

Modeling Haptic Communication in Cooperative Teams

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Abstract—A means to communicate by touch is established when two humans grasp a common rigid object, and such communication is thought to play a role in the superior performance two humans acting together are able to demonstrate over either agent acting alone. But the superior performance demonstrated by dyads, whether in making point-to-point movements or tracking unpredictable targets, is strictly empirical to date. Mechanistic accounts for the performance improvement and explanations relying on haptic communication have been lacking. In this paper we develop a model of haptic communication across a linkage connecting two agents that provides an explicit means for the dyad to achieve a higher loop gain than either agent acting alone and higher than the two agents acting together without haptic feedback. We show that haptic communication closes an additional feedback loop through the linkage and the sensorimotor control systems of both agents. This feedback loop contributes a new factor to the loop gain and thus a definitive mechanism for the dyad to improve performance. Our model predicts higher internal forces with haptic communication, which have previously been observed. Additional testable hypotheses emerge from the model and create a promising future means to transfer human-human dyad behaviors to human-robot teams.

I. INTRODUCTION

A team of two humans, or a *dyad*, is generally more capable than either human performing the same task individually. Experiments have shown that dyads demonstrate higher performance in completing point-to-point movements [1], [2], cyclical and continuous aiming movements [3], and tracking moving targets [4], [5] when compared with individual agents. The results seem to hold true regardless of the performance and skills of either partner [6]. Investigating the means by which a human-human dyad leads to an increased performance can help design robotic partners that can collaborate efficiently with humans [5], [7].

Common explanations for the performance improvement associated with a dyad include load sharing, social facilitation, and haptic communication. Load sharing, that results in lowering the individual forces required to perform a collaborative task, is often not a factor and can be eliminated by halving the load for the single agent (see, for example, [1], [5]). Social facilitation, or the effect that people work harder with someone present in the room [8], can also be controlled in the experiment design [1].

Haptic communication is believed to be one of the primary reasons for the performance improvement observed in dyads

[1], [5], [6], [9], [10]. Haptic communication involves exchange of force or velocity signals between the partners who are simultaneously engaged in perception (including haptic perception) and motor action. When interacting through a physical link, the members of a dyad grasp the common object or linkage, which then acts as a haptic channel between them. Through the haptic channel, the members can coordinate contributions, communicate intentions, negotiate roles, or adapt behaviors. Thus, haptic communication is thought to facilitate the development of a cooperative strategy and a shared action plan that is not available to dyad members when they work alone [1], [5].

While the literature provides significant evidence on the utility of haptic communication in establishing the performance improvement enjoyed by dyads, the evidence remains overwhelmingly empirical. There exists limited knowledge about the interpretation of haptic signals in human-human dyadic interaction, making it difficult to extend the insights derived from existing studies to designing intuitive human-robot collaboration [7], [11]. We are thus motivated to develop models of haptic communication among dyad members that can describe how a human-human dyad, by virtue of haptic interaction, can outperform a single human.

Existing models of haptically interacting dyads focus primarily on human-robot collaboration. For example, Evrard and Kheddar [10] presented a model to describe interaction behaviors of human-robot dyads in collaborative physical tasks. Wang et al. [12] presented a Hidden Markov Model approach to enable intuitive handshaking between a human and a robot. Inga et al. [13] proposed an optimal control approach to identify human behavior when haptically collaborating with an automation system. The majority of the existing methods do not describe the behavior of physically interacting human-human dyads.

Haptic human-human interaction has been studied by Feth et al. in [11] where they presented control-theoretic models to describe dyadic interaction in a pursuit tracking task. They showed that the McRuer crossover model [14] describes the behavior of humans working alone as well as when working as human-human dyads. Interestingly, they showed that the crossover model cannot describe the behavior of an agent within a dyad, indicating that haptic communication changes individual behavior. However, the authors did not offer a mechanistic explanation for how the individual behavior changed due to haptic interaction. Moreover, their models did not explain how haptic interaction improved the performance of a dyad.

In this paper, we present a simplest competent model for haptic communication that is aimed at describing the

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performance improvement observed in dyadic interaction and the changes in the behavior of an agent within a dyad. Like [11], we adopt the McRuer model to describe human tracking behavior of an individual, but we also explicitly model haptic communication through an object or linkage connecting two agents in the context of a pursuit tracking task. We uncover a haptic communication pathway that supports a means to describe how two agents acting together can outperform either agent acting alone, even when either agent acts only on half the mass.

