Impedance characteristic of the human arm during passive movements

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ABSTRACT

This paper describes the impedance characteristics of the human arm during passive movement. The arm was moved in the desired trajectory. The motion was actuated by a 1-degree-of-freedom robot system. Trajectories used in the experiment were minimum jerk (the rate of change of acceleration) trajectories, which were found during a human and human cooperative task and optimum for muscle movement. As the muscle is mechanically analogous to a spring-damper system, a second-order equation was considered as the model for arm dynamics. In the model, inertia, stiffness, and damping factor were considered. The impedance parameters were estimated from the position and torque data obtained from the experiment and based on the "Estimation of Parametric Model". It was found that the inertia is almost constant over the operational time. The damping factor and stiffness were high at the starting position and became near zero after 0.4 seconds.

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1.   INTRODUCTION

The human being is the best creature in this universe. In comparison to other creatures, the size and shape of the human body are most favorable in all respect and every movement of the human body is smooth and perfect. In the past, scientists have tried to build a mechanism that imitates parts of the human body to perform the task for mankind. The development of robots during the latter half of the twentieth century is its burning example.

Among the moving parts of the human body, the upper limbs are used most frequently. The main function of the upper limb is grasping and manipulating. This is also used as a walking aid to support the body during gait. The upper limb consists of three main parts, the upper arm, forearm, and hand. It is composed of three chain mechanisms, the shoulder girdle, the elbow, and the wrist, whose association allows a wide range of combined motion. Due to the complexity of the hand mechanism, the wrist was not studied, and the hand was taken as another rigid segment in the extension of the forearm. The movements of the human arm can be divided into three major types: i) active movement, an external force is exerted by the hand; ii) reaching movement, without exerting any external force; and iii) passive movement, a hand is moved by external force [1].

The arm is a multi-joint redundant manipulator. It is found that the normalized speed and velocity profiles for single and multiple joint trajectories are identical [2]. Shoulder velocity profiles remain

unchanged, but the acceleration phase of elbow trajectories is adjusted so that peak velocity and movement time match that of the shoulder joint. They argue that hand-path is the primary movement criterion, and that elbow movement is subordinate to elbow movement in a hierarchical scheme to reduce the available degrees of freedom.

Cruse and Brüwer studied planar reaching movements while recording shoulder, elbow, and wrist angles to determine how subjects solved the redundant degrees of freedom problem [3]. They propose that each limb has an almost comfortable position and that by associating a cost to deviations from this position, the posture adopted to reach a point in space minimizes this cost [4], [5]. Movements are executed as a compromise between simultaneous, smooth interpolation of joint angles, minimizing discomfort, and straight hand paths. Rossetti *et al*. studied variability in pointing movements and found that errors increased at extreme joint positions [6]. They also concluded that configurations are chosen to minimize the sum of discomfort at the participating joints.

The impedance characteristics of the arm must be affected by kinematic properties of the human arm, motor control signals from the central nervous system (CNS), individual properties of each muscle, and proprioceptive feedback via the muscle spindle and Golgi tendon organ. For multi-joint hand movements, the hand stiffness and viscosity can be predicted with sufficient accuracy under the assumptions that the length of the muscle moment arm and the muscle viscoelasticity can be approximated by polynomial models of the joint angles [7]. Flash and Mussa-Ivaldi examined to what extent the kinematic properties of the human arm can explain its spatial variations and found that the anatomical factors are not sufficient to account for the observations [8].

