Development of a Variable Viscoelastic Handshake Manipulator Based on the Analysis of Viscoelastic Property of Human Elbow Joint in Handshake Movement

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1. Introduction

In recent years, industrial robots are in an explosion, hundreds of thousands of robots in different shapes and sizes are working to replace human labor in manufactory lines. According to the statistics, the annual worldwide supply of industrial robots is growing over 14% on average [1]. The significant cost reduction of the mechanical parts used in robots and the development of microprocessors are the 2 main reasons why industrial robots suddenly started to boom about 3 years ago. As the microprocessors are growing smaller yet faster every year, the complicated calculations of kinetics and dynamics are made possible to be commercialized. Plus, the newly developed computer vision technology, robots begin to do some amazing work.

Conventional industrial robots are commonly shielded from humans. However, with the development of social robots [2] in recent years, robots are purposely put in contact with humans for interaction, such as rehabilitation or supporting for hard physical work. Therefore, social and physical interaction between robots and humans is foreseeably to extend in the future [3]. The cooperation between human and robots calls for attention to an inevitable question about the safety of the robot and how to plan the movement so that the robot can move along with a human. Furthermore, since robots are expected to participate in our daily life in the future, the physical interaction between human and robots are gaining more attention every day.

Based on all the development tendency in the robot industry this paper aimed at developing a manipulator for human-robot physical interaction research. Among all the possible ways to interact with robots, we have chosen handshake as a typical physical interaction for our research, because handshake is a fundamental part of human physical interaction that is transversal to various cultural backgrounds. It is also a very challenging task in the field of physical human-robot interaction.

2. Human handshake analysis

2.1 Experiment purpose

Base on the assumption that variation in joint viscoelasticity can create different handshake feelings, first we need to acquire the quantitative joint viscoelasticity property under different handshake situations for analyzing. However, because the joint viscoelasticity is not directly measurable in complete free motion, I used the estimation methods to estimate the joint viscoelasticity property. For that purpose, I need to measure the basic physical property during a handshake, i.e. length and weight of the arm, joint angle, angular speed, and interaction force, etc.

2.2 Experiment setup

In order to measure the different handshakes, an instruction video was made to explain two different feelings of a handshake: an enthusiastic handshake (firm handshake) and an indifferent handshake (weak handshake). Then we made a conversation with each subject to make sure that they had experienced the actual feelings of these 2 different handshakes and then they were asked to practice different handshakes until they were confident to perform both. During the experiments, the subjects were instructed to do the firm handshake and weak handshake 3 times each with the experimenter. Experiment system is shown in Fig. 1.

Each trial of the experiment started by the staff saying "start!" and press a button to send the start signal to the motion capture device. And each subject was instructed to shake hand ten times in each trial. This handshake duration was around 1.5 times longer than a common business handshake. The start trigger was applied for the convenience of comparison in the analysis of the data, and the handshake duration was determined to make sure there are enough data for analysis and the ending cycle of the movement will be trimmed in when the data was processed.