II. MODELING HAPTIC COMMUNICATION

Consider an object of mass m and another of mass $m/2$, each responding with velocity $\dot{y}$ to a force F applied by a single agent (see Figs. 1A 1B). We will also consider an object of mass m and velocity $\dot{y}$ responding the forces F_1 and F_2 applied by each of two agents, as shown in 1C. Assume $\dot{y}$, F , F_1 , and F_2 are all positive when directed to the right. To rule out the possibility of load sharing, that is that two agents can move twice the amount of load that a single agent can move, we will compare the performance of two agents acting on mass m against a single agent acting on half the mass $m/2$. Through this comparison we aim to show that haptic feedback between the agents will enable a performance that exceeds the additive performance of individual agents. But first we must develop a model for haptic communication, and key to that development is to split the mass m into two parts of mass $m/2$ with an intervening spring of stiffness k , as in Fig. 1D. The intervening spring may represent a force sensor with large stiffness located at the interaction point between the two masses [7].

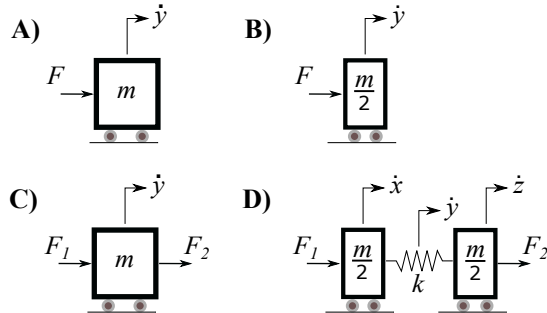


Fig. 1: A) and B) depict an object manipulated by a single agent; either a full or half-mass respectively. C) and D) depict an object manipulated by two agents. The internal force in a single rigid body (C) can be expressed as the action of an infinitely stiff spring connecting two body halves (D).

As a response to the forces they apply, each agent feels the (common) motion $\dot{y}$ of the object. Yet we know that the agents can communicate with one another through the object. That is, each agent knows what force the other agent is applying even as they modulate their own applied force to produce a desired motion. Intuitively, this haptic communication feels like a reaction force from the object—yet the reaction to an applied force must be a motion. One

way to describe haptic communication through the object is by way of internal models: using knowledge of their own applied force and the response motion $\dot{y}$ with a model of mass dynamics $\ddot{y} = \frac{1}{m}(F_1 + F_2)$, each agent can easily figure out the other agent's applied force. In the following, however, we will model haptic communication between the two agents through the internal force $F_k = \frac{1}{2}(F_2 - F_1)$. The internal force can be considered the action of an infinitely stiff spring at the center of the object that holds together the two object halves, each of mass $m/2$ (see Fig. 1D). To anticipate a parallel derivation below, we use a block diagram to express F_k as the action of a spring of stiffness k and then “close the loop” to produce an equivalent model.

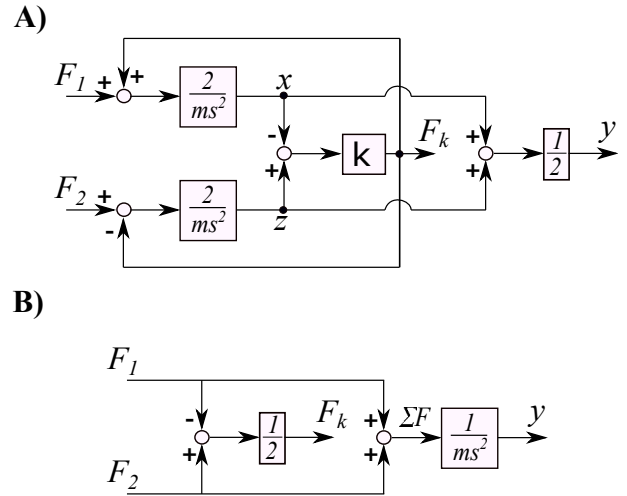


Fig. 2: As the stiffness k becomes infinitely stiff, it rigidly links the two mass halves. Block diagram (A) may then be replaced by (B), wherein the mass halves are combined and the feedback paths involving the spring force F_k have been eliminated. An internal force computed with the coefficient $1/2$ remains.

