Comfort Estimation During Lift-up Using Nursing-care Robot - RIBA

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Abstract— **In our research center, we have developed a nursing-care assistant robot - RIBA, which can lift up and transfer person between bed and wheelchair using its two human like arms. In this research, we develop a new method to estimate the comfortable feeling of human, which can help our robot - RIBA to find the best lifting-up motion automatically. By using a lifting-up model and optimizing a weighted evaluation function, we can calculate the lifting forces and the human joint torques during the lift-up. A weighted evaluation is used to reflect the change of comfortable feeling. We also carried out some experiments to check the model and the estimating method. During the lift-up, we measured subjects' EMG signal. And after the lift-up, questionnaires survey is conducted. The change trends between estimated and measured value show the effectiveness of the model and the method quantitatively and qualitatively.**

I. INTRODUCTION

Nursing care is a very important job for helping person to regain health or achieve the quality of life. With the increase of senior citizen and people with disability, the shortage of caregivers (i.e., Personal Care Assistant, PCA) is becoming serious. In recent years, using robotics technology, many assist devices and systems have been developed. Most of them were developed to directly increase caregivers' or patients' power by using some wearable/unwearable power-assisting devices [1], [2], [3], [4]. Some other devices were able to instant of caregivers to care person automatically or semiautomatically [5], [6], [7].

In our research center (RIKEN-TRI Collaboration Center for Human-Interactive Robot Research, RIKEN, Japan), we have also developed a nursing-care assistant robot named RIBA (Robot for Interactive Body Assistance) (Fig. 1), which was succeeded in lifting and transferring person between bed and wheelchair using two human like arms [8], [9]. By analyzing the motion of professional caregivers, a stable lifting-up movement has been realized [10]. However, it is still difficult for nursing-care assistant robot to plan or adjust its movement automatically to fit patient's height, weight and stiffness. Unfitted motion will lead to an unstable lift-up and make patient painful and uncomfortable. It has become a major issue for our robot to find a method to generate comfortable lifting-up motion automatically.

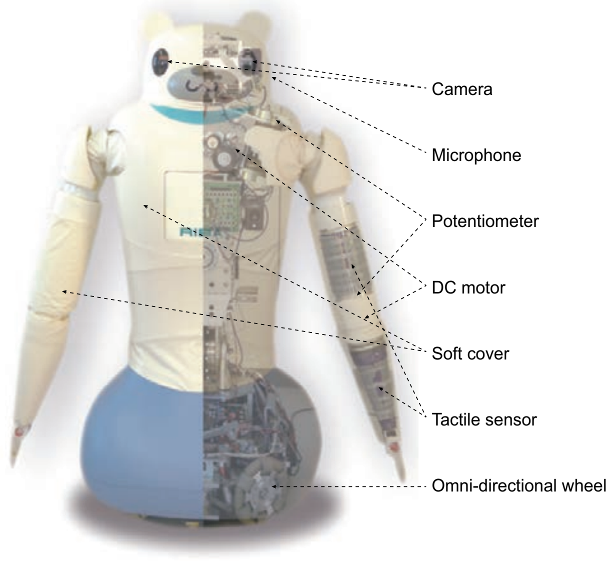

Fig. 1. Nursing-care assistant robot, RIBA

Comfort is a physical or psychological sense, which has been widely used for product evaluation and design (e.g., furniture, input devices of PC, work clothes, home electronics, etc.). In these research areas (psychology and ergonomics), many qualitative and quantitative methods (e.g., questionnaire survey, anthropometric) are widely used. With the development of sensor technology, the pressure distributions on the products and the EMG, EEG signals of users were also able to be measured directly to check the comfortable feeling [11], [12]. On the other hand, by creating detail geometric and dynamic model of human and products in computer, safety and comfort can also be estimated without using real prototypes or products and testing subjects. It is effective to reduce the cost and time that spent on designing product and developing control system. Thoese model have been often used in the research area of car design, development and test [13], [14].

In this research, in order to realize stable and comfortable lifting-up and transfer motion automatically, a model is developed to predict user's comfortable feeling. This model can estimate the forces from robot and estimate the torques from human joints based on the posture and lifting status of human and robot. These estimated forces and torques are used to calculate the comfort of human. In experiment, the

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Fig. 2. RIBA's movement when lifting a subject up from bed

calculated comfortable feeling is compared with EMG and questionnaire result, which verifies the effectiveness of our model and calculating method.