Several studies have been made for single-joint and two-joint arm movements, where one human moved or/and regulated a task. Dowben has shown that the viscoelastic properties of skeletal muscles, which are the major source of human hand viscoelasticity, largely change depending on their activation level [9]. It has been also shown that the change of viscoelastic coefficients depends on the activation level of muscle [10], task instruction of the subjects [11], joint angles [12], and speed of the arm movement and loading [13]. Tsuji *et al*. pointed out that muscle contraction for a grip force increases stiffness and viscosity of the hand [14]. Also, Gomi *et al*. estimated hand stiffness during two-joint arm movements and argued that dynamic stiffness differs from static one because of the neuromuscular activity during movements [15], [16]. Tsuji analyzed the spatial characteristics of the human hand impedance with considering of effect of arm posture and muscle activity [7]. Gomi and Osu again showed that the stiffness and viscoelasticity of human multi-joint arm change under different contraction conditions during posture maintenance tasks and during force regulation tasks [17].

All the studies described are related to active and reaching movements. But it has been pointed out that passive movement is important for the cooperative task [18] and a variable structure of impedance characteristics is regulated by a motor command from the CNS. No attempts have been made to find out the characteristics of the human arm in passive movement and the time-variant nature of the impedance characteristic of the human arm.

An investigation has already been made into the impedance characteristics of the human arm's passive movements (the arm is moved by an external force) in the forward and backward direction while the forearm was in the horizontal position. Both the upper arm and forearm were in the same vertical plane. The elbow and the shoulder joint were assumed to have a constant center of rotation. The forearm was treated as a rigid body. In that investigation, mass, stiffness, and damping factor for the variable impedance model had been considered. It was found that the stiffness and the damping factor varied with the operational time [18].

In the present investigation, one degree-of-freedom rotational passive movements of the forearm around the elbow were considered. Both the upper arm and forearm were in the same horizontal plane. As only two muscles, biceps brachii and triceps brachii, are used in this rotational operation, the mechanics of the muscles and bones are simple and it is easier to analyze the characteristics of the musculoskeletal system [19]. To learn more about human motor adaptation, works have investigated the adaptation to stable [20]–[22] and unstable [23]–[25] interactions produced by a haptic interface.

In a cooperation task performed by two humans, one human control the position of the carried object and the other human follows the motion of that object. The former can designate as a leader and the latter as a follower. The characteristics of the follower can be applied to the control method of a cooperative robot. Moreover, if the target trajectory controlled by the leader is known, then the characteristics of the follower can be investigated easily as a simple spring-mass-damper system [1]. The arm of the human is moved along the target position trajectory and the force exerted by the arm is measured. From the data of the target position trajectory and force, the impedance characteristics of the human arm can be estimated.

The time trajectory of position and velocity found during the experiment of cooperation between two humans is similar to the minimum jerk motion proposed by Flash and Hogan [26] and Ikeura and Mizutani [27]. They found that the human arm moves to minimize (1) and (2).

$$J = \int_0^{t_f} \left(\frac{d^3\theta}{dt^3}\right)^2 dt \tag{1}$$

where t_f is the time duration of motion. The trajectory was derived by minimizing the function J as:

$$\theta(t) = \theta(0) + a\{10(t/d)^3 - 15(t/d)^4 + 6(t/d)^5\} \tag{2}$$

where a is movement amplitude, $\theta(0)$ is the position at time t_0 and d is the duration. The position and velocity for movement of 60^0 are shown in Figure 1.
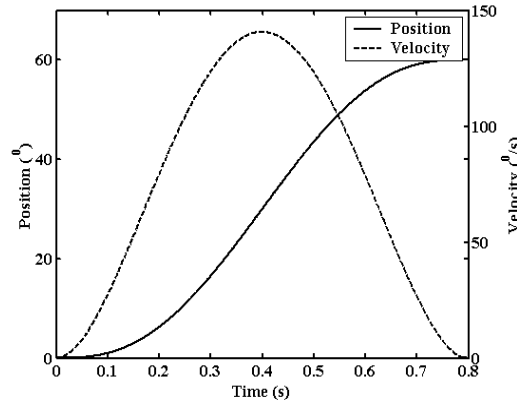

Figure 1. Time trajectory of position and velocity

The minimum jerk trajectory represents the free arm motion. Ikeura *et al*. found the minimum jerk trajectory in the cooperative motion of two humans [28]. This means that the tracking of the motion of the follower's arm is along the minimum jerk trajectory. In the cooperation between a human and a robot, the robot should follow the motion of the human so that the human can move his/her arm along the minimum jerk trajectory.

