient transfer motion as a mass-damper second order response system. This method enables control of the dynamic behavior of the robot by accurately fitting virtual mass and damping parameters to simulate the behavior of a real patient when being transferred. By analyzing the patient's motion, we used variable admittance control (VAC) to simulate the human intention and adjust the admittance parameters accordingly, and further improved the fitting results as well as the similarity. The system was experimentally validated using a UR10e manipulator.

II. MODELING

In this section, we present the modeling for the complete patient transfer motion that represents the correlation between the nurses force and patients motion. In this study, we consider the definition of complete patient transfer refers to the process from the patient leaves the bed until the support from the wheelchair is received. During the process, the patient is only supported by the nurse and the support force from the ground.

A. Data Collection

Three expert nurses with up to ten years of experience in nursing education were invited to participate in the experiment. The experimental task was to collect the motion data and the force data in real scenarios, with each expert nurse supporting the patient that had no clinical experience to accomplish the complete patient transfer motion 10 times. Position information of the patient's head, shoulder, hip, knee, and feet and nurse's wrist and feet were measured using an optical motion capture system (MAC3D system from NAC Image Technologies, Inc.). Considering the difficulty of directly measuring the nurses supporting forces in multiple directions and in the range of tens of kilograms, two force plates (BERTEC FP4060-05) were utilized to measure the ground reaction forces on the patient's and nurse's feet during transfer movements, as shown in the Fig. 2.

B. Simplified Force Model

A force model is established to analyze the nurses force applied to the patient during the patient transfer, as shown in Fig 3. During the transfer of the patient, if the nurse exerts a large force on the ground, the center of pressure (CoP) will be closer to the position of their feet; therefore, by calculating the relative position of the CoP to the nurse's and patient's feet, we can estimate the nurse's support force.

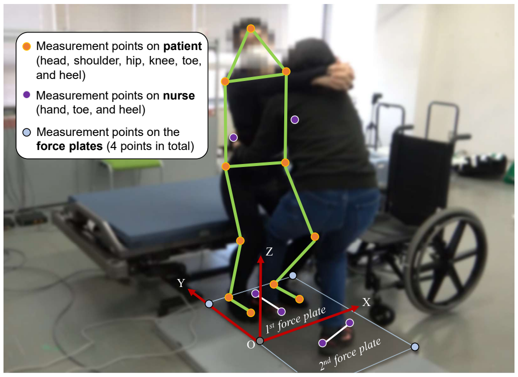

Fig. 2. Experimental setup: the position of measurement points using motion capture system and the setting of force plates

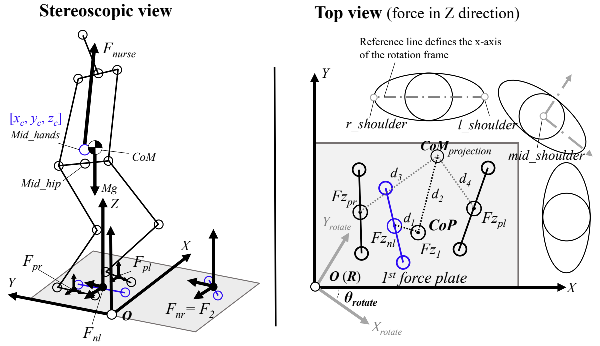

Fig. 3. Force model from the stereoscope and top view

The related parameters of the simplified model are listed in Table I. Following assumptions are made to simplify the force model to separate the nurse's and patient's force measured by the force plates: 1) the motion is considered as a quasistatic process and the experimenter is considered as a rigid body; 2) the nurse's force is considered to act at the patient's waist, which is also defined as the midpoint between the nurse's hands; 3) the point of action of the patient and nurse support was assumed to be the midpoint of the toes and heel, and 4) the patient's center of mass (CoM) is assumed to be at the geometric center of the upper body, and the projection of CoM on xy plane and CoP information from the force plate together can be used to differentiate the force distribution between the patient and the nurse.

