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Equilibrium Point Control of a Robot Arm with a Double Actuator Joint

Yuka Mukaibo
Keio University
mukabo@mbm.nifty.com

Shinsuk Park
Keio University
sspark@mech.keio.ac.jp

Takashi Maeno
Keio University
maeno@mech.keio.ac.jp

Abstract

This paper presents the Double Actuator Joint Mechanism, a novel mechanism for robots to generate human-like motion. The mechanism is based on the idea of the equilibrium trajectory hypothesis, a hypothesis that multi-joint limb movements are achieved by shifting the limbs equilibrium positions defined by neuromuscular activity. The magnitude of force exerted on the arm depends on the difference between the actual and equilibrium positions, and the stiffness and viscosity about the equilibrium position. Two actuators will be placed on each joint of a two-linked manipulator, one to control position, and the other to control stiffness of the joint. By so creating human arm-like behavior, this mechanism allows robot limbs to execute stable motion in an unknown environment, owing to its ability to tolerate shock upon contact using a very simple control scheme. The underlying theory and implementation issues of the proposed mechanism are discussed, and experimental results show the potential of our approach.

1. Introduction

Many robots have proven to be very successful in performing tasks that require movement in free space or known environments. Position control is usually used for a robotic manipulator. To overcome inertial force and to improve stability and bandwidth of position control, robots are thus designed to have high stiffness in its joints and interface between actuators and loads. High stiffness, however, has undesirable effects on robot systems. Because of their limitations on torque capacity, most electric motors, which are commonly used as actuators of robots, use gear trains, in order to achieve desired driving power. High gear ratio makes the robot ineffectively non-backdrivable, and shock load reflected on gear teeth can even cause failure. Robots that contact the surrounding environment and work within kinematic constraints require force control, and must be capable of accurately modulating and controlling its actuator torques and forces in addition to knowing where it is in its workspace, and such robots have mainly been limited to laboratory research so far. A more practical mechanism or control scheme for use in such environments would allow a broader range of applications. A conceivable application would be a master-slave system for tele-operation in medical fields, and extreme environments, where robotic systems that can precisely regenerate movement of the operator become necessary. Many studies have in the past attempted to create human arm-like compliant behavior. However, understanding the actual strategies adopted by the CNS (Central Nervous System) is a fundamental problem of neurophysiology yet to be deciphered.

Several studies have used compliant elements to solve the problems mentioned above. In their research on legged robots, Pratt et al. developed an electromechanical actuator with a passive linear spring in series with the transmission and the actuator output [20]. The mass spring model for the series elastic actuator consists of mass that has a driving force, and viscous friction. Force output of the actuator is determined by the amount of compression of the spring. The spring strain is measured to obtain an estimation of the force; this turns the force control problem into a position control problem. While the spring reduces bandwidth to a certain extent, the series elasticity provides stabilized force control during intermittent contact with hard objects, as well as impact tolerance. Another example of EP control in robotics is a bio-mimetic design inspired by insects. Cutkosky et al. developed a six-legged robot that mimics the movement of a cockroach. The robot has passive rubber spring joints that connect the legs to the body, which aids in disturbance rejection [5]. It has shown robust performance in unstructured environments under a simple control scheme with very little sensory feedback. Please note that the studies mentioned above employ passive compliant components.

The purpose of this paper is to present a force control scheme adopting the idea of the equilibrium point hypothesis, one of the many human motion control hypotheses. By considering the human muscular system to have a spring-like property, as does this hypothesis, compliant force control is possible. By doing so, controlling force becomes possible using position control, allowing the control logic to become very simple. A novel mechanism is proposed to convert the control scheme into tangible form, as is explained in section 4. Two actuators are implemented to each joint: one for position control and the other for compliance control. Experiments using a two-linked manipulator were conducted to show the validity of this mechanism in creating movement compliant to the surrounding environment much like the human arm.

2. Background of Equilibrium Point Control

A great number of studies have attempted to reveal the basic properties of the human neuromuscular control system, and yet were unable to explain the exact method to translate the desired movement into the muscle activity required to generate it. It seems, however, natural to assume that certain fundamental principles underlie the organization and performance of human motor behavior. In human motor control, a multi-staged process in transforming sensory input into motor output seems plausible and consistent with known neural architectures. It is argued that a multi-stage process is hierarchically organized with multiple levels ranging from an abstract specification of task goals to a concrete specification of motor neuron activities.