2. METHOD
2.1. Experimental set-up
Figure 2 illustrates an experimental system, in which a servo motor was used as the actuator. The servo motor was fixed into a frame vertically upward. One end of a splint (50×8 cm thin aluminum plate) was attached to the shaft of the motor. The arm was rotated along with the splint. A sensor located in between the arm and the splint was used to measure the torque needed to move the arm.

The output of the torque sensor was sent to the personal computer (PC) through the digital signal processing (DSP) board. An encoder was used to measure the angular position and the data was passed to the computer through the counter board. All boards were implemented on an industry standard architecture (ISA) bus of the PC.

2.2. Experimental procedure
The subjects are three right-handed male post-graduate university students (30-35 years old) with no previous history of neuropathies or trauma to the upper limbs. The subjects were given sufficient information about the experiment and then taken their consent to participate. In the experiment we defined a leader and a follower, the leader controls the position of the object and the follower tracks the motion of the object. Here, the robot was considered the leader and moved the splinter in the clockwise/anticlockwise directions. The leader controls the position, so the role of the robot was the same as a human leader at that time. The reason for choosing the robot as the leader was to move the arm at defined operating conditions.

As shown in Figure 2, a subject who followed the movement of the linear motor was seated beside the setup. The shoulder of the subject was restrained to the chair back and the elbow of the right arm was supported in the horizontal plane by a belt attached to the ceiling. He placed his arm on the splint so that the wrist was fitted into the torque sensor attached to the splint. Then the torque sensor was adjusted so that the elbow was positioned just above the center of rotation of the splint. A gap was maintained between the arm and splint as shown in Figure 3.
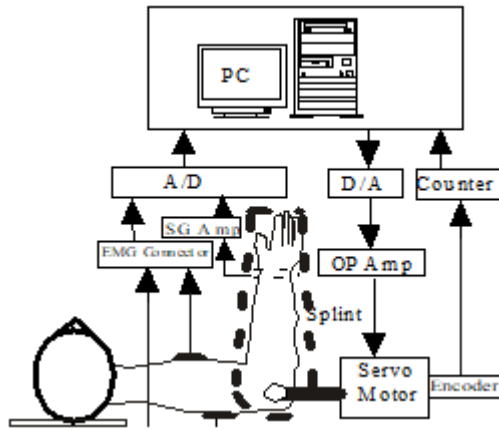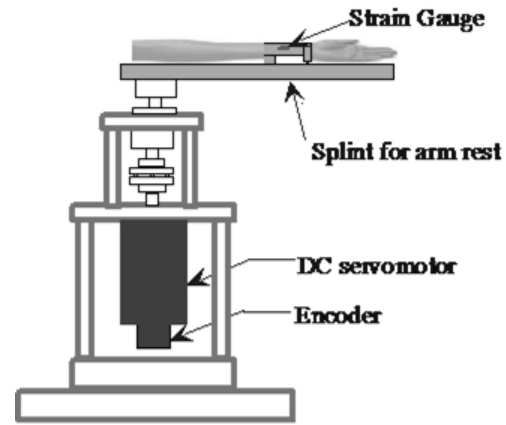
Figure 2. Experimental set-up

Figure 3. Servo-motor and splint

Figure 4 shows the control system of the experimental setup. Position trajectories used in the experiments were minimum jerk trajectories. The velocity trajectory was the first-order differentiation of the position trajectory. Movement amplitudes were 40^0-70^0 and the duration of the movements was from 0.6 to 1.2 seconds, with an increment of 0.2 seconds. The sampling time for the position control of the servo motor was 5 ms. The selection of position trajectory was done randomly so that the subject could not imagine the direction of rotation.

