Simulation–based Design for Robotic Care Device: Optimizing Trajectory of Transfer Support Robot

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***Abstract*— This paper presents a framework of simulation–based design for robotic care devices developed to reduce the burden of caregiver and care receivers. First, physical interaction between the user and device is quantitatively estimated by using a digital human simulator. Then we introduce a method for optimizing the design parameters according to given evaluation criteria. An example of trajectory optimization of transfer support robot is provided to demonstrate the effectiveness of the proposed method.**

I. INTRODUCTION

Robotic care devices have been actively developed in recent years. In the *Project to Promote the Development and Introduction of Robotic Devices for Nursing Care* by The Japan Agency for Medical Research and Development, they aim to support the independence of elderly people, alleviate the burden on caregivers, and create a new market for the robotic care devices [1]. The project concentrates on the devices listed in priority areas: transfer aids, mobility aids, toileting aids, bathing aids, and monitoring systems designated by the Ministry of Economy, Trade and Industry and the Ministry of Health, Labour and Welfare [2].

Among robotic nursing care devices in priority fields, the device intended for lifting aid or mobility aid supports people by close physical contacts. Such devices are required to be safe, easy to use, cost-effective, and to realize the desired effect on users. However, its design process still is not optimized: several hardware prototypes are fabricated and tested with human subjects before finalizing the design, which is time-consuming. The main issue here is that it is difficult to estimate the physical effects of the device to humans without tests with subjects using a prototype. We introduce a human simulator as a solution in this paper.

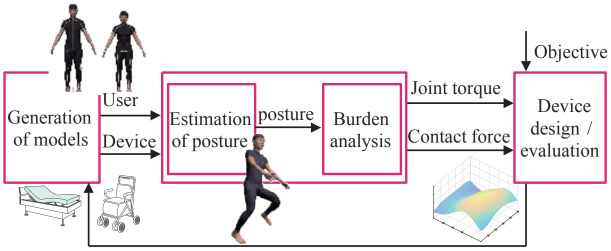

Fig. 1: Outline of evaluation framework.

There are a number of commercial software of digital human models for virtual assessment of affinity of products with human, and they are widely utilized for instance to assess reaching areas of limbs or visual fields geometrically for the industrial design in the field such as automobile, factory, and airplane [3]. Unlike those systems, since robotic care devices which we are dealing with have close physical contacts with the users, dynamic analysis of the physical interaction between the user and the device is necessary. The analysis method should be efficient enough to take into account multiple design parameters to optimize. Recently, efficient computational algorithms developed for multibody systems, such as humanoid robots, are applied to human biomechanics analysis and expand its scope of application [4].

In this paper, we aim at establishing a simulation–based design and evaluation method for robotic care device based on biomechanical analysis. The differences from the conventional sport biomechanics analysis are that the analysis should consider a large number of the contact points between the human and the device, and that the care receivers have low motility and physical weakness, therefore, the postures of the user are largely dependent on the movement of the device. Device design methods are necessary which are in consideration of the physical ability, the contact force tolerance, and the other evaluations. In order to perform such analyses, it is necessary that an analysis method can reproduce the distribution of forces under various conditions, and human models can reproduce individual condition such as muscle atrophy and decrease of range of motion. In this paper, we propose an overall evaluation and design framework based on physical burden analysis. Application

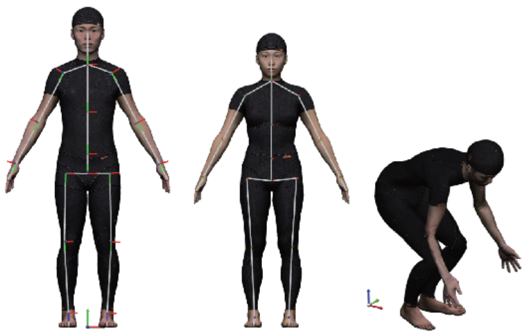

Fig. 2: DhaibaBody[6].

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examples of trajectory design of a robotic transfer aid are also introduced.