Here we introduced the moving reference coordinate for analyzing the correlation between force and motion from the patients perspective, in which the $\mathrm{X_{rotate}}$-axis is defined as from the right to the left shoulder measurement points. Based on the assumptions and definitions, the force model is expressed by the following equation:

$$
{}^{R}\boldsymbol{F}_{\text{nurse}} = \begin{bmatrix} 0 \\ 0 \\ Mg \end{bmatrix} - \operatorname{Rot}\left(z, \theta_{\text{rotate}}\right) \begin{bmatrix} F_{x_{pl}} + F_{x_{pr}} \\ F_{y_{pl}} + F_{y_{pr}} \\ F_{z_{pl}} + F_{z_{pr}} \end{bmatrix} \tag{1}
$$

TABLE I
MAIN VARIABLES OF THE MODEL AND METHODS

Symbol	Description
M	Mass of the patient
$F_{pl}, F_{pr}, F_{nl}, F_{nr}$	Ground support force of patient and nurse's feet in the global coordinate $\{\boldsymbol{O}\}$
F_1, F_2	Force measured from the first and second force plates in $\{\boldsymbol{O}\}$
$\mathrm{Rot}\,(z, \theta_{\text{rotate}})$	Rotation angle of the patient along the z-axis, in respect to $\{\boldsymbol{O}\}$
$^{R}\boldsymbol{F}_{\text{nurse}}$	Nurse's force applied on the patient, in body-based moving reference coordinate $\{\boldsymbol{R}\}$
$[x_c, y_c, z_c]$	Position of the mid of patient's hand, in $\{\boldsymbol{R}\}$
d_1, d_2	Distance between CoP and F_{nl} & CoM projection respectively
d_3, d_4	Distance between CoM projection and F_{pr} & F_{pl} respectively

where

$$\begin{cases} F_1 = F_{pl} + F_{pr} + F_{nl} \\ F_2 = F_{nr} \end{cases} \tag{2}$$

$$\begin{cases} F_{nl} = F_1 \cdot \frac{d_2}{d_1+d_2} \\ F_{pl} = F_1 \cdot \frac{d_1}{d_1+d_2} \cdot \frac{d_3}{d_3+d_4} \\ F_{pr} = F_1 \cdot \frac{d_1}{d_1+d_2} \cdot \frac{d_4}{d_3+d_4} \end{cases} \tag{3}$$

Equation (1) shows the force estimated force that exerts on the patient in the moving reference coordinate. Equation (2) describes the force directly read by the force plates in the global coordinate. Equation (3) demonstrates the simplified method of estimating the force distribution through the CoM position estimated using the patients motion data, and the CoP position directly calculated through the force plate.

C. Admittance Model

The admittance model enables the robot to exhibit the behavior of a mass-damper-spring second-order system [11]. By using the admittance model, the robotic system can be used to simulate a real patient, enabling nursing students to learn force interaction skills with patients, such as how much support force is needed and how to change the direction of the force to safely move the patient's body.

The admittance model in the Cartesian space is commonly represented by the following equation:

$$M_d\left(\ddot{x}-\ddot{x}_0\right)+D_d\left(\dot{x}-\dot{x}_0\right)+K_d\left(x-x_0\right)=F_{\text{ext}} \tag{4}$$

where M_d, D_d, $K_d \in \mathbb{R}^{n\times n}$ are controllers virtual mass, damping, and stiffness coefficients, respectively. Here x_0 denotes the end-effector's equilibrium position, with x, $\dot{x}$, $\ddot{x}$ represent the position, velocity, and acceleration.

With respect to the tasks the robot passively follows the human's motion, such as a patient in the patient transfer, K_d and x_0 are set to be zero. Therefore, Equation (4) can be updated as:

$$M_d\ddot{x} + D_d\dot{x} = F_{\text{ext}} \tag{5}$$

Based on Equation (5), parameters can be adjusted to achieve specific dynamic characteristics of the robot system in the presence of external forces, thereby dictating the properties of physical human-robot interaction.

