Proceedings of the
American Control Conference
San Francisco, California • June 1993

Destabilizing effects of muscular co-contraction in human-machine interaction

51

Karin Hollerbach
Graduate Group in Bioengineering

C. F. Ramos
Neurosciences Division

H. Kazerooni
Department of
Mechanical Engineering

University of California, Berkeley, CA 94720

Abstract

We are studying the control of human arm movements that are constrained by physical interaction with a machine such as a hand controller or a telerobotic system. One of the difficulties in controlling this type of constrained interaction is instability in the human arm-machine system. In this article, we present simulation results showing that increasing muscular co-contraction destabilizes human-machine interaction. Results of this work may have an impact on the design of machines that are to interact with humans.

Nomenclature

L	=	agonist muscle
R	=	antagonist muscle
a	=	joint acceleration
Bh	=	muscle damping constant
Bp	=	passive tissue damping
$B_{vL,R}$	=	muscle damping element
$f_{L,R}$	=	actual muscle tension
Jp	=	passive tissue inertia
K_1	=	muscle spring stiffness
K_2	=	muscle spring stiffness
Kp	=	passive tissue stiffness
$n_{L,R}$	=	neural input to muscle
$t_{L,R}$	=	hypothetical muscle tension
T	=	time constant
v	=	joint velocity
$v_{L,R}$	=	muscle velocity
$x_{L,R}$	=	muscle position
θ	=	joint position

1. Instability in human-machine interaction

When the human arm is interacting directly with a machine, its movement is constrained through physical contact with the machine; i.e., the human arm moves in such a way that the machine continuously exerts a dynamic constraint on the arm. Examples of constrained movements can be seen when the arm is operating a hand controller [1] or a telerobotic system [3] or is moving an exercise machine or an orthotic device. In systems of this nature, the human arm dynamics are integrated with the machine dynamics, resulting in behavior specific to the total system. The performance and stability of the system taken as a whole are both functions of not only the machine dynamics, but also the human arm dynamics. Evidence for instability in a human-machine system involving an interaction force between the human and the machine, as well as force feedback compensation within the machine, has been shown [1,3]. The goal of this article is to determine whether increasing muscular co-contraction levels may be a cause of such instability.

Kazerooni [1] has demonstrated a relationship between stability in active hand controllers and compliance in the hand controller and in the human arm. (Active hand controllers are defined as powered, multi-degree-of-freedom joystick-like mechanisms that are maneuvered by a human to generate command signals.) In order to guarantee stability, some compliance in either the hand controller or in the human arm is required. We extend these results by presenting simulation results that demonstrate the destabilizing effects of increasing arm impedance by increasing muscular co-contraction levels explicitly.

Empirical evidence has shown that "rigidity" of a limb is increased by simultaneous co-contraction of antagonist muscles, resulting in more effective postural maintenance [5,9]. Furthermore, model simulation studies have shown that high co-contraction levels cause a strong resistance to low-frequency disturbing forces [5,10]. We note, however, that the focus of our studies is not posture maintenance in the presence of disturbing forces and torques; instead, we are interested in the behavior of the arm-machine system as the arm is constrained by continuous contact with the machine. The instability in this type of interaction may be described as an increasing tremor in the arm, rather than an inability to reject disturbing forces. The hypothesis of the present study is that increased co-contraction levels in the human arm contribute significantly to instability in the human-machine system.

2. Simulation study

In the simulation study described here, we used a non-linear, lumped-parameter, antagonist muscle model of single-joint movements of the human arm [4,7,8,10]. A brief description of the model and of external torques ("load disturbances") and position constraints applied to the model in the present study is shown in Figure 1. The undisturbed agonist-antagonist muscle model is described by the following set of equations:

L = agonist muscle
R = antagonist muscle

$$\frac{d}{dt}\theta = v$$

$$\frac{d}{dt}x_L = \frac{t_L - f_L}{Bv_L} = v_L$$

$$\frac{d}{dt}x_R = \frac{-t_R + f_R}{Bv_R} = v_R$$

$$\frac{d}{dt}v = \frac{-K_p\theta - B_p v + f_L - f_R}{J_p} = a$$

$$\frac{d}{dt}t_L = \frac{n_L - t_L}{T}$$

$$\frac{d}{dt}t_R = \frac{n_R - t_R}{T}$$

$$f_L = K_1\left(e^{K_2(x_L - \theta)} - 1\right)$$

$$f_R = K_1\left(e^{K_2(x_R - \theta)} - 1\right)$$

$$Bv_L = \frac{1.25\, t_L}{B_h + |v_L|}$$

$$Bv_R = \frac{1.25\, t_R}{B_h + |v_R|}$$

The disturbances and constraints applied to the antagonist muscle model were used to model the possible modes of interaction of the human arm with the machine: it is possible for the machine to either apply a specific joint torque to the human arm, while allowing the human to determine the position; on the other hand, the machine may impose a position constraint, while the human imposes forces on the machine.

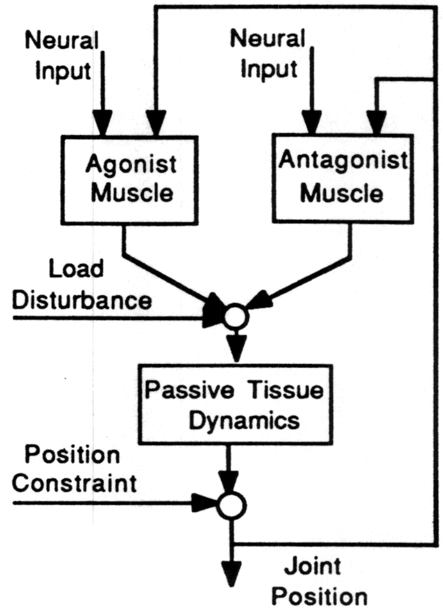

Figure 1. Model used in simulation studies. The model consists of an antagonist pair of muscles, a passive load, and neurological control signals to each muscle. Disturbances modeling machine input to the human arm may be imposed as load disturbances or as position constraints.

In the first three sets of simulations, we applied an external, time-varying load disturbance and examined the response of the system to the applied torque. These simulations involve predictable (constant or periodic) applied torques on the simulated arm. The model was simulated with varying co-contraction levels. Load disturbance amplitudes and co-contraction levels were normalized in the model, with minimum muscle forces at 80 grams and maximum muscles forces at 10,000 grams. The simulations were run for several seconds to observe long-term trends. However, plotted in each figure are the first 1000 milliseconds only, as this time proved to be sufficient to show the observed behavior.

In the first set of simulations, we applied a constant joint torque with an amplitude of 1000, comparable to a muscle force of 1000 grams (Figure 2). Co-contraction levels were varied from 6000 grams to 10,000 grams. In the results, increased levels of co-contraction correspond to an overall decrease in the position response (a smaller deviation from the initial position), and an increase in joint oscillation. The decrease in the amplitude of the position response represents an increase in the arm's ability to maintain its posture. The increase in joint oscillation (tremor) with increasing co-contraction levels, however, suggests a decrease in stability when the arm is disturbed by external forces. The frequency of the oscillations that result from a constant, externally applied joint torque in the presence of high co-contraction levels, is approximately 10 Hz.