II. ANALYSIS OF PHYSICAL BURDEN WHEN USING SUPPORTIVE DEVICES BY HUMAN BODY SIMULATION

Outline of the device evaluation and design based on the physical burden analysis is shown in Fig. 1. The procedure is as follows.

1) Modeling of the device and its user.
2) Posture estimation of human when using the device.
3) Physical burden analysis by using inverse dynamics calculation including the estimation of the contact forces.
4) Quantitative evaluation, design and improvement of the device based on the burden analysis.

Next, Details of step 1, 2, and 3 are described. Step 4 will be described in Section III.

A. Generation of models representing device and user

The device to be designed and its user are modeled respectively. We utilize a digital human model *DhaibaBody* and an ergonomic assessment support software *DhaibaWorks* for modeling and posture generation [5], [6]. The software can reconstruct individual whole–body human models from an arbitrary sparse set of anthropometric dimensions by referring to the database, and thus can generate a model corresponding to the physique of assumed user without actual measurements. The model contains triangular meshes which represent the skin surface and a link model which defines a local coordinate system of each joint and their connectivity (Fig. 2). The skin surface deforms according to the posture by using Skeletal Subspace Deformation algorithm [7]. The model of the device is also created, which consist of a rigid link and three–dimensional geometric meshes.

B. Estimation of human posture

In order to estimate the change in user's posture caused by the actuator motions or geometric changes of the device, a positional relationship between the device and the user is analyzed. Anatomical feature points are defined on the human skin surface and the corresponding feature points are placed on the body mesh of the device model. When the device parameters, such as the joint angles and length of the link, are changed, the global posture and the rotation angles of each joint on the human link model are obtained so as to fit those feature points with inverse kinematics algorithm [5].

C. Physical burden analysis with inverse dynamics calculation and contact force estimation

The joint torques exerted by the human for maintaining the estimated postures are analyzed in conjunction with the estimation of contact forces between the human and the device / environment. The equations of motion of the human link model are given by Eq.(1).

$$\boldsymbol{M}\left(\boldsymbol{q}\right)\ddot{\boldsymbol{q}} + \boldsymbol{c}\left(\boldsymbol{q},\dot{\boldsymbol{q}}\right) + \boldsymbol{g}\left(\boldsymbol{q}\right) = \begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{\tau}\end{bmatrix} + \sum_{i}\begin{bmatrix}\boldsymbol{J}_{B,C_i}^{T}\\ \boldsymbol{J}_{J,C_i}^{T}\end{bmatrix}\boldsymbol{F}_{C_i} \quad (1)$$

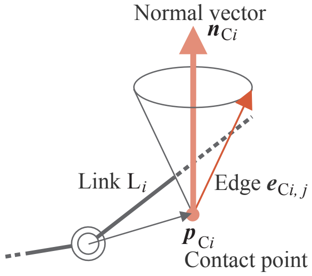


Fig. 3: Convex polyhedral cone approximation of contact forces.

where,

- $\boldsymbol{q}$ is the vector of the generalized coordinates,
- $\boldsymbol{M}$ is the inertia matrix,
- $\boldsymbol{c}$ is the Coriolis and centrifugal term,
- $\boldsymbol{g}$ is the gravity term,
- $\boldsymbol{\tau}$ is the generalized forces,
- $\boldsymbol{F}_{Ci}$ is the vector of external force exerted at contact point C_i,
- $\boldsymbol{J}_{B,C_i}^{T}$ is the Jacobian matrix which convert the external force at contact point C_i to the generalized force.

The generalized forces $\boldsymbol{\tau}_0$ that achieve a given posture can be calculated by inverse dynamics computation.

$$\boldsymbol{\tau}_0 = \boldsymbol{M}\left(\boldsymbol{q}\right)\ddot{\boldsymbol{q}} + \boldsymbol{c}\left(\boldsymbol{q},\dot{\boldsymbol{q}}\right) + \boldsymbol{g}\left(\boldsymbol{q}\right) \quad (2)$$

For this analysis, we utilize dynamics computation library of musculoskeletal model by Nakamura et al [4].