2.3. Data analysis

As the muscle is mechanically analogous to a spring-damper system, as shown in Figure 5, a simple second-order equation was used as the model for the arm dynamics. In the model, mass, damping factor, and stiffness were considered.

$$I_m\ddot{\theta} + c_m\dot{\theta} + k_m\theta = \tau \tag{3}$$

where I_m, c_m, and k_m are the impedance parameters for inertia, damping factor, and stiffness and τ is the torque to rotate the arm.
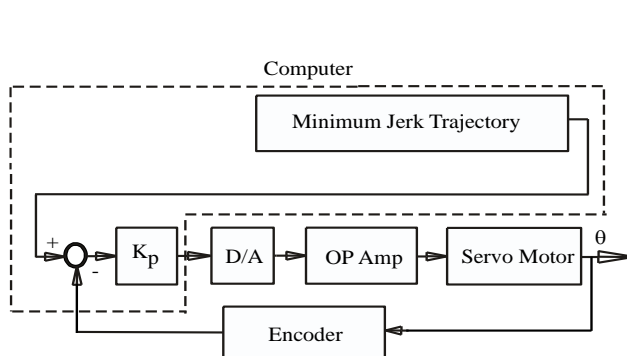

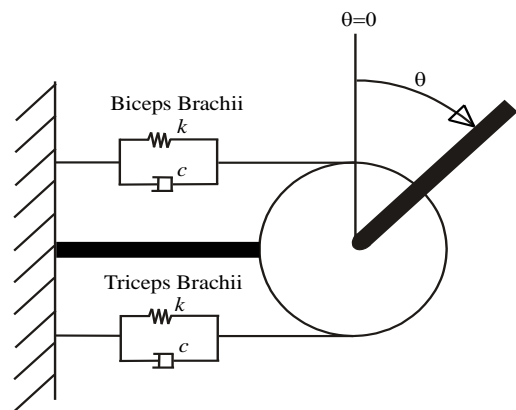Figure 4. Block diagram of control system

Figure 5. Impedance model of the human arm

For the estimation of the impedance parameters, the system identification toolbox of MATLAB (The Math Works, Inc.) was used [29]. For calculations, auto regressive exogenous (ARX) model was used. To make similarity with the ARX model, position $\theta(t)$ as an input and torque $\tau(t)$ as output was considered. If T is the sampling time then, $\dot{\theta}(t) = \frac{\theta(t)-\theta(t-1)}{T}$ and $\ddot{\theta}(t) = \frac{\dot{\theta}(t)-\dot{\theta}(t-1)}{T}$. By using these values in (3), obtained is (4).

$$\tau(t) = a_1\theta(t) + a_2\theta(t-1) + a_3\theta(t-2) \tag{4}$$

where, $a_1 = \frac{I+cT+kT^2}{T^2}$, $a_2 = \frac{-(2I+cT)}{T^2}$ and $a_3 = \frac{I}{T^2}$. In (4) is a form of the ARX model. Coefficients a_1, a_2, and a_3 were estimated by using the different variants of the recursive least-squares method. Then, the impedance parameters I, c and k were calculated.