One common assumption of hierarchical organizations is that the production of motor behavior occurs in at least two stages: planning and execution. For various limb movements, motor planning appears to be represented and planned at a kinematic level. In his study in self-paced point-to-point movements by hand, Morasso suggested that the central command for hand motion is formulated in body- centered Cartesian coordinates. Even if motor behavior is planned in terms of the kinematics of limb motion, the dynamics of the peripheral musculo-skeletal system heavily influence the execution of that plan. Inertial dynamics introduces nonlinear coupling (the Coriolis and centrifugal forces) between body segments.

In the so-called “inverse dynamics” approach, Hollerbach and Atkerson [8] claimed the CNS solves the inverse kinematics problem to determine joint trajectories from the desired limb endpoint trajectory, then explicitly derives the necessary muscle forces using an inverse dynamics solution. It implies that the CNS explicitly performs extremely demanding computation. An alternative approach assumes a look-up table instead of the complex computation [2][9]. However, such tables become very large in order to execute a wide variety of tasks, making this approach less likely. An alternative and simpler approach suggests that the CNS utilizes the effective dynamic and mechanical behavior of the muscles and neural feedback circuits to circumvent the computational complexities of coordinating multi-joint motions. The muscles and neural control circuits have a “spring-like” property: the muscle force varies with muscle length under constant neural input. For a single joint, the combined action of a group of muscles spanning the joint, both agonists and antagonists, define an equilibrium posture for the joint. Central command may generate a series of equilibrium points for a limb, and the “spring-like” properties of the neuromuscular system will tend to drive the motion along a trajectory that follows these intermediate equilibrium postures. This *equilibrium point hypothesis* applies to the control of both static posture and voluntary movement [10].

Fig.1 illustrates a mechanism of equilibrium point control in one-dimensional motion. In the diagram, mass M is driven by the force caused by stiffness K and damping B of muscles, and the difference between equilibrium position x_O and actual position x. Here, the equilibrium position x_O serves as a control input to the simple mechanical system. Flash (1987)[11] demonstrated that equilibrium point control can be used to model two-link planar reaching motions of the arm at moderate speeds. Using experimentally measured stiffness and the equilibrium point trajectories with a bell-shaped velocity profile, the simulations captured the kinematic features of experimentally measured trajectories.

In limb movements, the actual trajectory depends on environmental perturbations as well as the equilibrium point trajectory, commanded impedance, and limb dynamics. Equilibrium point control applies the same strategy to tasks requiring interaction with the environment, unrestrained motions and the transition between the two. Control of contact force can also be achieved through the use of an equilibrium point. Simply moving the equilibrium point to a point within a contact object will cause the limb to exert a force on that object.

There has always been controversy over the validity of the equilibrium point control hypothesis. Many investigators argued against the equilibrium point control hypothesis; they provided experimental evidence that the brain controls the movement, doing all the calculations to figure out all muscle activities (Pennisi (1996), Gomi and Kawato (1996))[20][15]. Indeed, there is considerable evidence that the motor control system takes into account the dynamic properties of the limb as can be seen in preprogrammed or anticipatory reactions (Shadmehr and Mussa-Ivaldi)[22]. Other studies have attempted to eliminate the contrast between equilibrium hypothesis and inverse dynamics by suggesting the existence of motor primitives that generate force fields acting upon the limbs.

The 1 D.O.F. EP model in Fig. 1 can be extended to multi-D.O.F. limb models. As an example, a simple 2 D.O.F. upper limb model is introduced. The two-link planar model of the arm is constrained to move in the transverse plane, and has two degrees of freedom corresponding to the shoulder and elbow joints. For simplicity, each segment is modeled as a rigid body and connected to each other by frictionless pin joints. The forearm and upper arm segments have masses of m_1 and m_2, respectively. Likewise, the respective centroid moments of inertia are I_1 and I_2. While muscle force is a complicated function with many variables, the mechanical property of a muscle may be simplified to be a function of muscle length and its rate of change. Hence, arm muscle groups may be modeled as a combination of linear torsional springs and dampers as postulated in the arm models by Hogan (1984)[25] and Flash (1987)[11]. In the framework of EP control, the resultant joint torques are assumed to be dependent only on deviation of the actual trajectory from the equilibrium point trajectory and on joint velocity. The following equation gives the joint control torques as a function of the instantaneous difference of actual and equilibrium point trajectories and joint velocity:

