DESIGN OF ROBOTIC ORTHOSIS ASSISTING HUMAN MOTION IN PRODUCTION ENGINEERING AND HUMAN CARE

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Abstract: Mechanical design of robotic orthoses capable of assisting human forearm motion is discussed. The robotic orthoses should be carefully designed such that two basic specifications will be satisfied simultaneously; 1) human motion is assisted, and 2) the user is safe and anxiety-free. A design concept for the robotic orthoses is presented first. A prototype of a robotic orthosis for production engineering is then described. Another design of robotic orthoses for human care is also discussed. A power assisting control scheme for the robotic orthoses with a macro-micro structure is proposed and investigated using simulations.

Key words: Assistive device, Robotic orthosis, Power assisting control

1 Introduction

Several studies have been carried out regarding mechanisms and control schemes for power assisting robotic mechanisms [1]-[4]. As for the design of their mechanical structures, one important fundamental problem still remains. That is, how we can design mechanisms capable of motion assistance providing users with a safer and more anxiety-free environment. We think that link and reliable safety mechanisms should be designed at the same time. Based on this idea, our group started to design of a robotic orthosis which would be attached to the upper limb [5], [6].

In this paper, we have discussed designs of robotic orthoses as power assisting systems. First, a design concept for robotic orthoses was studied. A basic design method satisfying the required motion capability and mechanical safety is described. A prototype of robotic orthosis for desktop production engineering is then given ample attention. Another design of robotic orthoses for human care motion is also dealt with. A power assisting control scheme for the robotic orthoses with a macro-micro structure is proposed. The power assisting motions produced are investigated using simulations for obtaining proper mechanical properties as the design parameters.

2 Robotic Orthosis Worn by Humans

2.1 Basic concept of mechanical design

Robotic orthosis worn by humans should be designed carefully so that they satisfy the following two basic requirements simultaneously:

- Capability of assisting humans motions
- Safety and no-anxiety

As for assisting human motion, we are making efforts to realize the following two functions [5]:

- Power Assist: Adds required power to human action movement. This function enables people to carry heavier objects with less fatigue.
- Motion Guide: Moves the human body to a desired position. This function enables us to trace given trajectories precisely.

As for safety of the system, mechanical methods must be installed initially, because they are the most reliable compared to other electrical or software methods. Also, in order not to create any additional worry to the user, we can use the following keywords as design guides for robotic orthoses.

- small
- light in weight
- easily to be attached
- easily to be detached during operation

Figure 1 shows two sets of mechanisms A and S, here each point in the sets means a corresponding basic structure. When the point P_1 is an element of the set A but not an element of the set S, the basic structure expressed by P_1 satisfies "Assisting human motion" but does not satisfy "Safety and no-anxiety". We must find a required basic structure expressed by the point P_0 directly, because it is difficult to change from a basic structure to another one, for example from P_1 to P_0. Therefore, we must consider the factors of assisting human motion and safety and no-anxiety simultaneously during the design stage.

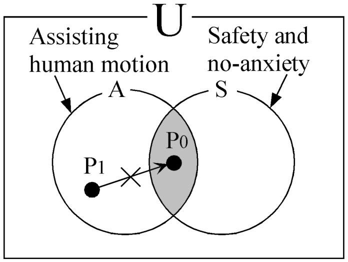


Fig. 1. Two sets of mechanisms satisfying the necessary requirements.

2.2 Basic structure and utilizing force information

In this section, the basic structure of a robotic orthosis and utilizing force information for power assisting control are discussed.

As for the basic structure, adopting a 'wearable type' is a good idea because it makes it easy to design robotic orthoses. A prototype of a robotic orthosis capable of assisting human motion with mechanical safety in mind is described as an example in Section 3.

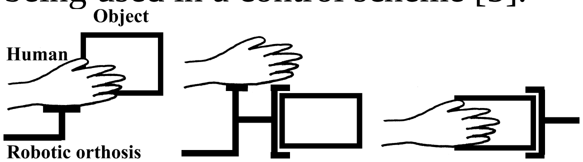
Another idea concerning the basic structure is constructing a macro-micro mechanism for unexpected excessive forces of the robotic orthosis on the user. A related topic is discussed in Section 4.

The following part deals with utilizing force information for power assisting control. Figure 2 shows three cases of connections between a human, a robotic orthosis and an object. H, R and O stand for 'Human', 'Robotic orthosis' and 'Object', respectively. Regardless of the three cases in Fig. 2, Eq. (1) represents the relationship of the forces.

$$\boldsymbol{F} = \boldsymbol{F}_{\boldsymbol{H}} + \boldsymbol{F}_{\boldsymbol{R}} \qquad (1)$$

Here, F_H and F_R denote the forces applied to the object by the human and robotic orthosis, respectively; and F is the resultant force applied to the object. Note that all the forces are converted to the same coordinate.