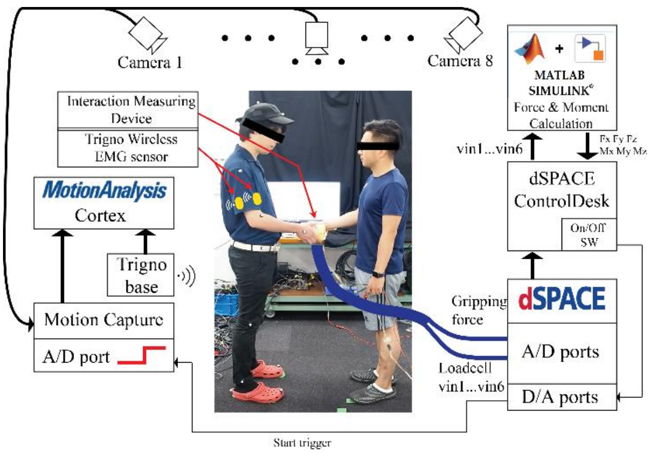


Fig. 1 The diagram of the complete handshake measurement system

2.3 Interaction force measurement device

In this experiment, the interaction forces and moments of 3 axes were measured by the measuring device shown in Fig. 2. The 6 output voltage signals of the loadcell were amplified by a special amplifier and sent into the A/D ports of dSPACE. A mathematic model of the loadcell was built by Matlab and the forces and moments of 3 axes were calculated. The measuring device comprises of two identical holding parts connected to each other with an angle of 180 degrees, which is the natural degree when two people hold hands in a handshake position. Between the two holding parts a 6-axis loadcell was installed to measure the interaction force and torque between two people when they shake hands.

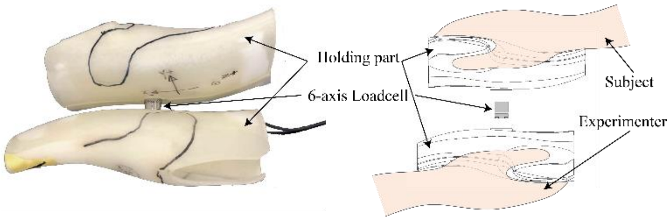


Fig. 2 Measuring device and how two people hold it

2.4 Joint stiffness and viscosity estimation

In this research, two different approaches of joint stiffness estimation were applied. The first on was using EMG signal as an indicator of muscle activations, and the second one was to used the calculated joint torque for estimating the joint stiffness. And for joint viscosity estimation, we modeled the joint as a harmonic oscillator and adopted the viscosity concept as the force moment per unit angular velocity. According to the result of a previous research [4], the estimated joint stiffness has a linear relationship with the processed EMG signal. Therefore, we added the bicep and triceps EMG signal together to be used as the estimation of the joint stiffness. And considering the respond time of the artificial muscles, we filtered the processed EMG signal one more time, with a low-pass filter of 2 Hz, and used the filtered signal as the target stiffness estimation.

Since the direct measurement of the joint stiffness is impossible in a free movement, we used the simplified spring-damper model as introduced in Eq.(1) as the quantitative estimation of the elbow stiffness.

$$T(t) = m(t)d^2\alpha(t)/dt^2 + b(t)d\alpha(t)/dt + k(t)[\alpha(t) - \alpha_0(t)] \quad (1)$$

It had been verified that although the damping of a joint is tightly linked to its stiffness under isometric conditions where the damping ratio remains relatively constant, it’s not the case during voluntary movement, because reflex torque contributes differentially to damping while stiffness depending on movement frequency. Also that angular velocity of a joint has a significant effect on the damping coefficient. In this research we modeled the elbow to be an underdamped mass-spring system. Mechanical parameters were estimated by fitting oscillations occurring in the velocity record. Without damping, it would not be possible to position a limb quickly and accurately, nor would it be possible to rapidly damp oscillations when the limb was subjected to an impulsive force. The term viscosity has frequently been used to refer to the velocity-dependent mechanical properties of joints. The estimated joint stiffness and viscosity are shown in Fig. 3