II. NURSING-CARE ASSISTANT ROBOT - RIBA

RIBA (shown in Fig. 1) is a human like nursing-care assistant robot developed in our research center, which has two high DOF and high power arms. RIBA is the first robot that can lift up and set down about 63[kg] real human and transfer him/her from a bed or wheelchair to other place stably and safely using two arms.

The height of RIBA is about 1400 [mm]; the weight is about 180 [kg]. There are 22 DOFs in whole RIBA's body, including two 7-DOF arms, 2-DOF waist and 3-DOF head. Link length, joint configuration, and movable range of all joints were determined by reference to human body. DC motors and potentiometers are used to control and measure the angles of every joint. Cameras, microphones and tactile sensors are also used to measure surrounding space, sound and pressure. Four omni-directional wheels are adopted to freely move RIBA around in a narrow space, such as the space between beds in hospital. In order to ensure stability and comfort of the lifted human by increasing the lifting area, the exterior of RIBA including its joints is covered with soft materials (e.g., polyurethane foam and silicone elastomer).

Figure 2 shows a motion when RIBA lifts a subject up from bed. arm arm holds subject's medial thighs above knee and the other one holds her back. From the contact positions between robot arms and human body, normal forces and friction forces are produced to counteract human's gravity. Sometimes subjects also have to rotate his/her joints by him/herself to modify his/her posture and keep his/her balance. One purpose of robot's lifting-up motion is to control the robot to reduce the joint torque of users. However, joint torque of human body are internal forces, which is difficult to be measured directly.

III. DYNAMIC MODEL IN LIFTING-UP

In order to realize stable lifting-up and holding motion in RIBA, Prof. Hasegawa's team has analyzed the kinematics and dynamics of lift-up by approximating human as a 2-link object [15]. However, we also find that not only the torque of hip joint but also the torques of knee and neck joints also affect the comfortable feeling during lift-up. Therefore, in this research, we improved Hasegawas's model and created a 4-link model for dynamics analysis, as shown in Fig. 3. Human head, upper-body, thigh and leg are modeled as rigid links and rotated by neck, hip and knee joints.

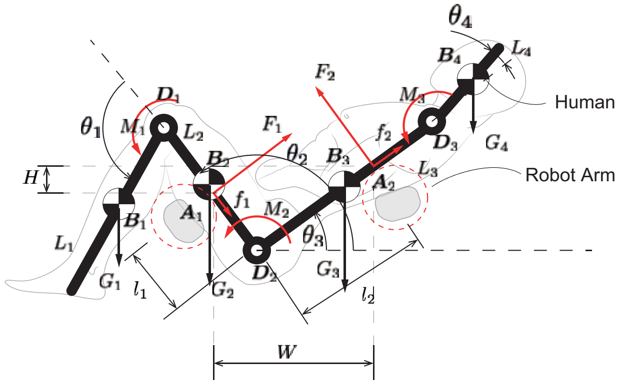


Fig. 3. 4-link Human-RIBA model during lift-up

$\boldsymbol{A}_1, \boldsymbol{A}_2$: Contact Positions between robot and human
$\boldsymbol{B}_1, \cdots, \boldsymbol{B}_4$: Positions of the center of gravity
$\boldsymbol{D}_1, \boldsymbol{D}_2, \boldsymbol{D}_3$: Positions of human joints
$L_1, \cdots, L_4$: Lengths of human links
$\theta_1, \cdots, \theta_4$: Joint angles
l_1, l_2: Lengths of from contact positions to hip joint
F_1, F_2: Normal force from robot
f_1, f_2: Friction force form robot
$G_1, \cdots, G_4$: gravity of human links
M_1, M_2, M_3: torque of human joints

In this model, the position of hip joint $\boldsymbol{D}_2$ is defined as the origin of this system. $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ are the contact positions between human and robot. From these two contact positions, lifting forces (normal forces (F_1, F_2) and friction forces (f_1, f_2)) are generated to lift and hold human body. M_1, M_2 and M_3 are the joint torques generated from human him/herself for keeping the balance. These joint torques can be adjusted by human to gain an optimum distribution of lifting forces (most comfortable or stable).