As shown in Fig. 2A, the spring force F_k creates a feedback loop around each of the mass halves. The displacement y is simply the center of the spring, or the average of displacements x and z . The transfer function relating the spring force F_k to the difference $F_2 - F_1$ reads

$$\frac{F_k}{F_2 - F_1} = \frac{1}{\frac{ms^2}{2k} + 2} \Big|_{k \rightarrow \infty} = \frac{1}{2}, \quad (1)$$

where s is the Laplace variable. Thus the block diagram in Fig. 2A, with $F_k = k(x - y)$ is equivalent to the block diagram with $F_k = \frac{1}{2}(F_2 - F_1)$ in Fig. 2B.

We will adopt the McRuer Crossover model [11], [14] to describe the process by which a human operator generates and applies force F to produce object motion y that tracks an unpredictable reference signal r (see Fig. 3A). An unpredictable signal does not have a perceptible pattern (for example a large sum of sinusoids) and cannot be addressed with anticipatory control. The McRuer model states that the open loop transfer function $L(s)$, comprising the human

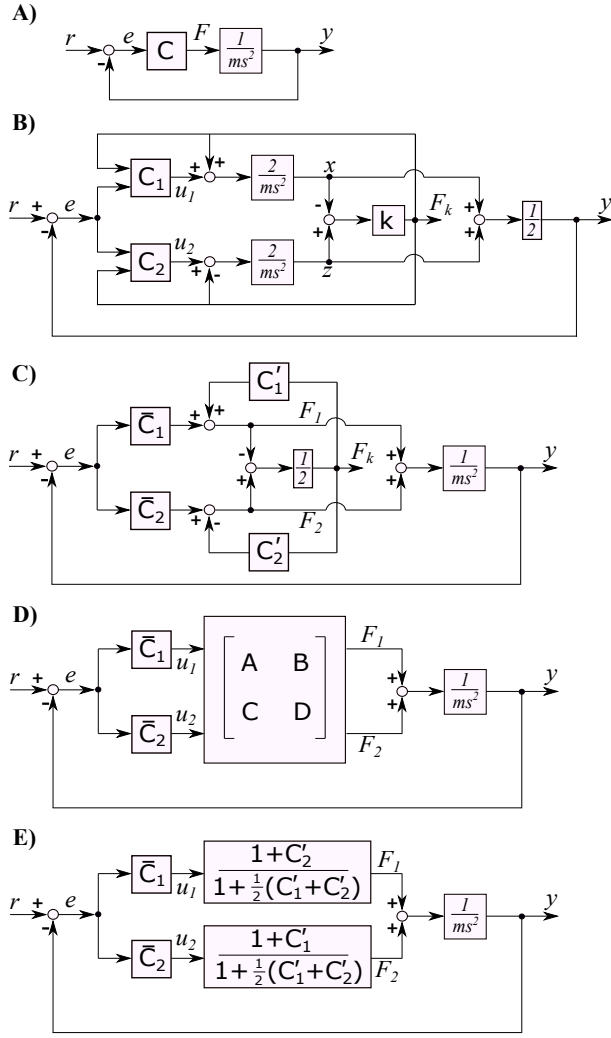


Fig. 3: Block diagram models of human tracking control in individuals (A) and dyads (B-E) guided by visual and haptic sensory feedback.

controller $C(s)$ and plant dynamics $P(s)$, can be described, within a decade bandwidth centered at ω_c , as an integrator having a crossover frequency ω_c .

$$L(s) = \frac{\omega_c}{s} e^{-\tau s}. \quad (2)$$

The pure delay of τ s accounts for neuromotor delay. Thus according to McRuer, the human operator inverts whatever portion of the plant dynamics $P(s) = 1/ms^2$ necessary to produce a loop transfer function $L(s) = \omega_c/s$. For simplicity, we ignore the neuromotor delay in this paper. In the case of a simple mass m , human control action becomes a product of mass m , gain ω_c and a differentiator, that is, $C(s) = m\omega_c s$. Assuming $m = 1\text{kg}$, human controller reduces to $C(s) = \omega_c s$. Also for the simplicity of model development, we do not bother to roll-off the differentiator at high frequencies. Note, however, that to produce the simulation results (presented in the next section) we did roll-off the differentiator using a first-order low-pass filter.