To realize power assisting movement by the robotic orthosis, these forces are being used in a control scheme [5].



(a) R-H-O (b) H-R-O (c) H-O-R

Fig. 2. Three connections between human, robotic orthosis and an object.

3 Robotic Orthosis in Production Engineering

In this section, an outline of a prototype of robotic orthoses in production engineering [5] is described.

Here, our concrete target is a person sitting in a chair and working with his/her upper limbs. Figures 3, 4 and 5 show the structure and appearance of the mechanism.

This robotic orthosis with eight DOF is designed to assist the human forearm motion and ensure user safety. It is capable of moving the human forearm and hand to an arbitrary position and orientation. The mechanical stoppers, mechanical breakers and mechanical interface were installed to ensure user safety mechanically. The mechanical stoppers are installed in the properly designed link mechanism to avoid any configuration of the mechanism that could injure the body. The mechanical breakers are installed to avoid any excessive force applied to the elbow toward the shoulder. The mechanical interface is installed for detaching the mechanism from humans during operation.

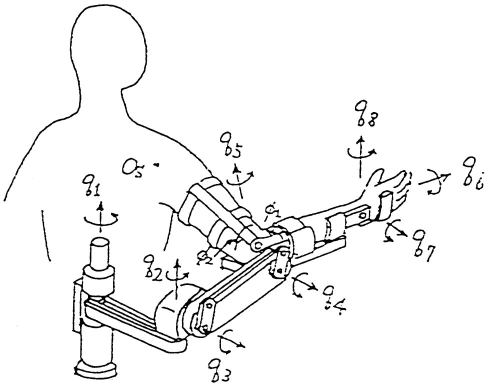


Fig. 3. A robotic orthosis for one of the upper limbs.

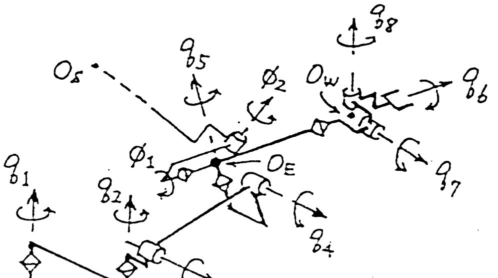


Fig. 4. Structure of the robotic orthosis.

4 Robotic Orthosis regarding Human Care

4.1 Adopting macro-micro structure

In this section, the basic structure of robotic orthoses assisting human care and its design procedures are discussed.

The fundamental requirements on the robotic orthosis are: 1) to assist workers when moving the aged or disabled, and 2) to ensure their safety and not causing any anxiety to the user.

Fig. 5. Photo of the robotic orthosis.

Here, we propose the adoption of a macro-micro structure for the robotic orthosis, because it enables us to decrease the inertia of the mechanism at the point of attachment. In particular, adopting a passive micro part without actuators is very effective. Its small inertia can contribute to avoiding any excessive dynamic forces during unexpected motions and to improving the feeling of the user.

If we have adopted the macro-micro structure with a passive micro part, and we have also determined its mechanical properties very carefully so as to utilize the small motion range of the micro part effectively. This robotic orthosis should be designed in the following way:

1) Determination of the required maximum force: We have to determine it at the endpoint of the robotic orthosis according to the target care motions. For example, the target care motion is lifting up the disabled with mass of 100 kg. It allows us to estimate the required maximum joint torque and the mass of the

macro part.

2) Design of a control scheme satisfying the required functions: We also have to determine the desired properties of the robotic orthosis under a control scheme. It allows us to find the desired mechanical properties of the micro part. As the mass property at the endpoint is dominated by that of the micro part and it should have similar mass properties as the desired one.

3) Determination of the design parameters such as the damping factors: Using simulations under power assisting control might be a reasonable way to deal with the complex dynamics of the robotic orthosis.

4.2 Power assisting control scheme

In this section, the power assisting control scheme for the robotic orthosis with a macro-micro structure is proposed based on the impedance control with a motion transfer function to change the desired position. The impedance control with this motion transfer function provides power assisting motions.

When we adopted a control scheme based on the above idea, the changes in the desired position and the displacement by the impedance control often appears in the opposite direction. However, we can avoid this problem when the gain of the motion transfer function is adjusted to be small in the high frequency domain that includes the natural frequency of the system employing impedance control.