Coulomb friction is assumed for contact points, and a friction cone defined by a normal vector of the contact point $\boldsymbol{n}_{Ci}$ and friction coefficient μ can be approximated by a convex polyhedral cone [8]. Under such an approximation, the contact force vector $\boldsymbol{F}_{Ci}$ is represented as the resultant force of the force on the edge $\boldsymbol{e}_{Ci,j}$ of the polyhedral cone, as shown in Fig. 3. When the number of edges is m, the contact force vector $\boldsymbol{F}_{Ci}$ is

$$\boldsymbol{F}_{Ci} = \sum_{j=1}^{m} f_{Ci,j}\boldsymbol{e}_{Ci,j} \quad (3)$$

where, $f_{Ci,j}$ is the magnitude of the force at each edge.

For the estimation of the joint torques and the contact forces, we use the quadratic programming problem which has an objective function Eq.(4).

$$Z = \|\boldsymbol{W}_f{}^{\frac{1}{2}}\boldsymbol{f}\|^2 + \|\boldsymbol{W}_\tau{}^{\frac{1}{2}}\left(\boldsymbol{\tau}_0 - \boldsymbol{J}^T\boldsymbol{f}\right)\|^2 \quad (4)$$

where, $\boldsymbol{f}$ is the vector having the norm of the force vectors on the edges of the polyhedral cones:

$$\boldsymbol{f} = \left[f_{C1,1}\ f_{C1,2}\ \cdots\ f_{Cn,m}\right]^{\mathrm{T}} \quad (5)$$

$\boldsymbol{J}^T$ is the matrix which convert $\boldsymbol{f}$ to the generalized force. The elements have the following inequality constraints.

$$f_{Ci,j} \geq 0 \quad (i = 1, ..., n,\ j = 1, ..., m) \quad (6)$$

$\boldsymbol{W}_f$ and $\boldsymbol{W}_\tau$ are weighting matrices, which are diagonal matrices with positive values w_f、w_b、w_j as diagonal elements.

$$\boldsymbol{W}_f = w_f \boldsymbol{I}_{nm} \tag{7}$$

$$\boldsymbol{W}_\tau = \begin{bmatrix} w_b \boldsymbol{I}_6 & \boldsymbol{0} \\ \boldsymbol{0} & w_j \boldsymbol{I}_{(DOF-6)} \end{bmatrix} \tag{8}$$

By adjusting these weights, the distribution of force and torque can be changed so as to reproduce the degree of relaxation of the user. The first term of Eq.(4) is for minimizing the sum of squares of external forces, the second term is for minimizing the square sum of the error of the base–link motion equation and the joint torque. Since the 6 DOF of the base–link of the free–flying systems are unactuated coordinates, the generalized forces are ideally zero. However, in consideration of modeling errors of the human, motions and external forces, the conditions are relaxed by incorporating them into the objective function instead of the equality constraint condition.
Furthermore, when assuming the physical ability, the following inequality constraint condition is added.

$$\boldsymbol{\tau}_{min} \leq \boldsymbol{\tau}_0 - \boldsymbol{J}^T \boldsymbol{f} \leq \boldsymbol{\tau}_{max} \tag{9}$$

In this way, the devices can be quantitatively evaluated, designed and improved based on the proposed evaluation method of the physical burden.

III. TRAJECTORY DESIGN METHOD CONSIDERING PHYSICAL BURDEN ON CARE RECEIVER

As the last step of the device design described in the section II, various evaluation axes, design indicators and parameters can be considered depending on the target device. This paper describes an example designing trajectory of a motion support device. The trajectory design is performed in the following procedure.

1) Generation of a physical burden evaluation map with respect to the actuator displacement.
2) Generation of trajectory of the device actuators based on the evaluation map.

Details of each step are described in the following.

A. Generation of physical burden evaluation map

First, the relationship between the evaluation values and device parameters are analyzed. When the DOF of the design parameters of the device is N, the designer creates a set of discrete values for each element of parameters $\boldsymbol{x} = [x_1 \; x_2 \; ... \; x_N]$, so as to cover the range of motion of each device actuator. The postures of user are estimated with the method in the section II-B, and the evaluation values $E_1, ..., E_M$, such as the joint torques, the contact forces, and joint angles, are calculated with the method in the section II-C. The parameters and evaluation values are normalized so that minimum and maximum values fit within 0 and 1.

