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3-D Rehabilitation Robot System for Upper Limbs and its Force Display Techniques

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Abstract

Movements of upper limbs are complicated, various and indispensable for daily activities. For patients with impairment of their upper limb, rehabilitation along with medical treatment is needed to recover function. For elderly as well, training is needed to keep their ADL or social activities. Application of robotics and virtual reality technology makes possible for new training methods and exercises and for quantitative evaluations to enhance the qualitative effect of training. However it is difficult for conventional robots to be commercialized for rehabilitation use because of safety insufficiency. The authors have involved in a project managed by NEDO (New Energy and Industrial Technology Development Organization), "Rehabilitation System for the Upper Limbs and Lower Limbs," and developed a 3-DOF exercise machine for upper limb (EMUL). In this paper, the authors report on EMUL which has been developed considering safety. They also mention some software with force display by EMUL, which can help doctors and therapists with their treatment.

Key Words: rehabilitation, upper limb, force display, virtual reality, safety, ER fluid

1. Introduction

The percentage of aged persons in society and their number are increasing, and their physical deterioration has become a social problem in many countries. Deterioration of body function has both direct influences degeneration of motion ability and obstructions in daily activities. Additionally, it is mentioned that deterioration has indirect influences such as brain degeneration. Reversely, persons having physical deterioration by influences of brain ills like stroke are also increasing. Thereby, early maintaining and/or recovering functions is necessary, not only to decrease the numbers of people who are bedridden or need nursing care, but also to enable them to take an active part in society.

Movements of the upper limbs, such as for eating and operating appliances are complicated, various and indispensable for daily activities. It therefore is important for the aged to exercise to keep their upper limb function. Also for disabled, rehabilitation along with medical treatment is needed to recover function [1]. It is, however, often difficult to let patients carry on with training over the long term because of physical and/or psychological pain. It is mentioned that people often neglect their training especially after leaving hospital or some institution. It also need to say that because of difficulty of quantitative evaluation of upper limbs, almost evaluation methods even STEF, which was developed for numerical evaluation, can not eliminate the estimator's subjectivity like awkwardness of movement.

On the other hand, using an apparatus that applies robotic technology of or virtual reality makes possible for new training methods and exercises to be introduced into upper limb rehabilitation. Feedback from the results of quantitative evaluations to patients by using computers can enhance the qualitative effect of training. For instance, Domen et al. studied on quantitative evaluation of smoothness of movement such as variance of joint torque and jerk of movement trajectory while training using a 2-DOF (degrees of freedom) robot arm[2]. Notably when applied VR technology, patient or aged can not just train with fan, they also keep their motivation for a long period. Besides them, the apparatus can be effective to rehabilitation doctors, physical therapists and occupational therapists; it reduces their physical load while training therapy, so that they can concentrate on therapeutic coaching and evaluating training.

Some rehabilitation systems for upper limbs have been developed but most of them apply training within a two-dimensional, horizontal plane, as does the MIT-MANUS [3] by MIT. Many movements, however, in daily activities need to move arms in a vertical direction. A system therefore that enables exercise in three-dimensions would seem to be more effective for such training. However, rehabilitation systems applying training within a three-dimensional to upper limbs have not been in practical use. Although the MIME system [4] and the REHAROB[5] can give training in three-dimensions, these system have robots originally developed for industrial use and may be not be sufficiently safe to train the aged and/or disabled.

This research has been involved in the development of a rehabilitation system for upper limbs in a NEDO (New Energy and Industrial Technology Development Organization as a semi-governmental organization under the Ministry of Economy, Trade and Industry, Japan) Project, "Rehabilitation System for the Upper Limbs and Lower Limbs" since 2001 [6]. Authors with Osaka University have already developed a 2-DOF force display system using ER (Electrorheological) fluid and have carried out experiments in the basic properties, and clinical trials of rehabilitation for upper limbs [7, 8]. The purpose of this research was to develop a 3-DOF rehabilitation system for upper limbs based on this existing knowledge and to construct a rehabilitation system that included a quantitative evaluation of the training and a feedback system of the training results to the trainees. This report presents the 3-DOF exercise machine for upper limb that the authors have developed considering safety.