$$Q_{act} = -K_J(\Phi - \Phi_0) - B_J\dot{\Phi} \tag{1}$$

$$K_J = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \tag{2}$$

$$B_J = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \tag{3}$$

where Q_{act} is the torque vector of muscle forces, Φ, $\dot{\Phi}$ are vector of joint angles and rates, Φ_O is the vector of equilibrium point joint angles K_J and B_J are joint stiffness matrix and joint damping matrix respectively. Additional assumption for the EP model in arm movement is so- called Minimum-Jerk equilibrium point trajectory [26]. The driving input to the EP model has a minimum-jerk velocity profile taking the equilibrium point from the start to the finish:

$$x(t) = x_i + (x_f - x_i)(10\tau^3 - 15\tau^4 + 6\tau^5) \tag{4}$$

$$v(t) = (x_f - x_i)(30\tau^2 - 60\tau^3 + 30\tau^4)/t_f \tag{5}$$

Here, τ is normalized time ($\tau = t/t_f$), and t_f is the duration of movement.

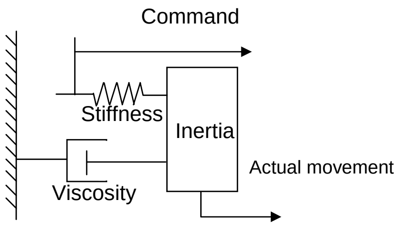

Figure1. 1 D.O.F. EP model

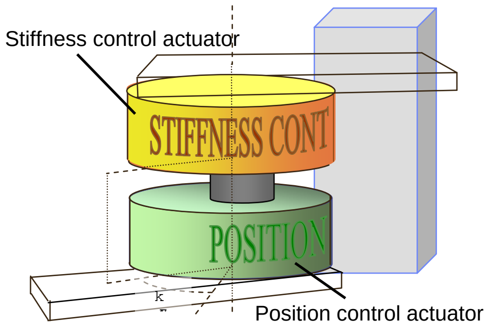

Figure 2. Double Actuator Joint

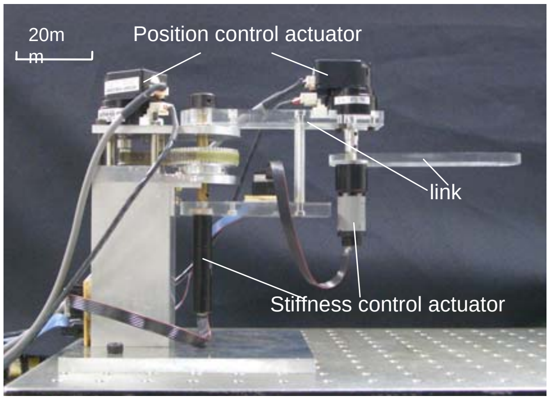

Figure 3. Two-linked robot arm

3. EP Control of Robot Arms

Though there has been controversy over whether humans execute EP control, yet EP control is still applicable to robotic manipulators, due to its simple structure compared to human limbs. In the framework of EP control, it is possible to establish muscle-like behavior on robotic manipulators using double joints and double actuators on one joint axis. For instance, by using two electric actuators along a joint axis, equilibrium point (angular displacement) and joint stiffness (or impedance) can be controlled at the same time: one electric motor commands the equilibrium point (positioning motor), the other joint stiffness (compliance control motor). Fig. 2 illustrates a simple form of the double-joint double-actuator mechanism. At each joint axis, there is a stack of three layers (base, positioning, and compliant layers) and two rotational joints connecting the layers (base-positioning layers and positioning-compliant layers). Positioning motor and compliance control motor are implemented on the base layer and on the positioning layer, respectively. In case the second and third layers are locked, the robot arm will work under conventional position control.