For stable lift-up, all lifting forces from robot arms (F_1, F_2 and f_1, f_2) have to balance with the gravity of human body $G\,(= G_1{+}G_2{+}G_3{+}G_4)$ in vertical and horizontal direction, which can be written as follows:

$$
\begin{aligned}
-S_2F_1 - S_3F_2 + C_2f_1 + C_3f_2 &= 0; &(1)\\
C_2F_1 + C_3F_2 + S_2f_1 + S_3f_2 - G &= 0, &(2)
\end{aligned}
$$

where, S_2, S_3, C_2, C_3 is the sine and cosine value of joint angles θ_2, θ_3,

$$S_i = \sin(\theta_i), \quad C_i = \cos(\theta_i). \tag{3}$$

The torques generated by all forces (F_i, f_i and G_i) also have to take a balance with the human joint torques (M_1, M_2, M_3). Considering the hip joint as the rotation center, the total moments for upper body (head and upper) and lower body (thigh and leg) will be 0, which can be defined using following equations.

$$\begin{aligned} l_1F_1 - b_{1x}G_1 - b_{2x}G_2 + M_2 &= 0; & (4)\\ l_2F_2 - b_{3x}G_3 - b_{4x}G_4 - M_2 &= 0, & (5)\end{aligned}$$

where b_{ix} is the horizontal distance from the position of the center of gravity $\boldsymbol{B}_i$ to hip joint $\boldsymbol{D}_2$, which is the moment arm of the gravity of each link.

The torques form knee and neck joints M_1, M_3 also have to balance with the gravities of leg and head (G_1, G_4) as follows:

$$\begin{aligned} (b_{1x} - d_{1x})G_1 - M_1 &= 0; & (6)\\ -(b_{4x} - d_{3x})G_3 + M_3 &= 0, & (7)\end{aligned}$$

where d_{jx} is the horizontal position of each joint $\boldsymbol{D}_j$. ($b_{jx} - d_{ix}$ is the moment arm between gravity and rotation center (knee and neck joints).

For a stable and static lift-up, (1)∼(7) will be the dynamics equations of the 4-link model (shown in Fig. 3), if human posture and robot position are fixed. Solving these equations can obtain the lifting forces from robot and the joint torques from human body. However, even for a measured posture (fixed joint angle and robot arm positions), the number of variables - forces and torques ($F_1, F_2, f_1, f_2, M_1, M_2, M_3$) are still more than the number of equations ($7 > 6$), which made this calculation be a ill-post problem.

IV. ESTIMATION OF HUMAN CONFORT

During lift-up, human can change the lifting forces by adjusting his/her posture and joint torques to get a most comfortable lift-up motion and minimize the load. In this research, we assume that the load of human during lift-up is related to the distribution of lifting forces and joint torques. For a fixed posture, the distribution of forces and torques is the one, which can minimize this load. Following weighted function v is used to define this load as a sum of squares of all lifting force (F_1, F_2, f_1, f_2) and joint torques (M_1, M_2, M_3).

$$\begin{aligned} v = \omega_1(\frac{M_1}{M_{1\max}})^2 + \omega_2(\frac{M_2}{M_{2\max}})^2 + \omega_3(\frac{M_3}{M_{3\max}})^2 \\ +\omega_4(\frac{F_1}{F_{1\max}})^2 + \omega_5(\frac{F_2}{F_{2\max}})^2 \\ +\omega_6(\frac{f_1}{f_{1\max}})^2 + \omega_7(\frac{f_2}{f_{2\max}})^2, \end{aligned} \tag{8}$$

where M_{imax} is the maximum torque for balancing to link gravity, when human body is horizontal and there are not any lifting forces from robot.

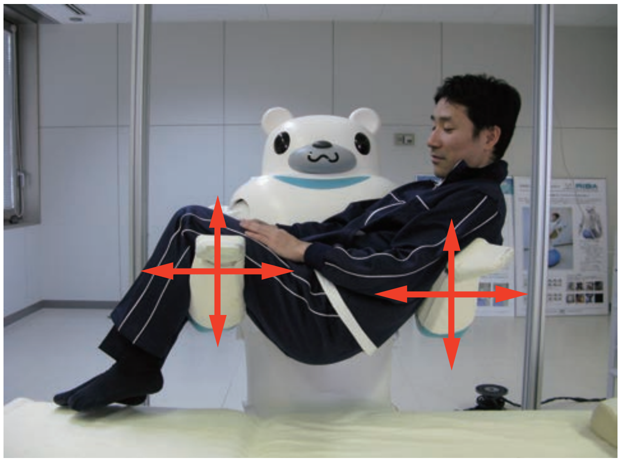


Fig. 4. Lifting-up experiment and adjustable robot motion

$$\begin{aligned} M_{1max} &= \|\boldsymbol{B}_1 - \boldsymbol{D}_1\|G_1; & (9)\\ M_{2max} &= \max\{(\|\boldsymbol{B}_1\|G_1 + \|\boldsymbol{B}_2\|G_2), \\ &\qquad (\|\boldsymbol{B}_3\|G_3 + \|\boldsymbol{B}_4\|G_4)\}; & (10)\\ M_{3max} &= \|\boldsymbol{B}_4 - \boldsymbol{D}_3\|G_4. & (11)\end{aligned}$$