Then, each evaluation value are approximated by using estimation expression $\hat{E}_i(\boldsymbol{a}_i, \boldsymbol{x})$ which interpolates the discrete analysis. Finally, a comprehensive evaluation map is generated by combining these estimation equations with arbitrary weightings.

$$E(\boldsymbol{a}, \boldsymbol{x}) = \sum_{i=1}^{M} w_i \hat{E}_i(\boldsymbol{a}_i, \boldsymbol{x}) \tag{10}$$

where, w_i is weights for each evaluation item. An example of the map is as shown in Fig. 4. The higher evaluation value means the larger physical loads on the selected body part. This map can provide the evaluation value E with respect to an arbitrary posture within the range of motion of the device. Evaluation items and their weights need to be determined by the designer taking into consideration the objectives of the device and the abilities of the target user.

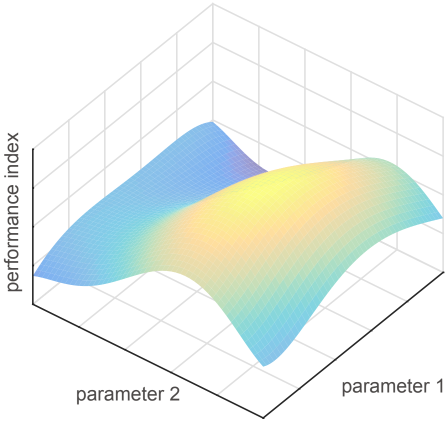


Fig. 4: An Example of evaluation map.

B. Generation of device trajectory

The trajectory of the device from an initial posture $\boldsymbol{x}_{init}$ to a final posture $\boldsymbol{x}_{goal}$ can be designed based on the comprehensive evaluation map. First, an initial trajectory $\mathbf{P}_0 = [\boldsymbol{x}_{01} \; \boldsymbol{x}_{02} ... \boldsymbol{x}_{0L}]$ is given with Dijkstra method using the evaluation value E as a cost. Then, the nonlinear optimization is performed using the following evaluation function to generate a smoother trajectory.

$$\begin{aligned} \min : & \sum_{l=1}^{L-1} (w_{p1} f_{p1} + w_{p2} f_{p2} + w_{p3} f_{p3}) \\ & f_{p1} = \|\boldsymbol{x}_{l+1} - \boldsymbol{x}_l\| \{max(E(\boldsymbol{a}, \boldsymbol{x}_{l+1}), E_{th}) - E_{th}\} \\ & f_{p2} = \|\boldsymbol{x}_{l+1} - \boldsymbol{x}_l\|^2 \\ & f_{p3} = \|\boldsymbol{x}_l - \boldsymbol{x}_{0l}\|^2 \\ & \text{subject to} : \boldsymbol{0} \leq \boldsymbol{x}_l \leq \boldsymbol{1} \quad (l = 1, ..., L) \\ & \boldsymbol{x}_1 = \boldsymbol{x}_{init}, \; \boldsymbol{x}_L = \boldsymbol{x}_{goal} \end{aligned}$$

where, w_{p1}, w_{p2}, and w_{p3} are weights for each item, E_{th} is the threshold of the evaluation value. f_{p1} is the path integral of the evaluation value, f_{p2} is the indicator for smoothing the trajectory, and f_{p3} is the constraints for approximating the initial path. In this way, it is possible to design the trajectory considering the burden on the user.

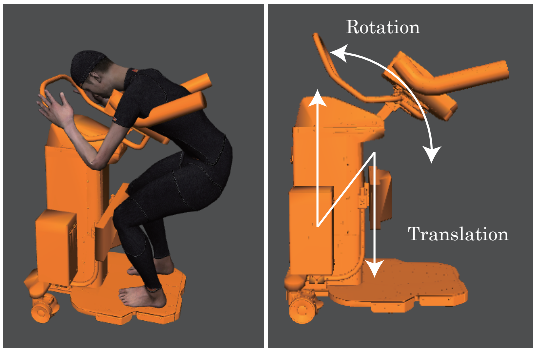


Fig. 5: Transfer aid with rigid–body link.