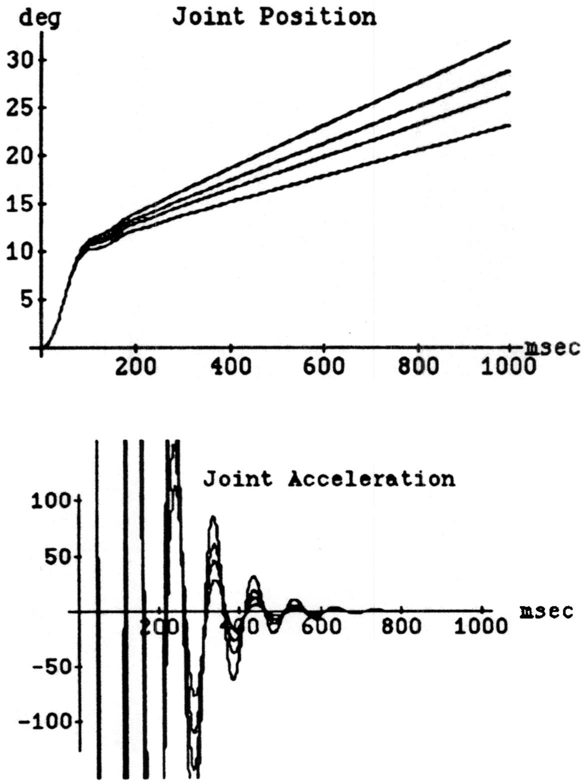

Figure 2. Joint position and acceleration as functions of time in response to a load disturbance with amplitude = 1000 grams. Co-contraction levels varied from 6000 grams to 7000, 8000, and 10,000 grams.

In the second set of simulations, we applied a sinusoidal torque disturbance with an amplitude of 1000 and a frequency of 10 Hz (Figure 3). In the steady state, the increase in co-contraction levels, from 5000 grams to 10,000 grams, caused an increase in the amplitude and a small decrease in the phase shift of the oscillations. As before, the increasing amplitude of the oscillations with increasing levels of co-contraction suggests a decrease in the stability of the arm.

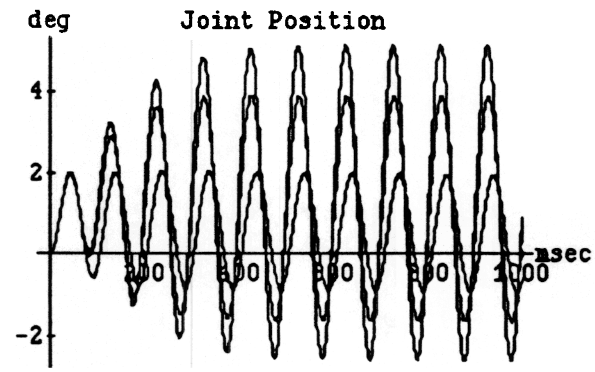

Figure 3. Joint position as a function of time in response to a sinusoidal applied torque with amplitude = 1000 grams and frequency = 10 Hz. Co-contraction levels varied from 5000 grams to 8000 grams and 10,000 grams.

In the third set of simulations (Figure 4) we examined the system's response to varying frequencies in the applied torque. The torque frequency was varied in order to determine whether the behavior pattern in response to the 10 Hz load is specific to 10 Hz loads. In Figure 4, the disturbance amplitude is 1000 grams, and co-contraction levels are high, at 9000 grams. An increase in disturbance frequency from 1 Hz to 5 Hz may be observed to cause a decrease in the amplitude of the position response. A further increase in frequency to 10 Hz decreased the mean position response but increased the amplitude.

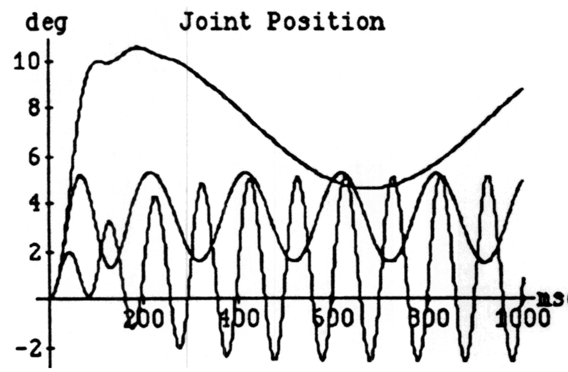

Figure 4. Joint position as a function of time in response to sinusoidal applied torque with amplitude = 1000 grams and frequencies = 1 Hz, 5 Hz, and 10 Hz. Co-contraction was kept high, at 9000 grams.