Maximum lifting forces $F_{i\max}, f_{i\max}$ are defined as half of the gravity of human body G.

$$F_{1\max} = F_{2\max} = f_{1\max} = f_{2\max} = \frac{G}{2}. \tag{12}$$

For a measured joint angles ($\theta_1, \cdots, \theta_4$) and contact positions (l_1, l_2), a set of lifting force and joint torques ($F_1, F_2, f_1, f_2, M_1, M_2, M_3$) can be obtained from (1)∼(7) by minimizing (8) ($v \rightarrow \min$). It is the best lifting-up motion, which can minimize the load of human body and make him/her most comfortable.

The weight $\boldsymbol{\omega}$ used in (8) shows the effect of comfortable feeling from lifting forces and joint torques. Larger weight means larger effect of human comfortable feeling, which can obtain smaller force/torque. Conversely, smaller weight means smaller effect, which can obtain relatively-larger force/torque. In this research, weight ($\boldsymbol{\omega}$) was set by analyzing the effect from measured data and questionnaire survey in experiments.

V. EXPERIMENT

A. Overview

In order to confirm the estimated forces/torques and the calculated comfort, some experiments were carried out. The force/torque estimation was checked by comparing the measured electromyography (EMG) signal and the calculated value from model. The comfort estimation was checked by comparing the result of questionnaire and the optimized value v.

As shown in Fig. 4, in experiments, our nursing-care assistant robot - RIBA lifted subjects up on the two arms same as the setting in our model. RIBA's arms were horizontal and

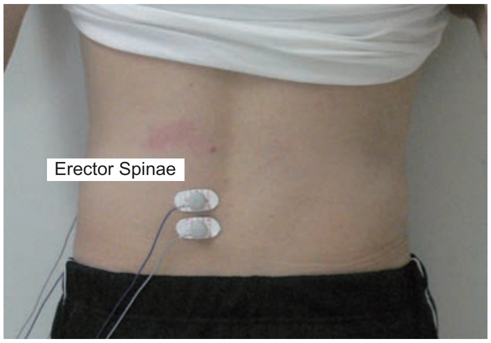


Fig. 5. Measuring position of EMG of Erector Spinae Muscle on back

parallel to each other. The horizontal and vertical distance (W, H) can be adjusted by operator following subjects' order. Subjects can change his/her posture and lifting forces by adjusting these distances to find a most comfortable status by him/herself.

We measured data for every subject using two different robot lifting-up motion.

1) Default robot motion (Before adjustment):
   First, robot lifted subjects up using a fixed default distance. The horizontal distance W is 420 [mm] and the vertical distance H is -30 [mm]. (Here, negative value means left robot arm lower than right arm).
2) Adjusted robot motion (After adjustment):
   Based on default robot motion, subjects adjusted robot and him/herself by giving his/her order to operator, until he/she gets a most comfortable position. Then, robot would lift subjects up again using this adjusted robot motion.

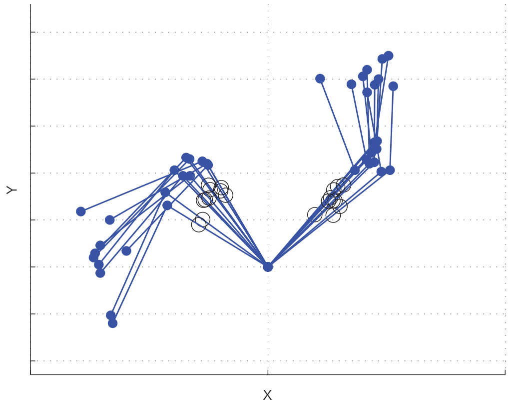
Experiments were conducted for ten health subjects (5 males and 5 females). The age of subjects ranged from 22 to 60 Y/O, and the average age is 35 Y/O. Heights and weights of subjects were also different to each other. The height was from 1.48[m] to 1.71[m] and the weight was from 47[kg] to 61[kg]. The link lengths (e.g., the length of thigh, lower leg, upper body, etc.) of every subject were also pre-measured, which were used for our model. The weights $(G_1, \cdots, G_4)$ and the gravity centers $(\boldsymbol{B}_1, \cdots, \boldsymbol{B}_4)$ of every link were calculated by referring the average value of Japanese people from the available database gathered by AIST [16].