D. Variable Admittance Control

Some researchers have proposed variable admittance control based on human intention to perform tasks more precisely and efficiently [12]–[14]. In these studies, the damping parameter is related to the human action intentions for the robot, such as acceleration, stopping, and reversal. In particular, systems with high damping exhibit short response and high accuracy, while systems with low damping exhibit long response and low accuracy [15].

In the patient transfer motion, we also consider the nurse's intention when moving the patient. In the standing phase, when the patient's knees are in a bent position, the nurse needs to apply a relatively large force to lift the patient; in the rotating phase, when the patient tends to stand fully, the nurse needs to reduce the force applied to make the patient sit down toward the wheelchair with an acceleration change greater than $1\ \mathrm{m/s^2}$ in 0.6 s; finally, the nurse applies a large force again to decelerate to prevent the patient from being injured during sitting.

In this paper, variable damping is utilized to imitate such intention during the patient transfer by the following simple update rule from [12]:

$$D_d = D_0 - \alpha_a\left|\ddot{x}\right| \quad \text{for acceleration} \tag{6}$$

$$D_d = D_0 + \alpha_d\left|\ddot{x}\right| \quad \text{for deceleration} \tag{7}$$

where D_0, α_a, and α_d are the fitting parameters to be tuned.

E. Modeling Fitting Result

Based on previous studies that some dynamic properties of the human motion including STS motion, can be described by mechanical admittance parameters [7], [16], [17], this study establishes the correlation between the nurse's force and the patient's waist motion during complete transfer in the admittance form using the following equation:

$$\boldsymbol{F}_{\text{nurse}} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} M_x\ddot{x} + D_x\dot{x} \\ M_y\ddot{y} + D_y\dot{y} \\ M_z\ddot{z} + D_z\dot{z} + T_z \end{bmatrix} \tag{8}$$

where virtual mass M, damping D, and a constant term T for gravity compensation are fitting parameter by least squares method, with a lower bound of mass and damping set with 10 kg and 10 Ns/m for safe interaction using a manipulator. The fitting parameters are shown in Table II.

Data from the first expert nurse, which was evaluated to be more consistent and being close to the typical actual motion, were utilized in the analysis. Fig. 4 shows the estimated force with margin of error over 10 trials, the fitting result using constant admittance control (CAC) and variable admittance control (VAC), respectively. According to the goodness of fit as shown in Table III, the predicted forces using VAC have a relatively good result of a R^2 value larger than 0.5 in all three directions. Compared with CAC, VAC improved the R^2 value by 11.8%, 40.8%, and 29.2%, respectively.

TABLE II

FITTING PARAMETERS

	Mass (kg)	Gravity (N)	Damping (Ns/m)			
			CAC	VAC		
	M	T	D	D_0	α_a	α_d
x	10		78.0	92.4	193.0	-193.0
y	10		34.2	25.2	23.6	47.1
z	68.4	376.6	171.7	310.0	787.0	75.0

TABLE III

COMPARISON OF THE GOODNESS OF FIT

	CAC		VAC	
	R^2	RMSE	R^2	RMSE
F_x	0.4607	3.440	0.5152	3.295
F_y	0.6297	5.445	0.8871	2.467
F_z	0.6488	27.17	0.8382	25.46

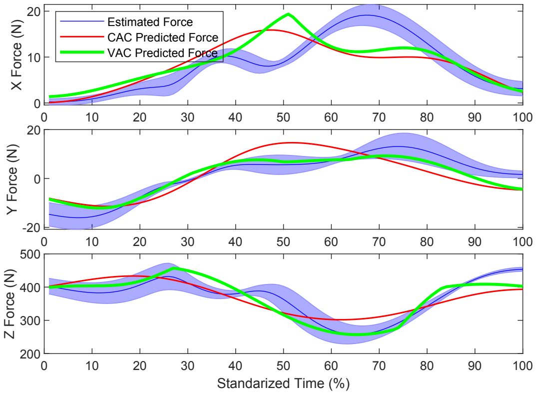

Fig. 4. Force estimation and fit result of a professional nursing teacher. The estimated forces with margin of error, fitted force using CAC, and fitted force using VAC in (a) horizontal, (b) forward, and (c) gravitational directions

III. EXPERIMENT

We tested the proposed system in two tasks: sit-to-stand (Fig. 1(a)), and complete patient transfer (Fig. 1(a)-(c)). The tasks were controlled by two methods: 1) conventional constant admittance control and 2) variable admittance control with damping update rule shown in Equations (6)(7).