The proposed control scheme is adapted to the model with one degree of freedom shown in Fig. 6. The dynamics of the macro part and the micro part are represented as follows:

$$M_M \ddot{q}_M + g_M + J_M{}^{\mathrm{T}} F_M = T_M - V_M \dot{q}_M \quad (2)$$

$$M_m \ddot{r} + g_m + F_R = F_M \quad (3)$$

$$F_M = -D_m \dot{r} - K_m (r_m - r_{m0}) \quad (4)$$

where M_M, M_m, g_M and g_m are the inertia matrices and the gravity forces of the macro and micro parts. V_M, $\ddot{q}_M$, $\dot{q}_M$ and T_M are the viscous friction coefficient matrix, the joint acceleration, the joint velocity and the joint torque of the macro part. J_M, F_R and F_M are the Jacobian matrix, the endpoint force of the robotic orthosis and the force of the macro part applied to the micro part. r is the position of the endpoint of the micro part, and r_m the length of the micro part. r_{m0} is the initial length of the micro part. D_m and K_m are the matrices for damping and stiffness of the micro part.

Before coming up with an accurate control scheme, we should determine the desired properties of the motion of the robotic orthosis. Here we have introduced the desired mechanical impedance:

$$M_d \ddot{r} + D_d \dot{r} + K_d r_e = F_{RE}\ , \ F_{RE} = -F_R \quad (5)$$

where M_d, D_d and K_d are the desired matrices of inertia, damping and stiffness. $r_e (= r - r_d)$ is difference between r and desired position r_d. F_{RE} is the external force applied to the robotic orthosis.

To derive the control scheme, $\ddot{r}$ is eliminated using Eqs. (3) and (5), and the desired inertia matrix is here determined to have the original properties. The obtained equation is substituted to Eq. (2) to eliminate F_M. Then we derive the following control scheme neglecting $M_M \ddot{q}_M$ to avoid using acceleration signals.

$$\begin{aligned} T_M &= J_M{}^{\mathrm{T}} (-D_d \dot{r} - K_d r_e + g_m) \\ &\quad + V_M \dot{q}_M + g_M \end{aligned} \quad (6)$$

To apply the above control scheme, we have to determine the desired position of the endpoint of the micro part detecting the desired motion in humans. Here, we decided to use the following motion transfer function:

$$\frac{r_{di}(s)}{F_{Hi}(s)} = \frac{C_i}{s(T_i s + 1)} \qquad (7)$$

where F_H is the force in humans, T the time constant, and C the gain of the desired velocity when F_H is constant. Then power assist motion can be realized using Eq. (6) with Eq. (7).

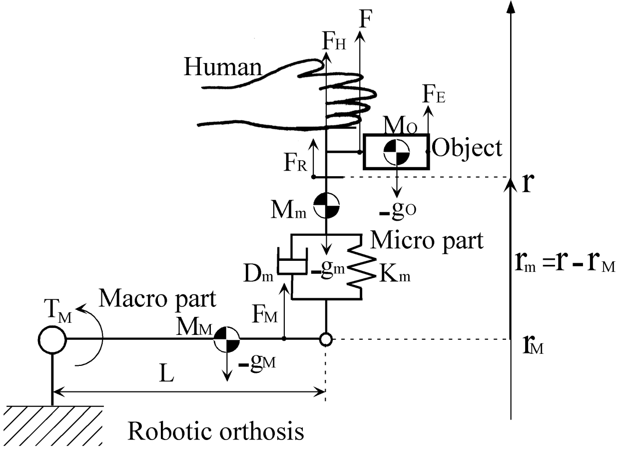


Fig. 6. A model of robotic orthosis with a macro-micro structure.

4.3 Simulation

In this section, the proposed control scheme is simulated. Lifting a mass of 20 kg is tested as a target task.

For carrying out simulations, we assumed that the force of the human F_H is produced in proportion to the difference in the desired position of human r_{Hd} and the position of human r. Proportional gain is K_H=1000[N/m]. Equation (2) is used with M_M=0.9[kgm^2], V_M=0 [Nms/rad] and $J_M = L$=0.3[m]. Equations (3) and (4) are used with M_m=0.5[kg], D_m=1000[Ns/m], K_m= 5000[N/m] and r_{m0}=0[m]. Equation (6) is used as the power assisting control scheme with $D_d = D_m$ and $K_d = K_m$. Equation (7) is used with T=0.25[s] and C=0.001[m/Ns].