EMG signals were measured from all subjects during the lift-up before and after adjustment. From our model computation and preliminary experiment, we find extension torque was mainly generated in hip joint for many lift-up. Therefore, in the experiments, the EMG signal of Erector Spinae Muscle was measured to check the torques of hip joint because it is one major muscle in human back for extending hip joint. Figure 5 shows the measuring position on subject's back. After lift-up (both before and after adjustment), we also carried out questionnaire survey for all subjects. The comfortable feeling during lift-up was rated on a one-to-six scale.

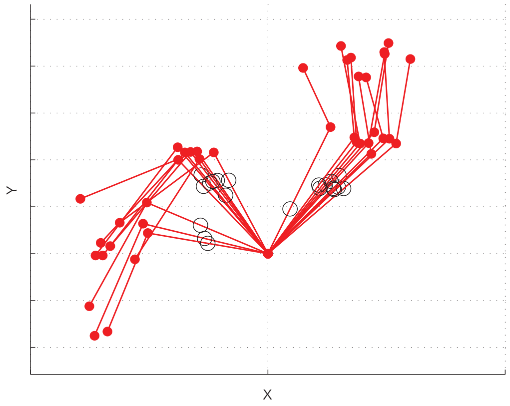
In order to set the weight $\boldsymbol{\omega}$ used in (8), we checked the measured postures and asked subjects his/her feeling after each experiment. We found that the slip of body, the torque around hip joint and the oppressing feeling in back are mostly focused when subjects adjusted the positions of robot arms. Therefore, we set:

1) large weights for ω_6, ω_7 to reduce the friction forces;
2) a large weight for ω_2 to reduce the torque of hip joint;
3) a large weight for ω_5 to reduce the normal force in the back.

In following calculation, $\boldsymbol{\omega} = [1, 10, 5, 1, 5, 20, 20]$ was used to calculate force, torque and comfort for comparing the value measured in experiments.



(a) Before adjustment



(b) After adjustment

Fig. 6. Subjects' posture before and after adjustment

B. Result and discussion

1) Change of posture: Figure 6 shows subjects' postures before and after adjustment. The blue and red lines and dots show the links and joints positions of subjects when robot lifted them up. The black circles on the links of thigh and upper body show the contact position of robot arms. Comparing with the postures of default robot arm position, dispersion postures of subjects were increased after adjustment. Table I shows the angles of modeled three joints (knee, hip and neck) before and after adjustment.

TABLE I

JOINT ANGLE CHANGE OF SUBJECTS

[Deg]

	Knee			Hip			Neck		
	Before	After	(Change)	Before	After	(Change)	Before	After	(Change)
Sub1	103	84	(-19)	105	113	(-2)	49	50	(+1)
Sub2	97	81	(-16)	100	115	(+15)	62	50	(-12)
Sub3	81	78	(-3)	76	76	(0)	46	32	(-14)
Sub4	107	99	(-8)	72	66	(-6)	48	42	(-6)
Sub5	100	99	(-1)	76	92	(+16)	37	40	(+3)
Sub6	100	103	(+3)	77	81	(+4)	31	32	(+1)
Sub7	90	78	(-12)	73	106	(+33)	54	51	(-3)
Sub8	97	112	(+15)	88	72	(-16)	45	41	(-4)
Sub9	98	98	(0)	86	84	(-2)	41	60	(+19)
Sub10	88	103	(+15)	90	83	(-7)	60	55	(-5)
Avg.	96	94	(-2)	84	89	(+5)	47	45	(-2)
Std.	8	12	(11)	12	17	(13)	10	9	(9)

TABLE II

CHANGE OF EMG AND ESTIMATED TORQUE

	EMG	Torque (Simu.)	
Sub1	1.01	0.86	×
Sub2	0.65	0.46	◯
Sub3	0.93	0.82	◯
Sub4	0.96	1.07	×
Sub5	0.90	0.56	◯
Sub6	0.75	0.91	◯
Sub7	-	0.13	-
Sub8	-	1.24	-
Sub9	-	1.44	-
Sub10	1.18	1.14	◯