4. Implementation of the Double Actuator Joint Mechanism

A double joint master-slave manipulator with the double-actuator joint mechanism was developed as shown in Fig. 3. The Double Actuator Joint mechanism is implemented on the slave arm, while single actuators where placed in each joint of the master arm so as to display force feedback. For the slave arm, ultrasonic motors (SHINSEI USR 30-E3a) were used to control position owing to its characteristics, such as fast response, high driving torque at low rotational speed, and high holding torque. The ultrasonic motors are controlled to precisely reach the target position. DC motors (maxon DC motor 144291, maxon A-max116088) are used as the secondary stiffness controlling actuators on each joint. The backdrivability of DC motors are effective when attempting compliant motion control using the proposed control scheme. Timing pulleys and a timing belt are used to achieve higher driving force at joint 1. The ultrasonic motor is secured to the base, while the DC motor is connected to the link. Encoders are equipped to each motor axis to obtain position feedback. The difference in joint angles between the equilibrium posture (equilibrium point) and actual posture of the slave arm will be reflected on the master arm. During an execution, when the slave arm is in contact with an object, the contact force with the object can simply be controlled either by moving the equilibrium point further into the object further or by modulating the compliance of the second motor (compliance control motor). With given stiffness K at the end-effector for desired contact force, joint stiffness K_J (or compliance) for compliance control motor can be calculated using Jacobian J as follows:

$$K_J = J^T K J \tag{6}$$

Force feedback can thus easily be applied by entering the same voltage command as the stiffness controlling DC motor to the force feedback DC motor, only in the opposite direction.

There are many benefits of the control scheme proposed. The first is the simplicity of control. EP control applies the same strategy to free motion and tasks upon contact. In cases when in contact, the contact force can be applied by simply moving the equilibrium point within the contact object, where compliance provides shock tolerance and stability. Contact force can also be separately tailored by tuning the compliance of the secondary motor. Secondly, EP control turns the force control problem into a position control problem. In this control scheme, output torque is proportional to the difference in the angles, and therefore position is much easier to sense and control. Since this mechanism is needless of force/torque sensors to detect the force applied on the robot, the robot can sense disturbance applied to any part of the arm. Finally, the elastic component in the mechanism provides energy storage, which may improve performance and energy efficiency, as in legged locomotion.

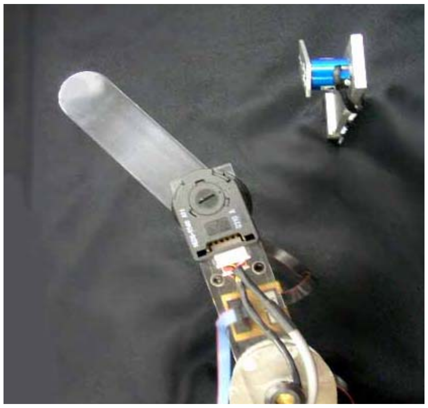

Figure 4. Experimental setup

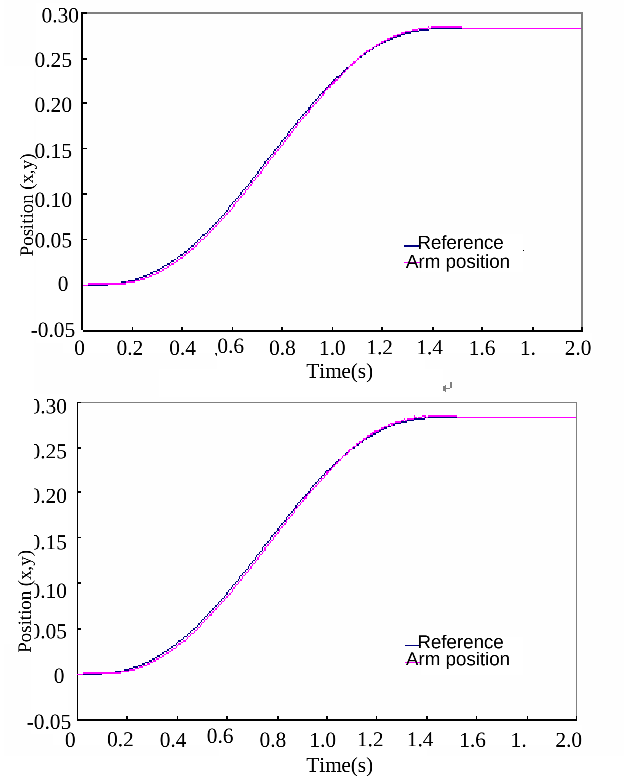

Figure 5. Slow position control

5. Experiments

With the developed robot arm, experiments were performed to verify the validity of the proposed mechanism. Position control experiments were first conducted by making the robot arm follow a target trajectory. Fast and slow position control were both performed, and angle transition each actuator was measured. This experiment was to confirm the robot arm with a double actuator joint could execute precise position control. Secondly, a force sensor was placed between the target position and the arm (Fig. 4) and force generated upon contact was measured when the arm hit an object unexpectedly. The force sensor was then positioned at various points of the arm to see if the arm could display compliance of the whole arm, not just its endpoint. Finally, force control experiments were conducted, where force applied on an object was controlled by first changing the target positions (equilibrium position) of the first motors, and secondly by adjusting the stiffness of the secondary motors. Force sensors placed at the point of contact to measure the force generated by the robot arm, and compared with calculations to prove that the proposed mechanism can indeed detect force applied from the environment.