For rehabilitation use, it is important to develop not only attractive hardware but also attractive software. The authors have developed some kind of rehabilitation software; motion control training software, range of motion training software, coordination training software and so on. In this paper, they report on amusing training software to let trainees move their arms widely in 3-D space without troublesome feeling that they bother to have training at that time.

2. Safety Rehabilitation System, the 3-DOF Exercise Machine for Upper Limb (EMUL)

2·1 Safety Required in Rehabilitation Robot

A rehabilitation system for upper limbs, different from systems for fingers or hands, needs to exercise a whole limb. The system therefore requires a large working space, a large display ability, a good backdrive ability and so on. Such features can not be satisfied with conventional human interfaces as keyboards, joysticks and so on. Thereby such rehabilitation systems are so-called robot systems, but are different too from current industrial robots. The system is operated its end-effector, the control element, in constant contact with the trainee. And since the position of the end-effector is close to the operator's face, there is necessary for operators to be able to use the system safely under any circumstances or conditions to avoid injury to the operators.

Such a type of robot system is near to a kind of force display system. Here, most active-type force display systems use servomotors as actuators. When the system using a servomotor gets out of control because of a bug in the software, computer trouble or the sensor, the end-effector could collide with the operator with very high speed. Most of the systems, however, which have so far been developed are small, like PHANToM [9], and they do not have so large risk of serious injury.

As for studies of medical robot applications, systems with special software and information from sensors have been proposed for safety[10, 11]. However, this makes the system complicated and does not necessarily improve reliability and maintainability of the system. Moreover they are expensive [12].

On the other hand, if the safety could be mechanically ensured, a safe system with high reliability and maintainability can be constructed relatively simply [13]. Thus, it is desirable that the following be realized mechanically.

(i) A speed limit: This will contribute to reduce the kinetic energy or the impact strength when emergency.
(ii) A generative force limit: This will reduce the damage to trainees when the controller went out of order.
(iii) Moving area limit: This will make the possibility of a collision with trainees small.
(iv) Gravity compensation at an end point: This will be effective both in lowering of the torque needed for the actuators and in keeping safe when the apparatus was suddenly shut down and could generate no supporting force for upper limbs.

2·2 Major Specifications of EMUL

This section describes the major specifications in the developed rehabilitation system for upper limbs as shown in Fig. 1 and Fig. 2.

A trainee gets exercise, sitting on a chair by gripping the handle of the upper limb support machine with the right hand and thus training the right limb. For a trainee who needs to train the left hand, another machine is used which has a mirror-image mechanism. If there is no problem, the case may be dealt with by adjusting the chair (moving horizontally). The major targets for this system are dystonic, ataxic or hemiplegic patients with stroke sequelae. The training is thought to include physical therapeutic exercises, such as passive and active exercises, occupational therapeutic exercise like eating movement and cognitive therapeutic exercises.

Fig.1 The Developed Rehabilitation System

Fig.2 The Exercise Machine for Upper Limb (EMUL)

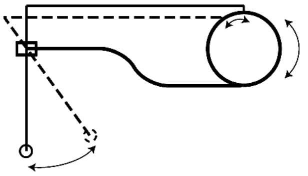

Fig.3 Top view of the machine model

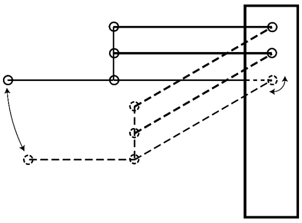

Fig.4 Side view of the machine model

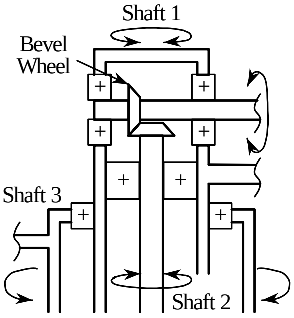

Fig.5 Inner mechanism of shafts

The authors have developed a 3-DOF upper limb support mechanism using ER actuators that has a performance suitable for rehabilitation systems for upper limbs, and can display force senses in three-dimensional space. They call the exercise machine for upper limb EMUL. Figures 2 shows the EMUL and Fig. 3 and Fig. 4 show the motion of the end link part. Figure 5 shows inside of the EMUL.