◯: Same change trend
×: Different change trend

TABLE III

CHANGE OF COMFORT LEVEL FROM QUESTIONNAIRE

	Before	After	Change	Simu.	
Sub1	5	4	0.80	0.91	◯
Sub2	5	2	0.40	0.55	◯
Sub3	4	5	1.25	0.84	×
Sub4	3	2	0.67	1.07	×
Sub5	3	2	0.67	0.60	◯
Sub6	4	3	0.75	0.92	◯
Sub7	4	3	0.75	0.27	◯
Sub8	4	1	0.25	1.21	×
Sub9	3	4	1.33	1.41	◯
Sub10	6	5	0.83	1.13	×

◯: Same change trend
×: Different change trend

Both increasing and decreasing changes were obtained from each joint. Even taking into account the difference between subjects, we still cannot find any coincidence from the change of postures before and after adjustment. No rule has been found from these postures and the changes.

2) Change of joint torque: Ten seconds EMG signals were measured during lift-up from all subjects before and after adjustment. We rectified, low-pass filtered and integrated every EMG signal. The obtained iEMG (integrated EMG) signals were used to show the largeness of muscle forces [17]. The left column in Table II shows the changes of measured iEMG. (Three subjects' EMG signals could not be measured because there was a same position between the contact position and the EMG measuring position on his/her back.) These changes were calculated based on the value measured before adjustment. If the change smaller than 1, it means he/she gave smaller force around hip joint after adjustment. From the result, we can find that smaller forces are obtained from most subjects after adjusted the position of robot arms. However, some subjects produced larger force around hip joint to keep his/her balance after adjustment. The changes of measured EMG signals of them were larger than 1.

3) Change of comfortable feeling: Table III shows the score change of comfortable feeling from the questionnaire survey. In one-to-six scale, lower score means better comfortable feeling. From this survey, we can also find most subjects felt more comfortable after adjustment than before. However some subjects (Sub3 and Sub9) might fail to adjust robot arms. They felt uncomfortable and gave a higher scale for adjusted robot motion.

C. Comparison with estimation results of model

The measured subjects' postures and the positions of robot arms shown in Fig. 6 were substituted into the developed model that described in previous chapters. The lifting force and joint torques were calculated by minimizing the evaluation function (8). Comfort was also estimated using this function.

1) Joint torque: The sencond column in Table II show the changes of joint torque M_2 calculated from (1)$\sim$(7) using measure subjects' posture $(\theta_1, \cdots, \theta_4)$ and contact positions (l_1, l_2). The right column shows the comparison between measured EMG and estimated torque. "◯" means the same change trends between answered and estimated comfortable feeling; and "×" means they are different change trends. Comparing with EMG signals (white boxes), we can find the changes of most subjects have same trends between measured and estimated data (five out of seven subjects). From other two subjects (Sub1 and Sub4), different change trends were obtained. It may be because of the small changes of the load around hip joint before and after adjustment, which made it easy to cause error from EMG signals or model calculation.

2) *Comfortable feeling:* The forth column (Simu.) of Table III shows the changes of estimated comfort v calculated from (8). The fifth column shows the comparison between estimated comfort and subjects' answer on questionnaires. Six out of all ten subjects have same change trends. From other three subjects (Sub3, Sub4, and Sub10), we obtained different change trends. However, for Sub3 and Sub10, comparing the change before and after adjustment, we can find that both the surveyed feeling and estimated comfort did not change so much, which may make the evaluation difficult.

These comparison results of measured and estimated joint torques and comfortable feeling show that our model and estimating method is almost effective for comfort estimation.

VI. CONCLUSION

In this research, we developed a dynamic model and an estimating method to calculate the lifting forces and joint torques when robot lifts human up by minimizing the load of human. Using the calculated forces and torques, we can also estimate the comfortable feeling of human. We also carried out some experiments to check the developed model and method. Robot lifted subjects up using two different motions. We measured subjects' EMG signal during lift-up and asked about their comfortable feeling after experiments. Most estimated joint torques had same change trends with measured EMG signal (five out of seven subjects). And most estimated comfort also had same change trends with the result of questionnaires (six out of ten subjects). Different estimated trends were mainly obtained from small changes. These quantitative and qualitative comparison results show that the developed model and estimating method are effective for comfort estimation during lift-up. In the future, we will find a better weight $\boldsymbol{\omega}$ and use this model and our estimating method to make robot find a best lifting-up motion automatically.

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