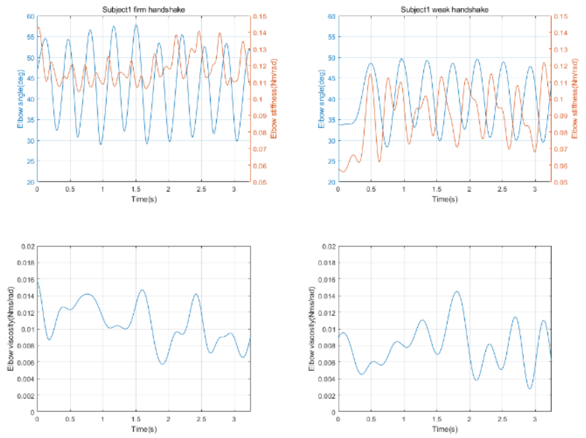


Fig. 3 Estimated joint stiffness and viscosity

3. Variable viscoelastic handshake manipulator

3.1 Concept of the manipulator design

The cooperation between human and robots calls for attention to an inevitable question about the safety of the robot and how to plan the movement so that robots can interact with humans. In order to meet the foreseeably coming demands, we proposed a new type of robot arm that is driven by a soft actuator comprised of antagonistic artificial muscles and MR-brakes (shown in Fig. 4). The artificial muscles drive the joint by pulling a wire that is connected to the pulley of the joint. Joint angle and joint elasticity could be controlled independently by applying different air pressure to the artificial muscles. And MR brakes are used to achieve variable viscosity, also used to compensate for response overshoot of the artificial muscle. The artificial muscles represent the elastic element of human muscle and the MR-brakes represent the viscous element of human muscle. In this research, the proposed robot arm was specialized for human-robot handshake research which is why it is referred to as the handshake manipulator. Each part of the handshake manipulator and its controller are explained in detail in the following sections.

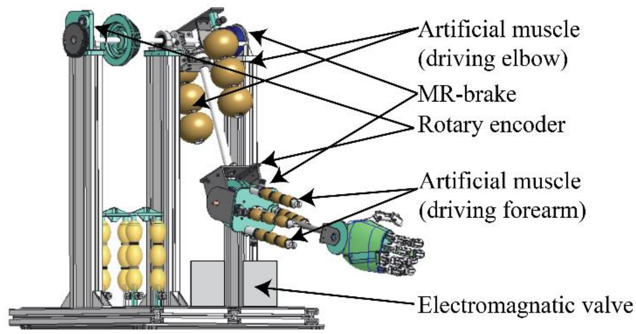


Fig. 4 Schematic diagram of the proposed handshake manipulator

3.2 The structure of the human elbow joint

Human joints are driven by antagonistic muscles. And the physical model of a joint comprised of two separate elements, the elastic element and the viscous element as shown in Fig. 5. The elastic element determines the angle and the stiffness of the joint, in which joint angle and joint stiffness can be controlled independently, while the viscous element determines the viscosity of the joint, which generates the velocity related frictional power in the joint. In this research, we made the assumption that human arms are able to perform different handshakes by controlling the viscosity and stiffness of the joints. Considering the variable viscoelastic features of the human joint, we proposed the combination of magneto-rheological fluid brakes (MR brake) and artificial muscles as the actuator for robots that aim at doing research on human-robot interaction.

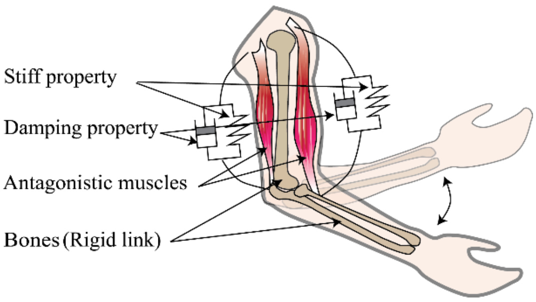


Fig. 5 Structure of human elbow joint

3.3 Structure of the actuator

In this research, we proposed a soft actuator comprised of one pair of artificial muscles which resemble the elastic part of the human muscle and MR-brakes which resemble the viscous element of the human muscle. The configuration of a single actuator is shown in Fig. 6. The artificial muscles were installed antagonistically when air pressure was applied to the artificial muscles, they would contract and pull the tendon connected to the pulley. The rotation axis of the joint was connected to the rotor in the MR-brake, and by controlling the current applied, the MR-brake generates friction force the same as the damping element in a real human joint.