- The EMUL has 2-DOF for horizontal rotation and 1-DOF for vertical rotation; the actuators drive them. This machine has three shafts: shaft 1 (horizontal rotation), shaft 2 (vertical rotation) and shaft 3 (horizontal rotation) from the foundation to the end. Link 1 is connected to shaft 1, link 2 to shaft 2 and link 3 to shaft 3.
- The end-effector has a 3-DOF handle, which does not impede 3-DOF at the end posture.
- The lengths of link 2 and link 3 are 0.45 [m] and the height of the whole machine is about 1 [m].
- The motion range is about $0.9W \times 0.54D \times 0.50H$ [m] at the maximum and the range of practical training area is about 0.4 [m]-cubic.
- The generative force at the end is about 23 [N] in each shaft direction within the horizontal plane, about 60 [N] in vertical directions.

2·3 The Safety Mechanism of EMUL

The EMUL has larger motion area and the generative force than conventional and standard rehabilitation robots or force display systems. The EMUL has, however, the following characteristics besides the advantages of ER actuators mentioned in Sections 2·4, so that the EMUL keeps safety of trainees.

- All the actuators are set on the base which does not move. A disadvantage in using ER actuators is the increase in the weight the actuators cause. Not moving the actuators themselves, however, can lower equivalent inertia of the control element and the necessary control force.
- The vertically operating part (link 2) has a parallel link mechanism, so constant gravitational torque acts on the vertical-rotation shaft irrespective of the posture of the end link part (link 3). This makes it easy to mechanically compensate for gravity because of the counterbalance, which leads to a lowering of the torque needed for the actuators and is effective both in saving space for the machine and in making the mechanism safer. (*cf.* (iv) in the Sec. 2.1)
- The rotating part of link 3 has a spatial parallel link mechanism. This makes the friction loss low and the machine light. It also leads to a mechanism whose equivalent inertia as seen from the end-effector is low.
- The handle can be moved even if the system downed, so that the trainee is not wedged because the EMUL has large back-drive ability.
- All shafts are limited their rotatable angle by piles. Thereby the motion area of the EMUL is limited in necessary area mechanically as Sec. 2.2. (*cf.* (iii) in the Sec. 2.1)

2·4 ER actuators for safety

Although pneumatic actuators [14] and metal hydride actuators [15] have been proposed as actuators for medical and welfare apparatus instead of servomotors, their response speeds, generative force and mechanical rigidity are not sufficient. The authors consider an actuator using particle-type ER fluid [16] to be effective. ER fluid is a fluid whose rheological properties can be changed by applying an electrical field. Figure 6 shows the principle of an ER fluid actuator. The ER actuator is composed of an ER clutch and drive mechanisms such as a motor driving its input shaft and a reducer. The characteristics of the ER actuator [7, 13] and the advantages of using it for a rehabilitation system are as follows:

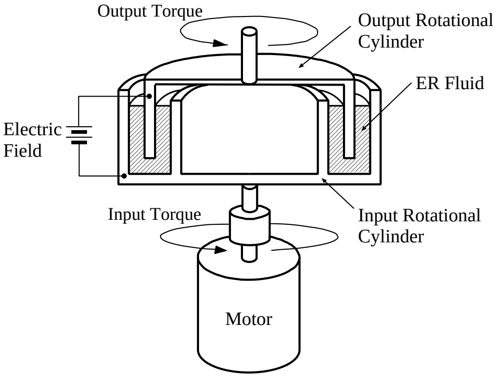

Fig.6 Principle of ER actuator

- The maximum rotational speed of the output shaft is mechanically governed by the input shaft. Thus the speed at the handle can be mechanically limited and the risk of going out of control can be greatly reduced. (*cf.* (i) in the Sec. 2.1)
- It is not necessary to precisely control the rotational speed of the input shaft, so it is possible to drive the input by a simple method. This contributes to high reliability of the safety system.
- The output can be limited in a mechanically fashion by slipping at the ER fluid. Then the EMUL can not generate overladen force. (*cf.* (ii) in the Sec. 2.1)
- It can be used at low speed and high torque, so the reducing ratio after the output shaft can be set low. Thus the moment of inertia at the end point becomes low and it has good back-drive ability.
- In an emergency, cutting off the electrical field can quickly stop the output of the ER actuator.