With empirical support from [11], we assume that each human operator acting as part of a dyad also behaves according to the McRuer model, but acts also on half the mass $m/2$. To model haptic feedback, we have made the internal force F_k available to each human controller as an additional signal input (see Fig. 3B). Let us now assume that the response to visual signals r and y that follows the McRuer model can be separated from the response to the haptic signal F_k , and call the two parts $\bar{C}_i(s)$ and $C'_i(s)$. In Fig. 3C we have both separated $\bar{C}_i$ from $C'_i(s)$ and closed the loop around k (as in Fig. 2A). Note that before closing the loop around k , it becomes apparent that $C'_i(s)$ is a signal path in parallel to the spring force F_k for each of the two human operators comprising the dyad. Let us then reduce the block diagram in which $C'_1(s)$ and $C'_2(s)$ appear as feedback operators (we shall assume they are simply gains). What emerges is a two-port, or 2×2 matrix of transfer functions that relates the applied forces F_1 and F_2 to the control actions u_1 and u_2 (see Fig. 3D). A straight-forward reading of the block diagram in Figure 3C produces:

$$\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \frac{1}{1 + \frac{1}{2}(C'_1 + C'_2)} \begin{bmatrix} 1 + \frac{1}{2}C'_2 & \frac{1}{2}C'_1 \\ \frac{1}{2}C'_2 & 1 + \frac{1}{2}C'_1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (3)$$

Note that if $C'_1 = C'_2 = 0$, the coefficient matrix reduces to the identity matrix, representing the case of no haptic communication between the agents. Otherwise it is quite apparent from Fig. 3D that the haptic communication has established a means for the two human agents to cooperate with or compensate for one another. The diagonal entries of the coefficient matrix describe gains that the *other* agent has available to compensate for *each* agent's own control action. For example, C'_2 is a gain belonging to agent 2 that multiplies u_1 and appears on the direct path for the applied force F_1 (and vice-versa). The off-diagonal entries of the coefficient matrix add components to each agent's applied force that depend on the other agent's control action. That is, C_1 is a gain belonging to agent 1 that multiplies u_2 and adds to the applied force F_1 . Combining the signal pathways yields the alternative expression

$$y = \frac{1}{ms^2} \left[\frac{1 + C'_2}{1 + \frac{1}{2}(C'_1 + C'_2)} u_1 + \frac{1 + C'_1}{1 + \frac{1}{2}(C'_1 + C'_2)} u_2 \right], \quad (4)$$

as shown in Fig. 3E. From this block diagram and expression it becomes apparent that if $u_1 = u_2$ (the two agents apply perfectly balanced control actions) and either $C'_1 = C'_2 = 0$ (no haptic communication) or $C'_1 = C'_2$ (perfectly balanced compensation), the loop gain $L(s) = C'_1 + C'_2$.

Let us assume, in the manner of McRuer, that the signals u_1 and u_2 are produced in response to $e = r - y$ using the control actions $\bar{C}_1(s) = \omega_{c1}s$ and $\bar{C}_2(s) = \omega_{c2}s$. The gains ω_{c1} and ω_{c2} set the crossover frequencies, and in general they carry different values to represent different skill levels of the two agents. The performance of the dyad acting without haptic feedback will be determined by the parallel configuration of controllers $\bar{C}_1(s)$ and $\bar{C}_2(s)$ and can be characterized by the crossover frequency $\omega_{c1} + \omega_{c2}$. With the

addition of haptic feedback, the controllers $C'_1(s)$ and $C'_2(s)$ are made available to the two agents. These control design variables $C'_1(s)$ and $C'_2(s)$ can now be set by each agent to achieve dyad performance that exceeds the performance of either agent acting alone and the performance of the dyad acting without haptic feedback. The new design variables enter the expression for the loop gain in the coefficients u_1 and u_2 appearing in Eq. 4. Let us suppose that ω_{c1} and ω_{c2} are fixed and further suppose that $C'_1(s)$ and $C'_2(s)$ are simply gains. Essentially *any* performance can be achieved by the dyad with haptic feedback. Dyad performance can be assessed in terms of the crossover frequency ω_c achieved in the loop transfer function $L(s)$ pertaining to the model in Fig. 3E. Any loop gain or system crossover frequency can be achieved by setting gain values for C'_1 and C'_2 . However, to achieve a specific ω_c , the variables C'_1 and C'_2 must be selected in a coordinated fashion and as functions of ω_{c1} and ω_{c2} .