6. Experiment Results

A. Position Control in Free Space

Fig. 5 shows the results for slow speed position control in free space, under no environmental constraints. The ultrasonic motors were adjusted so that the slave arm followed the master arm trajectory with minimal delay. Precise position control was possible regardless of the stiffness of the joint. However, when attempting fast motion control, precise position control could not be achieved when the stiffness was low. There was also great delay between the target trajectory and the actual movement of the robot arm. When the stiffness of each joint was increased, precise and fast position control was achieved. As indicated by Fig. 6, results for high speed position control show

B. Contact Experiment

Fig. 7 shows the measured force at various gain values of the secondary motor when the robot arm hit the force sensor. When the stiffness is low, the arm hardly generates force upon contact, but as the gain increases, the impulsive force also increases and continues to apply force on the sensor while it maintains contact. When the force sensor was placed so that it hit a different point of the arm, force upon impact resulted as can been seen in Fig. 8 This shows the compliance of the whole arm could be controlled by adjusting the gain to the secondary stiffness controlling actuator.

C. Force Control

The results of the force control experiments are shown in Fig. 9 and 10. In Fig. 9, force was controlled by changing the target position of the position control actuator, and the results show the measured generated force matches the calculated force. The same can be said of the stiffness-based force control in which force was generated by controlling the stiffness of the joint. Again, the calculated force and measurement corresponded.

We believe the noise generated by the force sensor attributed to the high frequency noise that can be seen throughout Fig. 7 through 10. However, we consider the results were enough to prove the validity of the proposed mechanism and control scheme and therefore do not at this point take this issue into consideration.

As the experimental results above have suggested, the double actuator joint mechanism and its control scheme can successfully control the stiffness of each joint. This means for a specific task, the stiffness ellipse at the endpoint can easily be manipulated. A stiffness ellipse is a diagram that expresses the stiffness field at the endpoint of an arm, measured by Mussa-Ivaldi et al. [18], and said to be determined by the position of the arm. However, this control scheme enables the system to intentionally create a stiffness ellipse, which would be highly effective for safe robot manipulation (Fig.11). For example, if you want to move the arm along a wall, you would want rigid and precise position control in the operating direction, but stay flexible in directions against the wall to avoid damage under unexpected collision. This idea can easily be applied for difficult tasks such as writing and surgery.

7. Conclusion and Discussions

In this paper, we have described the theories of human motor control and introduced the equilibrium point hypothesis. Based on equilibrium point control scheme, a novel mechanism was then proposed for robots to generate human arm-like motion by placing two actuators on each joint of a robot arm. Experimental results showed the mechanism could successfully control position and compliance of the robot using the simple control scheme. Both precise position control and force control may be actualized under this control scheme.

The proposed control scheme may also be extended to robot hand design, walking robots, and master-slave applications, where stable force control upon contact is critical. In addition to the robot application, this may form the basis for developing better motor control schemes. In the field of neuroscience and cognitive science, equilibrium control in motor control has been one of the major issues of debate in relation to internal model-based control. While the biological system and artificial robot systems are structurally different, the