A. Experimental Setting

In this study, we utilized a UR10e manipulator equipped with a six-axis force/torque sensor mounted at the end-effector. As introduced in the section II, we assume that force contact of the nurse's force applied on the patient waist. Among the techniques employed by the three nursing experts, we have adopted the technique of lifting the patient's waist for its simplicity. Herein, referring to the average waist circumference of elderly Japanese male [18], we designed a waist part printed in ABS plastic materials. The overall experimental setting is shown in Fig 5. Besides, the robot is controlled by a host PC connected via Ethernet with a communication frequency of $500Hz$.

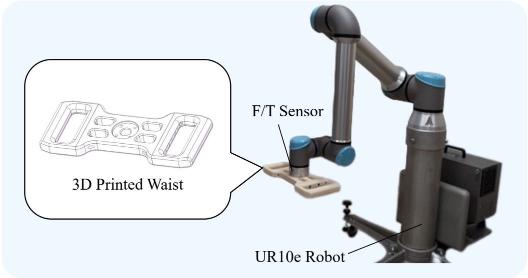

Fig. 5. Experimental setup use a UR10e robot and a 3D printed waist to simulate the actual interaction between nurse and patient

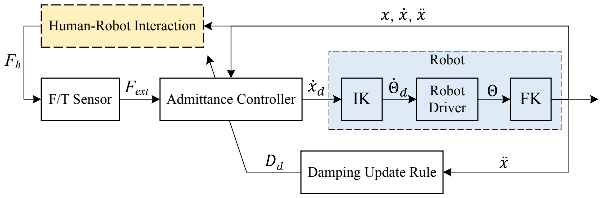

Fig. 6. The block diagram of the velocity-based variable admittance control

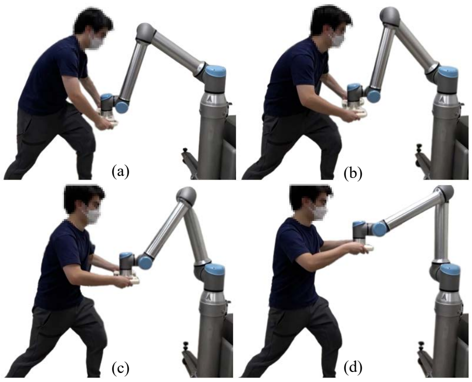
(a) (b) (c) (d)

Fig. 7. Sit-to-stand experiments by a novice. STS only include translational movement in Y and Z directions. Five trials are conducted for each method.

Due to the limited payload, the robotic manipulator cannot fully imitate the gravity of the patient in the Z-direction, as a preliminary test and verification of this system, we set the value of T parameter to be zero instead of the fitted value.

B. Control Strategies

Fig. 6 shows the control architectures block diagram, here we utilize the Cartesian velocity controller. When actively moves the 3D printed waist, the desired velocity in Cartesian space can be calculated from the sensed interaction forces, the fitted virtual mass parameters and the damping parameters under the update rule. Then, by inverse kinematics, the Jacobian matrix $J(q)$ of the robot is used to determine the desired velocity of the robot joints.

C. STS Experiment

In the STS experiment, referring to the movements of the expert nurse, the novice grasps the lift handle of the end-effector and moves it up and backward (Y and Z directions)

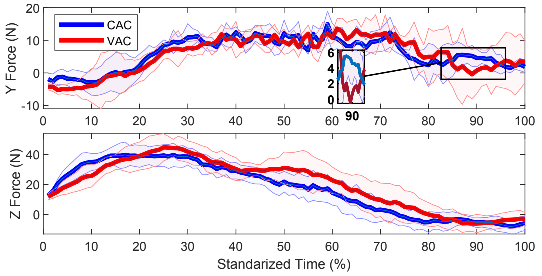

Fig. 8. The average force with margin of error by the novice during the STS motion using CAC and VAC.