Given a specific desired crossover frequency ω_c for the overall system, and given the baseline performance ω_{c1} and ω_{c2} of either agent, Eq. 4 can be used to establish a relationship between C'_1 and C'_2 :

$$C'_1 = \frac{(\omega_{c1} - \omega_c)}{\omega_c - \omega_{c2}} C'_2 + \frac{(\omega_{c1} + \omega_{c2} - 2\omega_c)}{\omega_c - \omega_{c2}} \quad (5)$$

The values for C'_1 and C'_2 that together achieve a given dyad performance ω_c lie along a straight line $C'_1 = mC'_2 + b$ with slope $m = \frac{(\omega_{c1} - \omega_c)}{\omega_c - \omega_{c2}}$ and intercept $b = \frac{(\omega_{c1} + \omega_{c2} - 2\omega_c)}{\omega_c - \omega_{c2}}$. These lines are presented in the form of a color map in Fig. 4. Interestingly, if the skill levels are the same ($\omega_{c1} = \omega_{c2}$) then there is nothing to be done through haptic communication!

III. SIMULATION RESULTS

A simulation study was undertaken to visualize the contribution, as predicted by our model, of haptic communication to the performance of a dyad. We aim to validate that with haptic communication the dyad can outperform either agent acting alone, even when either agent acts on only half the mass. In our simulations we supposed that each agent acted to realize a single integrator in the loop transfer function (each agent acted as a pure differentiator), but the second agent used 50% more gain. That is, $\omega_{c1} = 1$ rad/s and $\omega_{c2} = 1.5$ rad/s, or $\bar{C}_1 = s$ and $\bar{C}_2 = 1.5s$. We chose 6 rad/s for the desired loop crossover frequency or loop gain ω_c , as indicated in Fig. 4. We then selected $C'_2 = 1$ and used Eq. 5 to obtain $C'_1 = -11/3$. The mass m was set to 1 kg.

To visualize the performance of the dyad relative to either agent acting alone, Fig. 5A shows the step response of the dyad and each agent acting on the full mass m . Fig. 5B shows the dyad and each agent acting on the half mass $m/2$. The dyad outperforms the single agents in both the full and the half mass cases in terms of the response times.

Fig. 6A shows that the dyad attempting to track a unit step reference with the benefit of haptic feedback outperforms

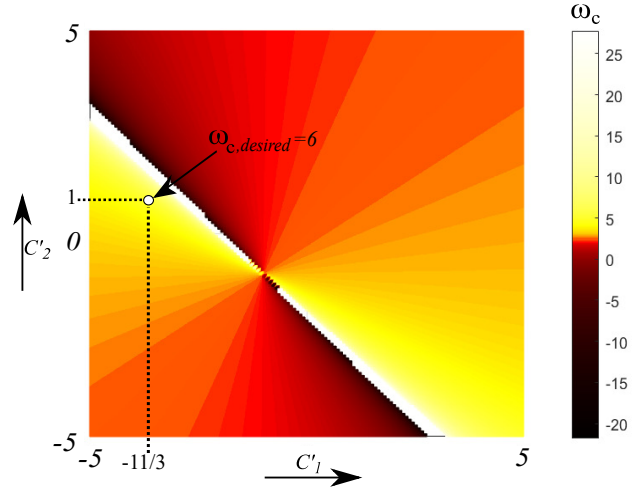


Fig. 4: The system crossover frequency ω_c is shown as a colormap. The crossover frequency is a function of C'_1 and C'_2 corresponding to the loop transfer function $L(s)$ of Fig. 3E. For the plot shown $\omega_{c1} = 1$ rad/s and $\omega_{c2} = 1.5$ rad/s. Note that the frequency ω_c is not defined for the coordinates (C'_1, C'_2) on the line $C'_1 + C'_2 = -2$ according to Eq. 4.