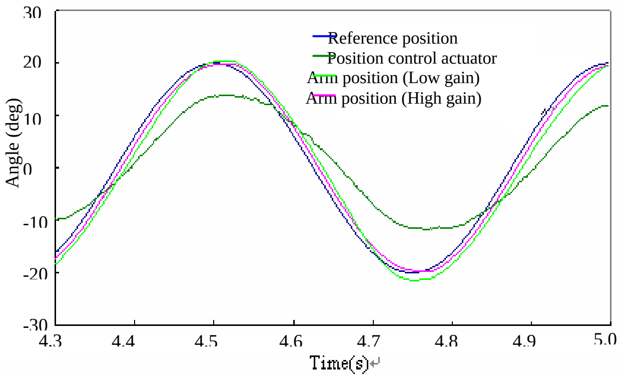

Figure 6. High speed position control

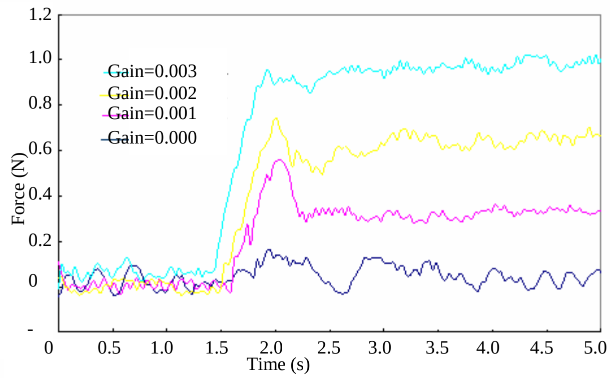

Figure 7. Contact experiment

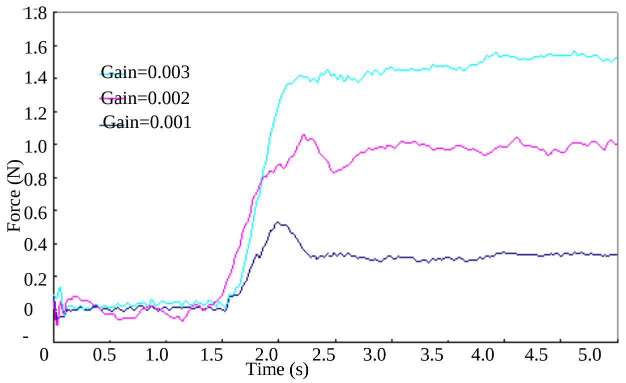

Figure 8. Contact at a different point

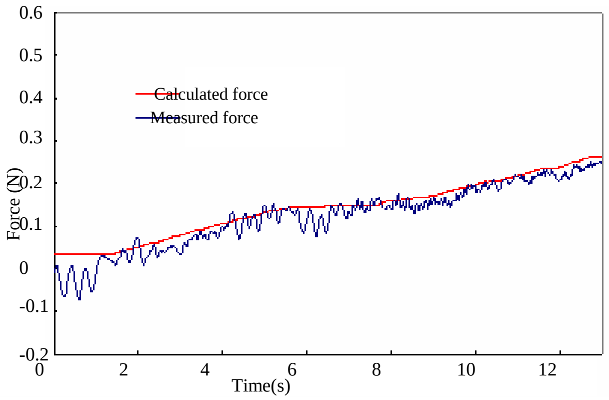

Figure 9. Position-based force

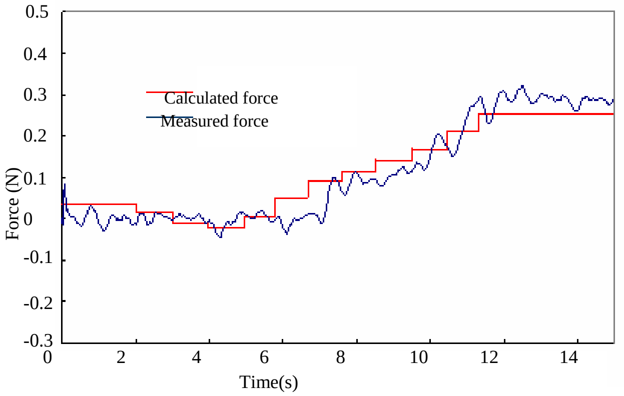

Figure 10. Stiffness-based force control

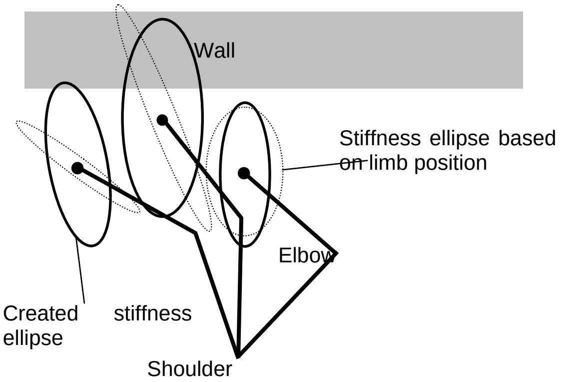

Figure 11. Stiffness ellipse at endpoint

robot manipulator developed in this study may be used as a platform to compare various control schemes. On the platform, we may test equilibrium control scheme and internal model scheme, or the combination of the two. For example, feed forward internal model may be incorporated to control the first motor, while the secondary motor emulates the mechanical properties such as stiffness and damping.

Acknowledgments

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