3. RESULT

Figure 6 shows a typical time trajectory of position and torque measured during the experiments. This data was used for calculating the impedance parameters. Fifty-four replications were observed for the calculation of impedance parameters at different angles and speeds of movement. The angle of movement varied from 40 degrees to 70 degrees and the duration of movement varied from 0.6 seconds to 1.2 seconds with an interval of 0.2 seconds. Calculated impedance parameters of two operations are shown in Figure 7. Figure 7(a) represents the impedance parameter for the movement of 40 degrees in 0.6 seconds. A sample of impedance parameters for the movement of 70 degrees in 1 second is shown in Figure 7(b).
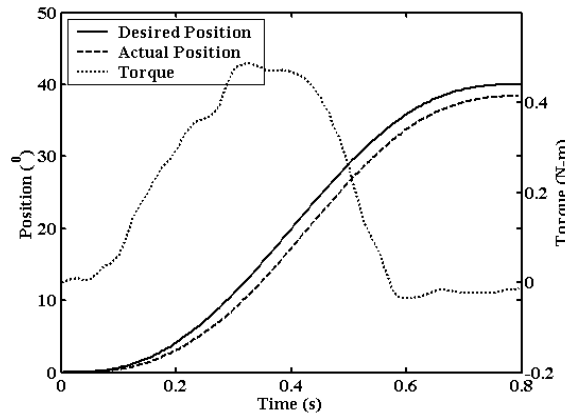
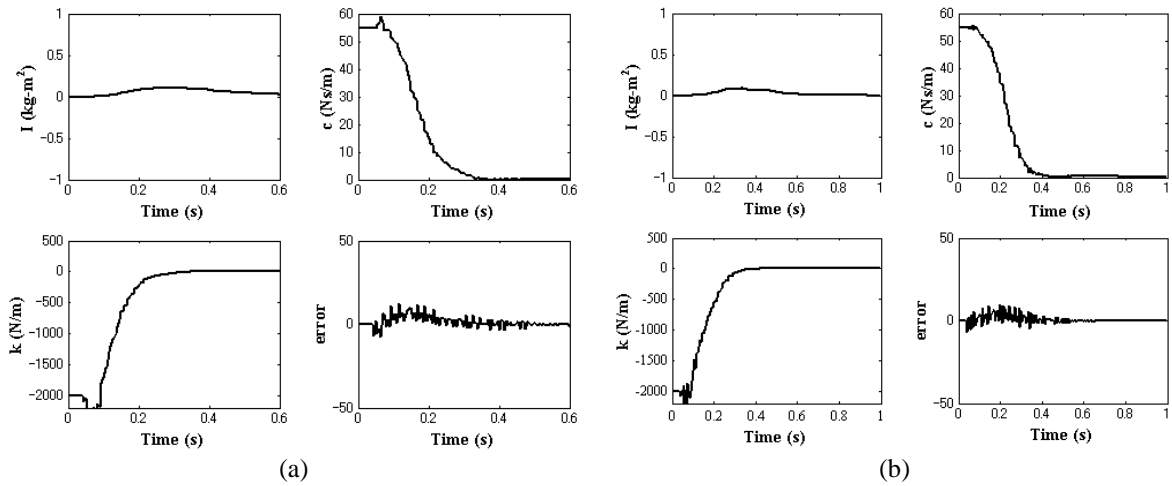Figure 6. Time trajectories of the position and the torque

Figure 7. Impedance parameters (a) $a=40^0$ and $d=0.6$ seconds and (b) $a=70^0$ and 1.0 second

4. DISCUSSION

In the present paper, the impedance of the human arm including inertia, stiffness, and damping factor was estimated for a single joint while it was moved by a robot. Figure 7 shows that the inertia is almost constant and the damping factor is high at the starting position and is near zero at 0.4 seconds. Stiffness has

also a similar characteristic to the damping factor. Similar results were found for the multi-joint arm movements with a higher viscous effect [1]. For a faster movement (Figure 7(a), $a=40^0$ and $d=0.6$ second) the parameters come to zero earlier (about 4% of total operation time). But in the case of other movements, the parameters come to zero at 0.4 seconds. Even for a very slow movement ($a=40^0$ and $d=1.2$ seconds) parameters come to zero at 0.4 seconds. Therefore, it is proved that the impedance characteristics of a human arm in passive movements do not depend upon the speed of movement or movement amplitude.

5. CONCLUSIONS

Impedance characteristics of the human arm during passive movement were analyzed. It is found that the impedance characteristics of a human arm for passive movements, maintain a model, which does not depend upon the speed and the movement amplitude, the inertia was constant, and the stiffness and damping factor varied from high to low within 0.4 seconds. Several subjects were used, and similar results were found.

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