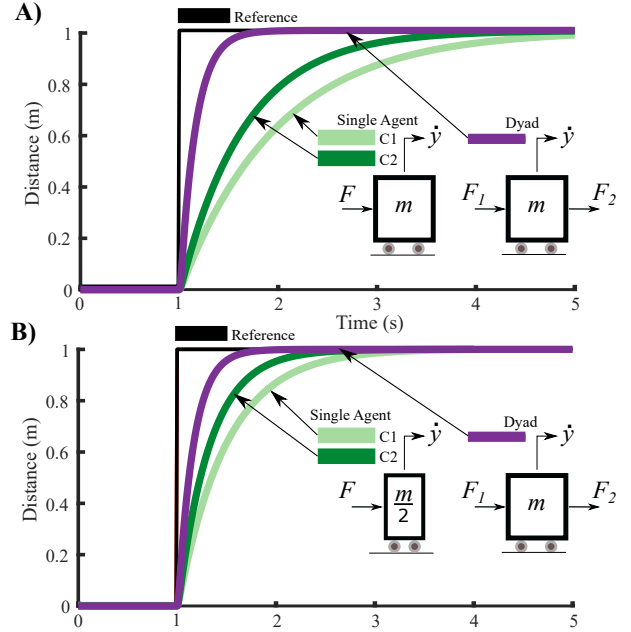


Fig. 5: Step response of a dyad interacting with a full mass overlaid with the step response of two agents interacting with: A) a full mass and B) a half-mass. The corresponding free-body diagrams for a single agent and a dyad are also shown. The dyad demonstrates faster rise times and outperforms the single agents in both cases.

a dyad acting without haptic feedback. The response with haptic feedback corresponds to Eq. 4 (and Fig. 3E) with $C'_1 = -11/3$ and $C'_2 = -1$, and the response without haptic feedback corresponds to Eq. 4 with C'_1 and C'_2 set to zero.

The response is faster (the rise time is lower) without haptic feedback in comparison to the case with feedback. Fig. 6B shows the tracking performance for a multi-sine reference. Both the tracking error and the response time of the dyad with haptic feedback are lower indicating higher performance with haptic feedback than without feedback for the multi-sine case as well.

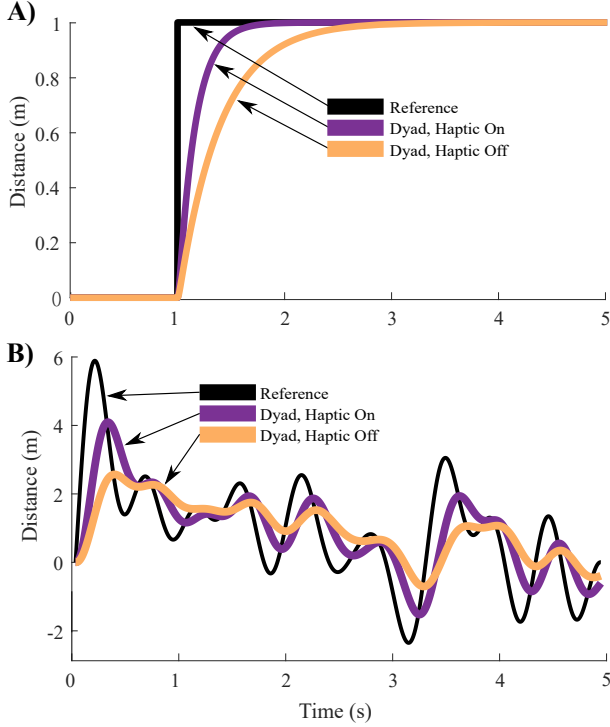


Fig. 6: The response of single agent and dyad to: A) a step input and B) a multi-sine signal (a sum of sinusoids). The dyad with haptic feedback outperforms the dyad without haptic feedback both in terms of tracking performance and rise times.

The forces applied by the two agents to track a unit step reference are shown in Fig. 7A and Fig. 7B respectively. The two agents apply larger individual forces, and hence a larger net force, when haptic feedback is present. Moreover, the magnitude of internal force applied by the agents is larger in the presence of haptic feedback as shown in Fig. 7C.

IV. DISCUSSION

Using the internal force as a means to describe haptic communication through an object, we have developed a dyad model that is capable of outperforming either individual acting alone and the same dyad without haptic feedback. Whether the communication pathway that we have modeled actually underlies the performance benefit enjoyed by dyads will have to be empirically validated. A comparison of dyad performance across conditions with and without haptic feedback requires an apparatus capable of rendering the force transmitted across a linkage connecting the two object halves, such as that developed for the experiments presented in [5], [7], [11]. Indeed, a performance benefit was observed in a