In the final set of simulations, we added a disturbance to the system, in the form of a position constraint imposed upon the arm. As before, we simulated the resulting model under varying mean co-contraction levels. The position constraint was taken from data measured in experiments with a real arm and machine; the resulting simulated contact force (between the human arm and the hypothetical machine imposing the position constraint in the simulation) was calculated and compared with the actual, experimental force data. The simulation, in this case, was run for several seconds. The applied position constraint is shown in Figure 5. Simulations were carried out at three different levels of co-contraction, 2000 grams, 5000 grams, and 9000 grams. The contact force, between the arm's endpoint (hand) and a hypothetical machine imposing the position constraint, was calculated and is shown in Figure 6. The force behavior at all three co-contraction levels is qualitatively similar to that observed in the laboratory. Increasing co-contraction levels, however, increases the amplitude of the contact force response.

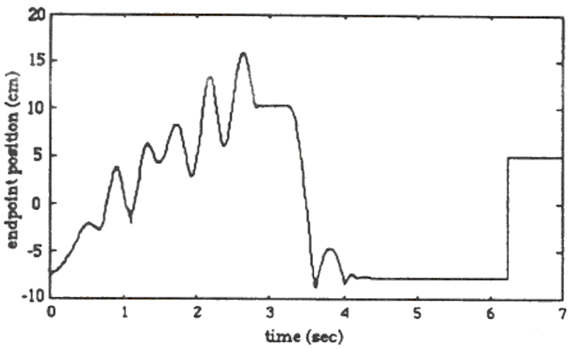

Figure 5. The joint position as a function of time. The position constraint shown here was imposed upon the arm, and the resulting contact forces between the human arm (hand) and a hypothetical machine imposing the constraint were calculated in the simulation and are shown in Figure 6.

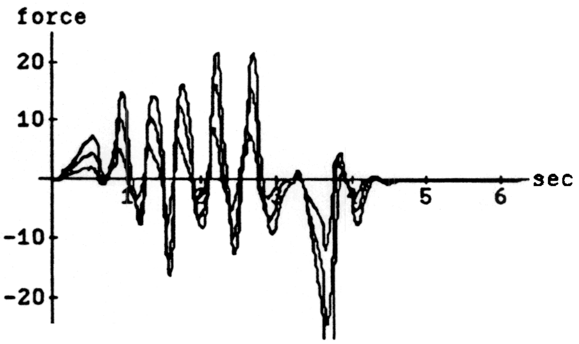

Figure 6. The contact force between the human arm (hand) and a hypothetical machine imposing the position constraint shown in Figure 5. The contact force is shown for three different co-contraction levels, 2000 grams, 5000 grams, and 9000 grams.

3. Discussion

It has been observed [1,2] that increasing human arm impedance leads to instability in human-machine interaction. The significance of the work presented here is to examine the specific link between increasing muscular co-contraction levels in the arm and instability. In order to test the hypothesis that increased co-contraction leads to instability, we simulated single joint arm behavior with load disturbances and position constraints that might be imposed on the arm by an actual machine.

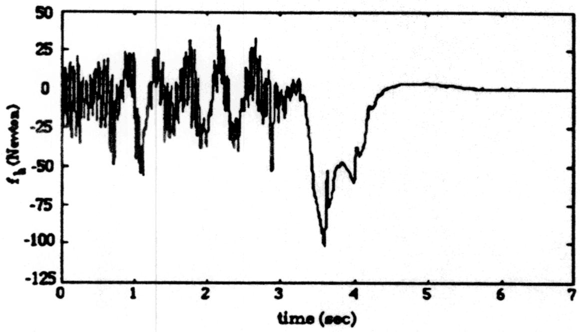

Figure 7. The contact force between the arm (hand) and the machine, as measured by sensors in the machine. The contact force was generated in response to the imposed position constraint shown in Figure 5. For more information on how these data were gathered, the reader is referred to (2).

Our simulations indicate that high co-contraction levels lead to smaller steady-state displacements of the arm, in response to applied load disturbances; i.e., high co-contraction levels improve the disturbance rejection properties of the arm. This result supports previous data [5,10] regarding the role of co-contraction levels in posture maintenance. However, our simulation results indicate that, in the presence of such externally imposed constraints, high co-contraction levels do lead to increasing transient oscillation of the arm. This oscillation, unless it is sufficiently filtered out by the machine, could be enough to cause growing oscillations, leading to total (unbounded) instability of the human-machine system.