The authors reported in their previous paper [13] that even though the input shaft speed is set so low, there is no major problem with the basic performance of the force display. In this case, the end speed of the EMUL is limited to about 25 [cm/s] at maximum. This is the standard value in ISO [17], so there is little risk of damaging a trainee in the case of a runaway and the system can be said to be more suitable for rehabilitation than other systems.

3. Training Software with Force Display Technology

3·1 Calculating the Force to Display

On the developed rehabilitation system, coordinate systems are different between that for motor control of the EMUL displaying the force sensation and that for graphical control displaying the position of the handle and other virtual circumstance. A coordinate system for the EMUL, Σ_A, and that for graphics, Σ_B are shown as Fig.7. The handle position ${}^B\boldsymbol{x}_H$ on Σ_B can be written as Eq.(1) by the handle position ${}^A\boldsymbol{x}_H$ on Σ_A and ${}^BT_A$, which is a homogeneous transformation matrix of Σ_A from the view of Σ_B.

$$\begin{bmatrix} {}^B\boldsymbol{x}_H \\ 1 \end{bmatrix} = \begin{bmatrix} {}^B\boldsymbol{x}_O \\ 0 \end{bmatrix} + {}^BT_A \begin{bmatrix} {}^A\boldsymbol{x}_H \\ 1 \end{bmatrix} \tag{1}$$

${}^B\boldsymbol{x}_O$ means the initial position on the graphics coordination and is set to the middle of the screen. Then, the value of ξ makes Σ_B rotate on an vertical axis. The trainee operates the handle, sitting down in the front of the axis Y_B. ξ is in the matrix ${}^BT_A$ and adjusted as the trainee can operate the handle in the convenient area. At present, ξ is set at zero.

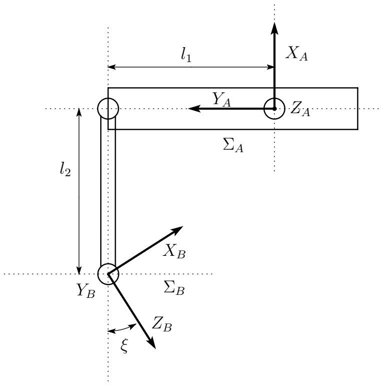

Fig.7 Coordinate Axes in the Standard Orientation (Top View)

Reaction forces from virtual objects are calculated with the spring model. The force vector to display to the trainee, ${}^B\boldsymbol{F}$ on Σ_B, is shown as Eq.(2) by the matrix ${}^BK_P$, which has spring constants of the objects along the direction of axes on Σ_B as its diagonal elements.

$${}^B\boldsymbol{F} = -{}^BK_P\boldsymbol{f}({}^B\boldsymbol{x}_H, \boldsymbol{w}) \tag{2}$$

$\boldsymbol{f}(\boldsymbol{x}_B, \boldsymbol{w})$ means deviation between the handle's position and the nearest object, or the value in what the depth the handle dives into the object.

By the Jacobian matrix, ${}^{A}J$, torques which each ER actuator should generate, $\boldsymbol{T}$, can be shown as follows. Where, ${}^{A}R_{B}$ is a rotation matrix part of ${}^{A}T_{B}$.

$$\boldsymbol{T} = {}^{A}J^{T\,A}\boldsymbol{F} = {}^{A}J^{T}\ {}^{A}R_{B}{}^{B}\boldsymbol{F} \tag{3}$$

3·2 The Options of the Software

In the training software introduced in the following section, one of the three options is chosen for the free space: active exercise, active assistive exercise or resistive exercise.

These are realized by displaying a following force, ${}^{B}\boldsymbol{F}$, in the free space by a matrix ${}^{B}K_{D}$.

$${}^{B}\boldsymbol{F} = -{}^{B}K_{D}{}^{B}\dot{\boldsymbol{x}}_{H} \tag{4}$$

Where,${}^{B}K_{D}$ has velocity feedback coefficients along the direction of axes on Σ_{B} as its diagonal elements. When the coefficients are zero, the training is active exercise training. When the coefficients are negative, the training is active assistive exercise training. When the coefficients are positive, the training is resistive exercise training.