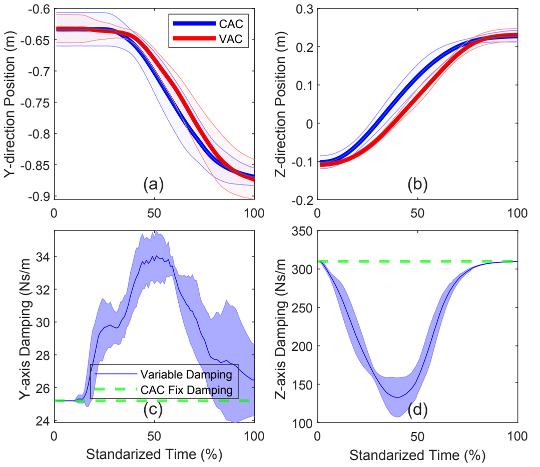

Fig. 9. The average force (a)-(b) and the variable damping (c)-(d) with margin of error during the STS motion using CAC and VAC.

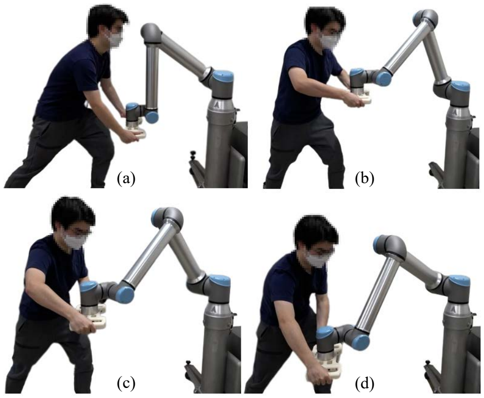

Fig. 10. The complete patient transfer by a novice. Includes transitional movement in X, Y, Z directions. Five trials are conducted for each method.

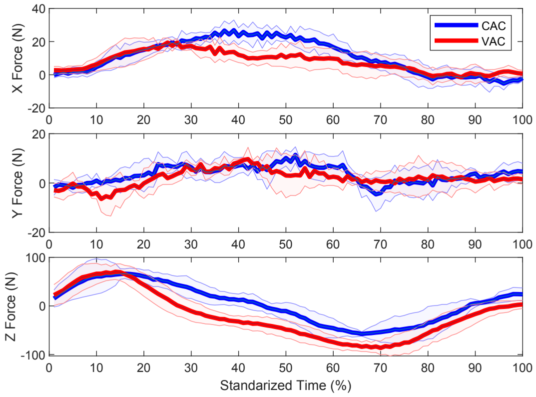

Fig. 11. The average force with margin of error by the novice during the complete patient transfer motion using CAC and VAC.

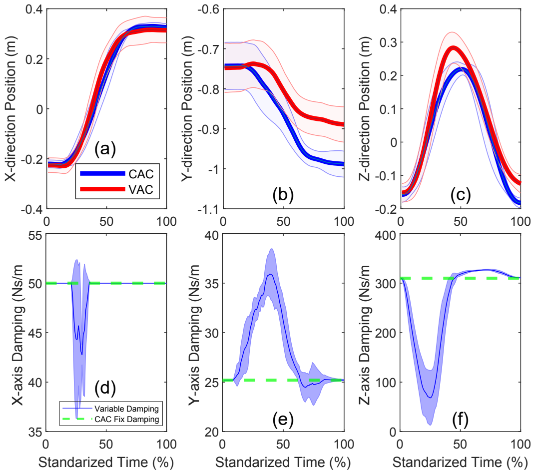

Fig. 12. The average force (a)-(c) and the variable damping (d)-(f) with margin of error during the complete patient transfer motion using CAC and VAC.

until reaching the fully standing pose, as shown in Fig 7. In such a motion, we can assume that the STS becomes a two-dimensional model in the sagittal plane. For each control method, we performed 5 trials each.