The model used in the simulations permitted us to specify the co-contraction levels explicitly. We tested the effects of co-contraction levels in several sets of circumstances. The first included constant and periodic applied joint torques. In all cases, increasing co-contraction in the muscles led to increased tremor. Increased co-contraction in the presence of applied joint torques, thus, tended to destabilize the system. In the last set of simulations, a position constraint was applied to the arm, and the resulting contact force was calculated at three different co-contraction levels. The position constraint data were taken directly from an experiment using a real machine and human. In that experiment, the machine was commanded to move along a trajectory, imposing the position constraint shown in Figure 5. The contact forces in the resulting, unstable system were measured and are shown in Figure 7, for comparison with the calculated contact forces shown in Figure 6. We note the similarity of the low frequency components of the measured force in Figure 7[1] to the calculated force in Figure 6. In addition, we observe that, while qualitatively the force response is similar at all co-contraction levels, the amplitude of the force increases with increasing co-contraction. Thus, the simulations that were used to verify the arm model's predictions appear to be in agreement with experimental data gathered using a real machine and human.

The results of the preceding sections indicate that co-contraction of the muscles in the human arm plays a role in determining the relative stability of the human arm-machine-load system. Increasing co-contraction increases the magnitude of the arm's impedance. When it becomes great enough, the magnitude of the impedance causes at least a conservative Nyquist stability condition describing the human-machine system to fail [2] As a result, the stability of the system can no longer be guaranteed. Thus, the model predicts one cause of instability in the arm-machine-load system: increasing muscular co-contraction.

4. Summary

In this article, we use a model of the human arm to predict one cause of instability in a human arm-machine-load system: increased co-contraction of the arm muscles. This prediction is based on experimental observations indicating that varying arm impedance causes instability. The prediction of the model is verified using data from a simulation and compared with experimental observations. Other factors that may play a significant role in causing instability include machine and compensator design. It is the interaction of each of these factors that ultimately determines the stability of the system, and it is the understanding of this interaction that is the goal of this research. In future research, we plan to test these simulation results with an actual machine simulating the modeled arm behavior.

[1]The high frequency components of the force shown in Figure 7 represent unmodeled dynamics of the sensors in the real robot and should not be expected to be duplicated in the simulation results.

5. References

[1] Kazerooni, H., 1990, Human-robot interaction via the transfer of power and information signals. *IEEE Trans. on Systems and Cybern.*, Vol. 20, No. 2, 450-463.

[2] Kazerooni, H., 1992, Human-induced instability in powered hand controllers. *Proc. of the 1992 IEEE Intl. Conf. on Robotics and Automation.*

[3] Kazerooni, H., Tsay, T.I., and Hollerbach, Karin, 1993, A controller design framework for telerobotic systems (to appear).

[4] Kim, W. S., Lee, S. H., Hannaford, B. and Stark, L., 1984, Inverse Modeling to obtain head movement controller signal. *Proc. of the IEEE 20th Annual Conf. on Manual Control.* 601-620.

[5] Murray, W. R. and Hogan, N., 1989, Experimental observations on the maintenance of elbow posture in the presence of disturbances. *Issues in The Modeling and Control of Biomechanical Systems* (Edited by J. L. Stein, J. A. Ashton-Miller, and M. G. Pandy), pp. 19-28. ASME.

[6] Ogata, K., 1970, *Modern control engineering.* Prentice-Hall, Inc., pp. 407-417.

[7] Ramos, C. F. and Stark, L., 1987, Simulation studies of descending and reflex control of fast movements. *J. Motor Behav.* **19**:38-62.

[8] Ramos, C. F., Hacisalihzade, S. S., and Stark, L., 1990, Behavior Space of a stretch reflex model and its implications for the neural control of voluntary movements. *Med. & Biol. Eng. & Comput.*, **28**:15-23.

[9] Wilkie, D. R., 1950, The relation between force and velocity in human muscle. *J. Physiol.* K110, pp. 248-280.

[10] Winters, J. M. and Stark, L., 1985, Analysis of fundamental human movement patterns through the use of in-depth antagonistic muscle models. *IEEE Trans. on Biomed. Engr.* BME32, 10, 826-839.