3·3 Virtual Maze

This is a threading maze software in vertical plane. Why the maze is not 3-D but 2-D is because if a 3-D maze was shown on an ordinary computer display it is high possible that pure motion function training of upper limbs becomes impossible due to requirement of high cognitive function to the trainee. The trainee must move his/her upper limb against gravity for the motion in vertical directions. Thereby, the motion is more difficult than that in horizontal directions for objects like ataxia patients whose effective force available from their generative force is not large. By the way, when using a system which can not compensate for gravity, the trainee is influenced by unwanted load except his/her own upper limb. Because the EMUL can mechanically compensate for gravity, however, the trainee can make necessary training with little feeling of the handle weight.

Figure 8 shows a graphic of the virtual maze. The maze is constructed by combination of virtual walls, which are surfaces of the objects displayed in the computer display. The virtual walls are represented with high stiffness springs. Although the trainee can operate the handle freely in the free space, he/she feels a reaction force when the handle collides with a wall. This reaction force is a function of a distance how deep the handle dives into the wall, and calculated by Eq. (2). Here, friction on wall surfaces is ignored, the reaction forces at sharp edges are displayed separated to two directions by their diagonal lines.

Time needed to thread the maze, difficulty of the maze and so on are used for quantitative evaluating and feedback to the trainee. This software will be effective in a range of motion training, a muscle strengthen training, and a coordination training.

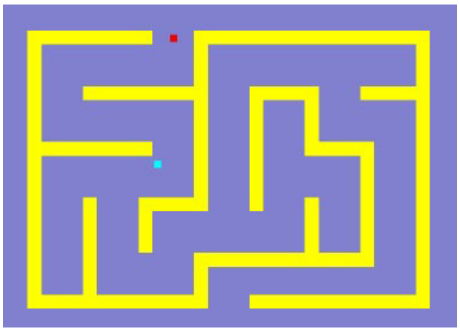

Fig.8 The Virtual Maze

3·4 Erase the Wall Paint !

Figure 9 shows Erase the Wall Paint !, which is similar to Virtual Maze. In this software, a spherical rubber equivalent to the handle position and some vertical walls are displayed. The trainee moves the blue ball and erases the painted mask on the picture on the wall. Walls are represented virtually and the trainee can feel reaction force by them. When the trainee erases the most of the mask, he/she clears this stage and goes to the next stage. In the next stage, another masked wall stands on farther than the last stage. The percentage how the trainee must erase the mask can be changed optionally.

This software can be used as a range of motion training and its evaluation, because there are walls one by one as the stage goes, or the trainee has to extend his/her arm as it does. This software is also for a muscle strengthen training and a coordination training, with fun to keep trainees from getting bored. Fig. 10 shows a sample of an evaluation. A range of motion is displayed with a volume figure.

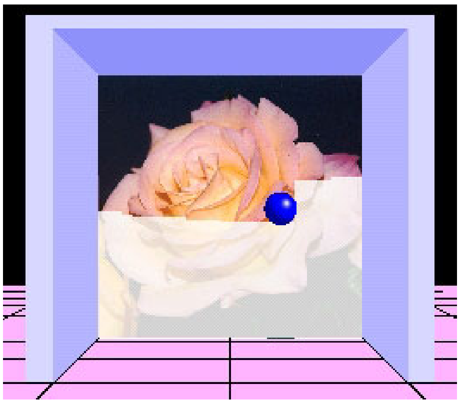

Fig.9 Erase the Wall Paint !

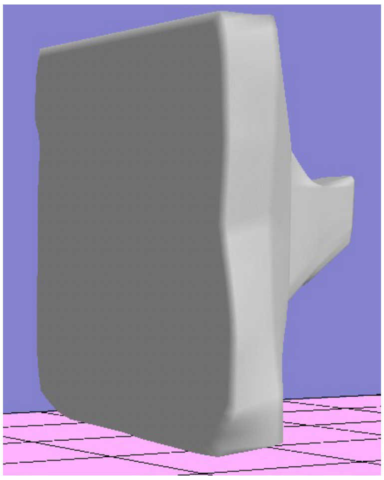

Fig.10 A Sample of an Evaluation by Erase the Wall Paint !