The average force with margin of error using the two methods are compared in the Fig. 8. The position change is shown in Fig. 9 (a)(b) and Fig. 9 (c)(d) show the changing damping parameter during the motion. It can be found even though the difference is not significant in the first half of the Y-direction, the VAC enables the operator to accomplish more smooth force conversion when the standing pose is reached (i.e., the nurse begins to reduce the force applied to help the patient sit toward the wheelchair). Besides, by setting the estimated force changing trend in Fig. 4 as the performance indicator, it can also be found that, compared to CAC, the force in the Z-axis direction reaches its maximum with a delay, which is close to the trend as in Fig. 4(c). This further demonstrates that the patient's characteristics during transfer motion can be better represented by changing the value of damping.

D. Complete Transfer Experiment

To evaluate our proposed system, a complete patient transfer was also implemented. In this experiment, we conducted an investigation into the translational movements that are involved during the transfer of individuals, with a particular focus on the primary factor of waist movement. Specifically, we set the condition that the patient's sitting orientation from the bed to the wheelchair remains unchanged.

Fig. 10 shows the motion in the experiment, as the user lifts the end-effector to the standing pose and then move the end-effector downwards, the complete process is accompanied by a translation along the X-axis. The force, position, and changing damping with margin of error are shown in the Fig. 11 and Fig. 12 respectively. From the comparison between the estimated force in Fig. 4 and the actual forces using CAC and VAC, the performance of VAC is still much improved compared to CAC. The error of the force in the X-direction is smaller and the range of the force in the Z-direction is larger.

IV. DISCUSSION

The current experimental results provide preliminary evidence of its effectiveness, and at this stage the system allows for the implementation of basic nursing skills training. However, several issues remain to be noted and considered.

First and foremost, we set no gravity compensation (as the T term in Equation (8)) in the experiments due to the payload limitation of the manipulator. Consequently, different from actual scenarios, the trainee was able to move the end-effector even with only a relatively small force, leading to a large variance in X and Y directions during the trials. In addition, the nurse's support force in the Z direction is always positive in the actual patient transfer (Fig. 4(c)), but without gravity compensation, the trainee exerted a downward force in the sitting phase of the complete transfer experiment. From an educational standpoint, it is deemed essential that students engage in repetitive practice of transfer motions. To minimize fatigue and for safety considerations, we plan to incorporate a 15 kg payload onto the end-effector in future studies. This will effectively simulate partial gravity acting on patients. It is expected that such intervention will enhance the efficiency and effectiveness of training efforts in the future.

It is worth mentioning that our proposed force model cannot estimate the torques exerted by the nurse. To simulate a more common scenario, rotational movement should be considered. Since the force and torque are uncoupled by the admittance control, the actual motion of the patient can be reproduced once the correlation between the torque and the rotational motion is determined. To improve this, as well as to correct and evaluate our force model, we will employ custom wearable force/torque sensors in subsequent studies.

For the data collection in this paper, we only invited a young male to imitate the patient with challenging movements. Theoretically, our model allows for simulation of patients of varying ages, genders, body shapes, and various conditions by adjusting the fitting parameters. As another future work, we would like to investigate how the parameter settings reflect the performance of the training system to simulate the characteristics of different patients. We plan to collect more data by inviting patients with different characteristics. Finally, we plan to invite professional nurses and nursing students to evaluate the effectiveness of the system from a subjective perspective.

V. CONCLUSIONS

In this study, a nursing skill training system based on manipulator variable admittance control was proposed. A simplified force model was used to estimate the nurses supporting force to the patient. Meanwhile, we advanced prior research by modeling the correlation between the nurse's force and the patient's motion throughout the complete transfer process using admittance equations. By incorporating variable damping parameters in the fit to represent human intention to some extent, the result is satisfactory with R^2 values of 0.5152, 0.8871, and 0.8382 in three force directions, respectively. Finally, in the experiments, we performed sit-to-stand and complete patient transfer motion using the proposed system on a UR10e manipulator and compared variable admittance control with constant admittance control. The results demonstrate that our proposed system can effectively simulate real patient behavior, suggesting its potential applications in nursing education.

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