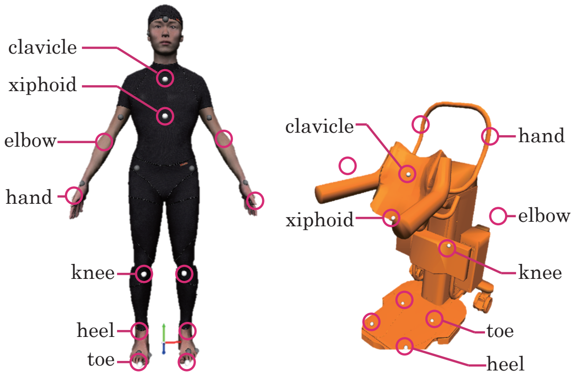


Fig. 6: Feature points on human and device for posture estimation.

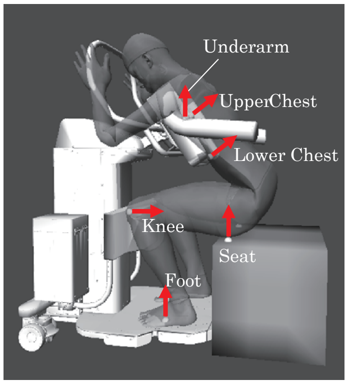


Fig. 7: Contact force vector. Since Underarm, Seat, Knee, and Foot are symmetrical, only the forces applied to left side is displayed.

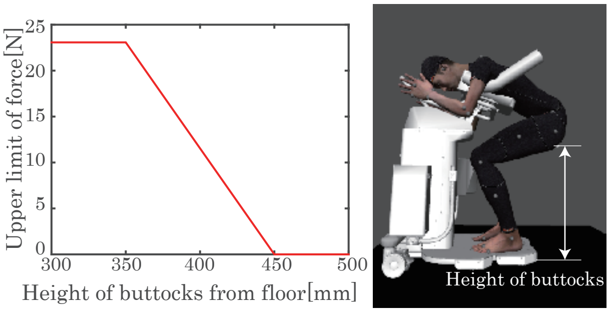


Fig. 8: Upper limit of contact force to buttocks.

IV. TRAJECTORY DESIGN EXAMPLES

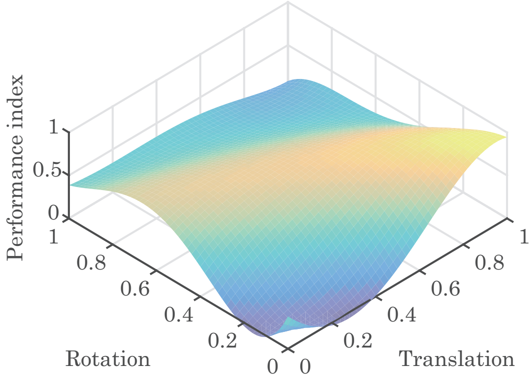
In this section, we demonstrate an application example of the proposed evaluation method to a transfer support device that is designed to help the user (care receiver) to stand up with smaller burden on the body. The target device supports a user to be transferred from a wheelchair or a bed as shown in Fig. 5, and it has 2DOF comprising translation and rotation. These two parameters were normalized by each minimum and maximum values. The user model is 1740 mm in height and 66 kg in weight. Figure 6 shows the feature points used in the posture estimation, and Fig. 7 illustrates contact force vectors applied to the user body from the device and the seat. Although the force vectors at *Underarm*, *Knee*, *Foot*, and *Seat* are set to be symmetrical, only vectors on the left side are shown in the figure, and the number of contact points is ten in total. User's hands are grasping the grip actually, however, it assumed that they do not exert forces for standing. Because *Seat* is the reaction force on the pelvis from the seat of the chair or the bed and can not obtain the force after leaving the chair, we set the upper limit of the external force with respect to the height of the buttocks as shown in Fig. 8. When the height from the floor reaches 450 mm or more, the contact force becomes zero completely. The friction coefficient μ was 0.5, and the friction cone was approximated by ten ridgelines.