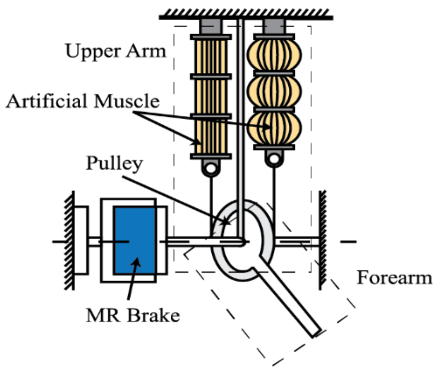
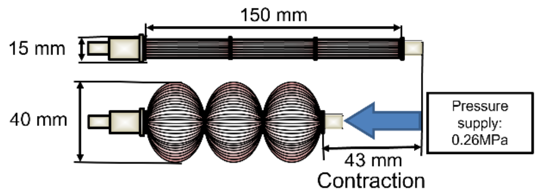


Fig. 6 Movement of hybrid pneumatic system

Artificial muscle

The artificial muscle we used in the proposed actuator is called the straight-fiber-type artificial muscle. It contracts in the axial direction and expand in radial directions when air pressure is applied. Varies by diameter, length and section number of the artificial muscle, the maximum contraction rate of a straight-fiber-type artificial muscle is between 25-30%. The schematic diagram of a straight-fiber-type artificial muscle is shown in Fig. 7. The shape of the artificial muscle is a tube, and the material is natural rubber-latex liquid. When air pressure is applied, the rubber will expand, but since there is a carbon fiber layer in the axial direction, the fiber restrains the expansion so that the rubber is not extended. As a result, the artificial muscle only expands in the radial direction while contracts in the axial



direction.

Fig. 7 Schematic diagram of Straight-fiber-type artificial muscle

MR-Brake

The magneto-rheological fluid is a functional fluid which generates frictional torque when subjected to a magnetic field. MR-brake is a device that utilizes the characteristics of the MR fluid to generate controllable brake torque. Since the response of MR fluid is very fast, MR brake can reach the target output torque within approximately 10 ms. MR brake is small enough in size to install in a robot arm and generates torque high enough to suspend the arm's movement, and the torque can be controlled accurately at a very high-speed response. Therefore, MR brake is ideal to use as the viscous element for the handshake manipulator. A schematic diagram of the MR brake is shown in Fig. 8.

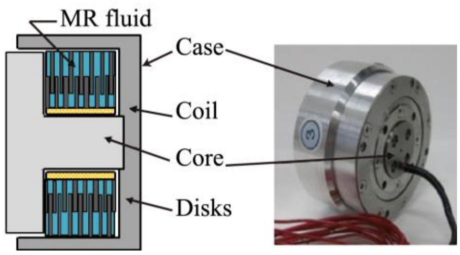


Fig. 8 Schematic diagram of the MR brake

3.4 Feed-forward controller

The mathematic model of elbow joint was derived in the previous study [5]. With the proposed mathematic model, a feed-forward (FFW) controller can be developed. This is the most straightforward controller for the actuator comprised of artificial muscle and MR brake, which takes target angle, target stiffness and target viscosity as inputs and controls viscosity, elasticity and joint angle independently. In order to focus on studying how joint stiffness and viscosity can affect the feeling of handshake, we applied this controller in this research. Based on the force equilibrium equation (3.1) and the elastic characteristics equation of the artificial muscles (3.3) (3.4), the desired air pressure for the artificial muscle can be calculated. The controller developed for the elbow is shown in Fig. 10.