3·5 Virtual Hockey

The virtual hockey has been developed for a training required quickness of motion and higher brain function (*cf.* Fig. 11). Trainee's paddle equivalent to the handle position and a puck are displayed on the court set in a horizontal plane. The trainee moves the handle, or operates the paddle and hits the puck to enemy's goal. When the puck moves into enemy's (the trainee's) goal, the point of the trainee (the enemy) is added, the puck reappears at a randomized point after a few seconds, and the game restarts. The game is completed when one of the scores becomes a point set up beforehand. The height of the court, the puck size and the goal mouth size can be changed optionally. Time needed to win, the numbers of hitting the puck and so on can be evaluation metrics.

The authors will add enemy side players to this software in future work.

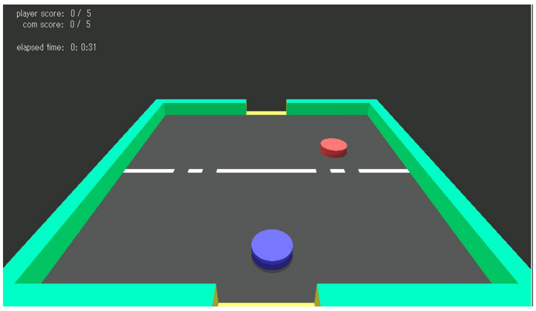

Fig.11 The Virtual Hockey

3·6 Struck Out !

For a training necessitating speed and precision of motion, the authors have developed Struck Out ! (*cf.* Fig. 12). This software is a kind of shooting game, and displays nine targets located in a vertical plane, a ball indicating the handle position and a start point of trial. The trainee controls the ball by manipulating the handle from the start point, and pierces the target wands. The game is end when the all targets are broken. Evaluation metrics are time needed to pierce the all target wands, the total move distance, and so on.

Just after the start of a training or breaking a target, the game condition turns into what the trainee can not pierce. In this condition, the EMUL does not display a force. When the ball returns to the start point, the condition returns into what the trainee can pierce. To be more accurate, this software has three types of criteria which the trainee can pierce the target. These are as follows and one of these is chosen optionally.

Hard mode In this mode, the trainee can attack each target with five seconds time limit. That is to say, the trainee must pierce one of the targets within five seconds after returning to the start point. In addition, the target wands are thicker ones. The thicker wand feels like a panel or a wall.

Easy mode This mode also has the time restriction. The target wands, however, are thinner ones. The thinner wand feels like a paper stretched tightly.

Practice mode This mode has no time limit. The targets are thicker ones. The trainee can attack again and again until he/she breaks a target.

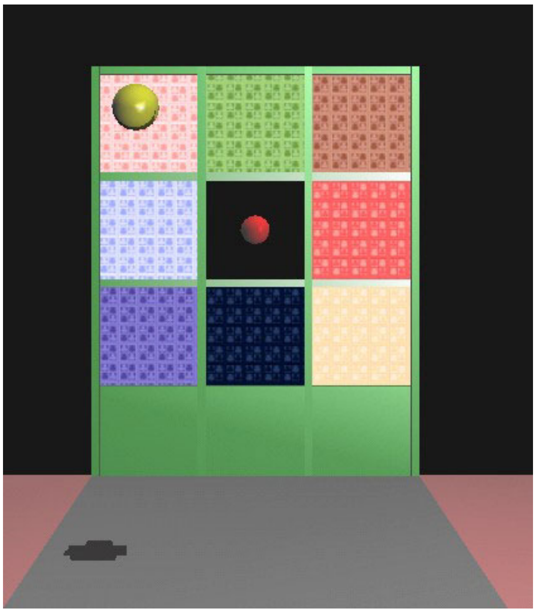

Fig.12 Struck Out !

4. CONCLUSIONS

The EMUL, a 3-DOF motion exercise machine for upper limbs has been developed for a 3-D rehabilitation system. Notably, ER actuators have been installed to make the system safer. The EMUL has following safety systems as mentioned in this paper:

- A speed limit
- A generative force limit
- Moving area limit
- Gravity compensation at an end point

The authors has next been developed some software to train with fun. These are the Virtual Maze, Erase the Wall Paint !, the Virtual Hockey and Struck Out !. All these software consists of force display techniques, and can evaluate motion functions of trainees quantitatively. Some software has options to make trainings suit to the trainee's condition.

In future work, the effect of our rehabilitation system will be experimentally proved in medical facility.

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