In this analysis, we approximate evaluation items by the following polynomial of the fifth degree, and the coefficient vector $\boldsymbol{a}_i = \{a_{jk}\}$ $(i = 1, ..., M)$ is obtained using least squares method.

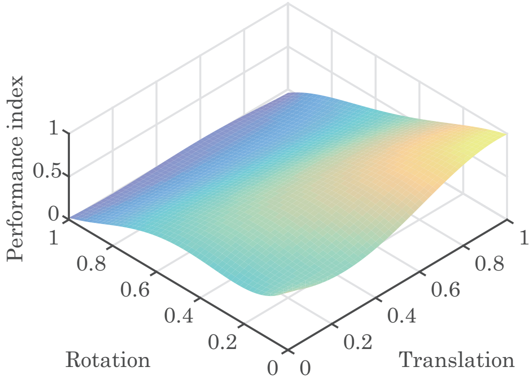
$$\hat{E}_i(\boldsymbol{a}_i, \boldsymbol{x}) = \sum_{j,k} a_{jk}(x_1)^j (x_2)^k \qquad (0 \le j+k \le 5, j \ge 0, k \ge 0) \tag{11}$$

The calculation time was around 20 msec for the physical burden analysis (described in Section II-C) for one posture, and around 20 sec for creating the optimized trajectory from the results of the burden analysis (described in Section III), when executed on Intel Core i5 3.50 GHz processor.

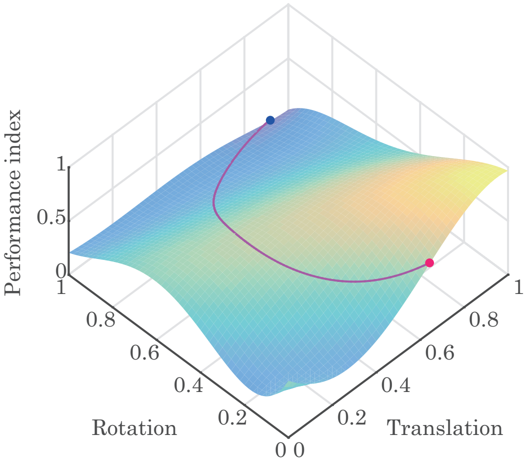
Here, we will show two examples with different evaluation criteria. In the first example, we employed two factors as evaluation items: the joint torque of knee and the contact force on the underarm. Fig. 9(a) and 9(b) show the analysis results of each evaluation index with respect to the actuator parameters. Then, these items were combined at 1:1 ratio to create a comprehensive evaluation map shown in Fig. 9(c). In this figure, the red dot represents the initial posture, the blue dot represents the final posture, and the curved line is the designed trajectory. The threshold E_{th} in the objective function Eq.(III-B) was set to be $E(\boldsymbol{a}, \boldsymbol{x}_{init})$. The sequence of the user motion is shown in Fig. 11(a). This trajectory makes the user tilt his upper body forward and stand up gradually from the sitting posture. The user can take a seated posture in the region where translation is small, and obtain external forces from the seating face to maintain posture. By



(a) Evaluation map of joint torque of knee.

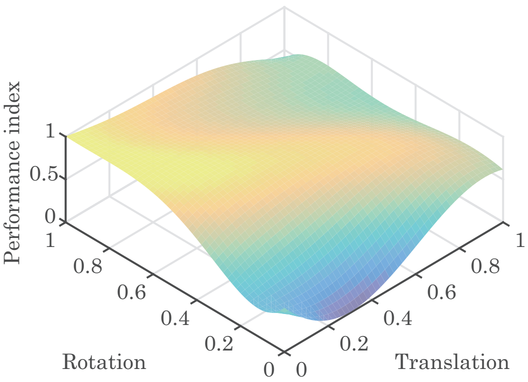


(b) Evaluation map of contact force on underarm.