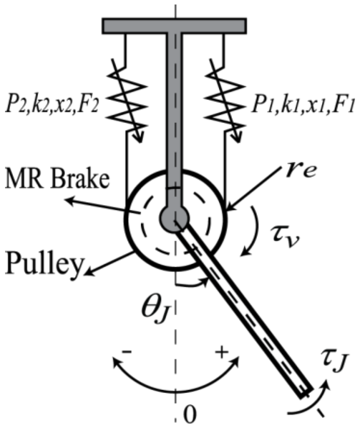


Fig. 9 The mathematic model of elbow joint

$$P_{in}(x,F)=\frac{\{G_1(x)+FG_2(x)\}}{G_3(x)} \qquad (3.1)$$

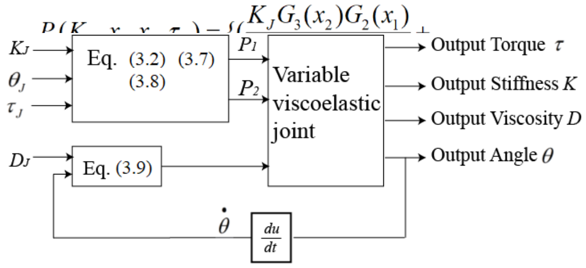
$$x_i=c_i+r_e\theta_J \qquad (3.2)$$

$$K_J=r_e^2(k_1+k_2) \qquad (3.3)$$

$$K_J=r_e^2k_a(P_1+P_2) \qquad (3.4)$$

$$F_i(x_i,P_i)=\frac{\{P_iG_3(x_i)-G_1(x_i)\}}{G_2(x_i)} \qquad (3.5)$$

$$F_1(x_1,P_1)-F_2(x_2,P_2)-\tau_J/r_e=0 \qquad (3.6)$$



$$\tau_v=D_J\frac{d\theta}{dt} \qquad (3.9)$$

Fig. 10 Feed-forward controller of elbow joint

4. Human-robot handshake experiment

4.1 Experiment setup

The human-robot handshake experiment utilized the experiment results of the estimated joint stiffness and viscosity of different subjects to the handshake manipulator in the expectation of creating the feeling of shaking hand with different persons. The experimenter in the human-human handshake experiment was asked to be the subject in the human-robot handshake experiment. His muscle activation and subjective evaluations were taken to be compared when handshake with the manipulator and with different human subjects.

The concept of this experiment was that by changing the viscoelasticity properties of the handshake manipulator, the manipulator can perform handshakes like different persons. The experiment setup was shown in Fig. 11

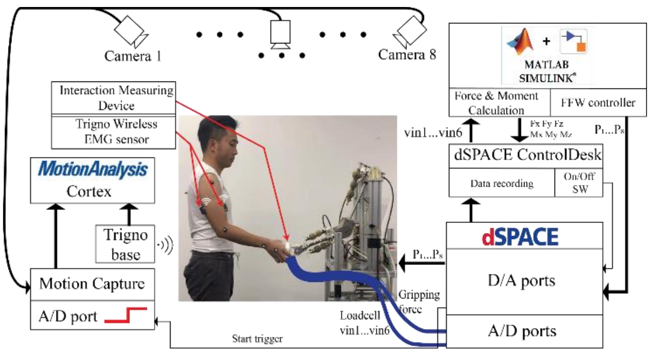


Fig. 11 System setup of human-robot handshake experiment

4.2 Subjective evaluation

Subjective evaluations were taken after each trial in the form of a questionaire. The quesitonair was shown in Fig. 4.14. It asked the subject about how did he think the experiment condition was. And the questionair was comprised of 2 parts about the stiffness condition and viscosity condition separately.

Can you tell the stiffness and viscosity condition of this handshake?

Stiffness condition

☐ Firm ☐ Weak ☐ Can't tell

Viscosity condition

☐ No viscosity ☐ Low viscosity ☐ High viscosity ☐ Variable viscosity ☐ Can't tell

Fig. 11 Questionnaire of subjective feelings

5. Conclusions

In this research we proposed a new variable viscoelastic handshake manipulator to research the human-robot handshakes, and built the prototypes. The manipulator has been proven to have high compliancy and back-drivability, it's effectiveness as a handshake research device has been demonstrated by experiments. The experiment results indicated that by controlling the viscoelasticity of the joint it is possible to generate different type of handshakes.

6. 参考文献

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