The simulated results are shown in Fig. 7. The forces F, F_H and F_R are plotted in Fig. 7 (a). The plus values show that the forces are directing upward. The positions r_{Hd}, r_d and r are plotted in Fig. 7 (b). The positions r_m, r and r_M are plotted in Fig. 7 (c). The ratio of F_R to F is referred to as the power assisting ratio and is plotted in Fig. 7 (d).

The user wears the robotic orthosis on one of his/her upper limbs, and the limb is assumed to be fixed at the initial position before $t = 0$. At $t = 0$, the upper limb is released and a mass of 20 kg is put on the user's hand. The user is trying to keep the upper limb at 0 m position when $0 \le t < 5$. The user is then trying to move the upper limb upward for lifting up the mass when $5 \le t < 11$. After that the user tries to keep the position of the mass at a desired position when $t \ge 11$.

The user is not required to produce a large force since power assisting ratio is being kept at more than 0.77 when $5 \le t < 11$. The changes of the desired position produced by the motion transfer function and the displacement by the impedance control appear in the opposite direction when $0 < t < 0.5$. However, the position of the user's upper limb returns to the initial position. As the gain of the motion transfer function is adjusted to be small in the high frequency domain that includes the natural frequency of the system under the impedance control.

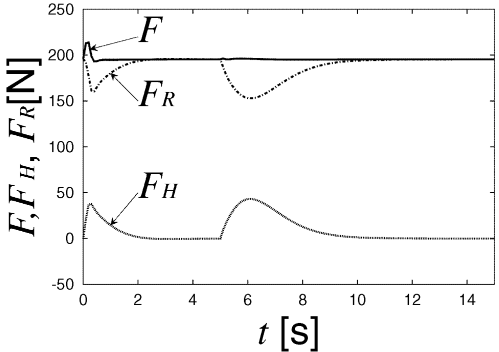
The above results illustrate that the proposed control scheme is available to provide power assisting motions using robotic orthosis.

5 Conclusion

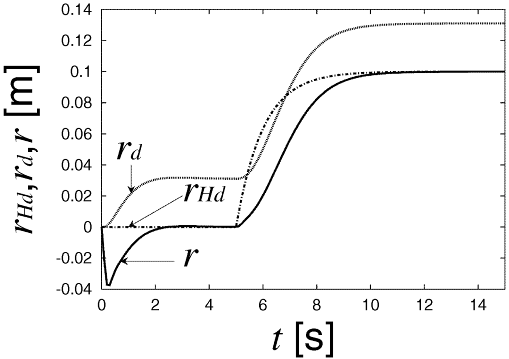
The main results obtained in this paper are summarized as follows.

1) A basic concept on design of robotic orthoses assisting human motion is shown. This concept is utilized to design mechanisms providing re-

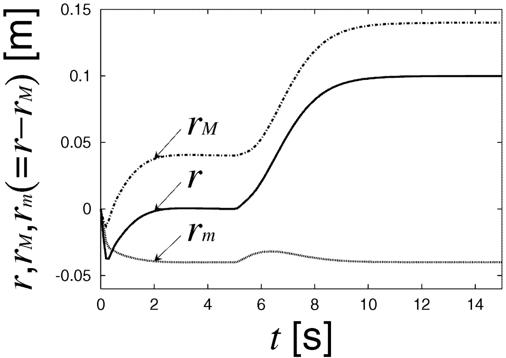
quired motion and mechanical safety simultaneously.



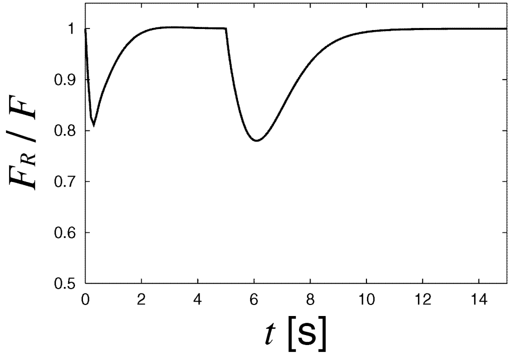
(a) Endpoint forces



(b) Desired positions and their responses



(c) Length of the micro part and endpoint positions



(d) Power assisting ratio

Fig. 7. The simulated results of power assisting motions.

2) A mechanical design of the robotic orthosis based on the concept in production engineering is described.

3) Adopting the macro-micro structure is proposed for the robotic orthosis regarding human care. A method to determine the property of the passive micro part is investigated using simulations.

The concepts and techniques are now being utilized to design a robotic orthosis as regards human care.

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