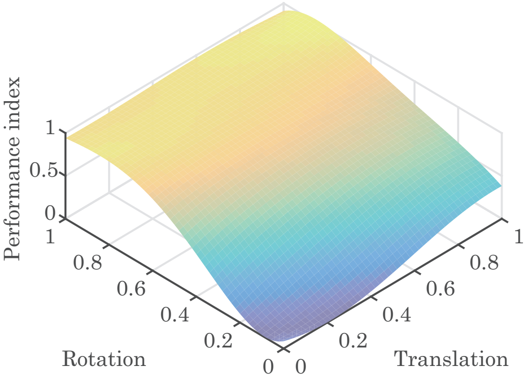


(c) Combined evaluation maps, and designed trajectory.

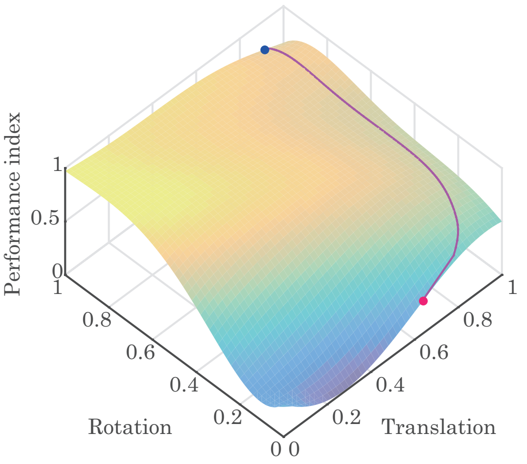
Fig. 9: Analysis example 1.



(a) Evaluation map of joint torque of hip.



(b) Evaluation map of contact force on lower chest.



(c) Combined evaluation maps, and designed trajectory.

Fig. 10: Analysis example 2.

leaning forward while taking that seated posture, the user will move to the posture of getting external forces from the trunk support. As a result of passing through such a route, the device is considered to decrease the other necessary forces for standing such as the knee joint torque and the reaction force on the underarm.

As another design example, the results of selecting the hip joint torque and the contact force on the lower chest as evaluation items are shown. Analysis results of each evaluation value are shown in Fig. 10(a) and 10(b). These values were combined at 1:1 ratio, and the trajectory design was carried out. The device parameters at the initial posture and the final posture and the threshold E_{th} are the same as those of the example 1 mentioned above. The postures during the created trajectory is shown in Fig. 11(b). This trajectory translates in the height direction first, contrary to the trajectory example 1, and then leans forward. As the body falls forward, the upper body approaches parallel to the ground, and the torque required for maintaining the upper body increases. Because this force is obtained by hip joint torque or external force to the chest, it is thought that these burdens become large in the forward–bent posture. Therefore, the trajectory passed through such a route as to avoid the forward–bent postures.

V. CONCLUSION

The paper presented a method for evaluating the physical burden on humans quantitatively, and introduce its application to the design of the movement of the robotic transfer aids based on the analysis.

The proposed method is a basic framework for designing devices in consideration of the physical effect on the user. As can be seen from the analytical results, the designed trajectory is completely different depending on the selected evaluation factors. It is important to carefully consider the physical ability of users and the purpose of the device when deciding the evaluation items. In addition, since the contact pressures distributed according to the contact area, the actual sense of burden will change depending on fitness between the device and the user.

As future work, we plan to perform analysis considering actual use situation such as the user model restricting physical abilities or the change of optimum trajectory depending on different physique of the user. We also apply this method to the analysis for different types of supporting devices and evaluate the effect in the actual design cycle, and aim to establish a unified evaluation framework to support human–centered design. At the same time, we will carry out subject experiments for actual measurements of the contact forces and the postures in order to verify and improve the accuracy of estimation of the posture, the contact forces, and the joint torques.

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(a) Trajectory of analysis example 1.

(b) Trajectory of analysis example 2.

Fig. 11: Resultant sit–to–stand motions. Example 1 reduces the knee joint torque and the contact force on underarm, and example 2 reduces the hip joint torque and the contact force on lower chest.