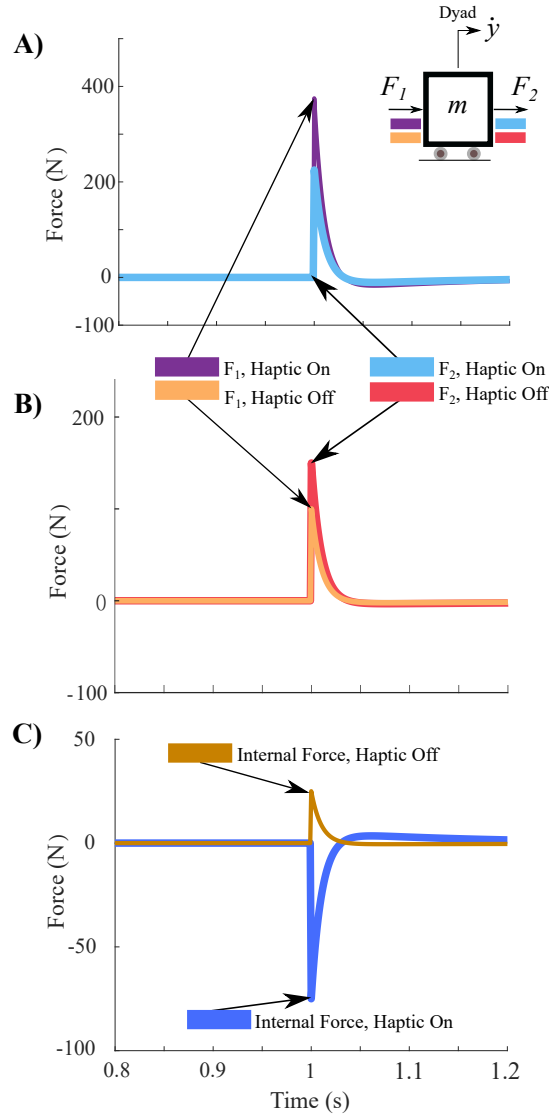


Fig. 7: The forces F_1 and F_2 applied by each member of a dyad to track a unit step reference A) with haptic feedback and B) without haptic feedback. The resulting internal force is shown in C). Without haptic feedback the dyad members apply lower individual forces and an internal force of lower magnitude when compared with the forces with haptic feedback.

tracking task for a dyad with haptic feedback compared to individuals acting on either a half or full mass [5]. It will be interesting to add the dyad acting without haptic feedback and further to determine whether our model predicts the internal forces.

It remains to extract additional testable hypotheses from our model. While the signals u_1 and u_2 are not accessible to measurement, one could imagine running a human subject experiment and monitoring the motion y in relation to the reference r along with the applied forces F_1 and F_2 to estimate values for the gains C'_1 and C'_2 of our model. The force plots in Fig. 7 indicate that the dyad members apply larger individual forces and larger internal force $((F_2 - F_1)/2)$

to improve performance when haptic feedback is available, an observation that is already corroborated by experiments [11], [15]. Thus one way to validate the model would be to compare predicted and observed internal forces and check their correlation with performance improvements. The relationship to cognitive load would also be worth exploring.

As previously highlighted in [1], [5], the performance advantage conferred on the dyad does not accrue because of load sharing. As highlighted in Fig. 5, the dyad can reach a level of performance that exceeds either agent acting alone, even when the agents move only half the mass. The dyad performance can in fact be specified in terms of the loop gain ω_c , and with the use of the relationship in Eq. 5 and Fig. 4, values for C'_1 and C'_2 can be found to satisfy the desired system loop gain. We showed that it is precisely haptic communication through the object, or awareness of the other agent's actions in addition to one's own actions that enables new feedback loops to be closed around the manipulation goal.

The adaptation that each dyad member undertakes in response to the other member is not a dynamic process in our current model. Nor have we used an adaptive control framework to describe mutual accommodation, though such a treatment might be profitable. A model that includes support for adaptive processes would be necessary to describe negotiation, the adoption of distinct roles, and specialization in dyads. Such processes have been the theme of several conjectures and empirical demonstrations of dyad superiority [16]. Members of specialized dyads may adopt the distinct roles of accelerating and decelerating the shared object [1], of executing and initiating object motion [7], and of controlling and stabilizing the object [17]. While currently there seems to be no interpretation of the feedback gains C'_1 , C'_2 as roles adopted by the members of a dyad, we believe that insights derived from our model can be used to understand how specialization occurs in dyadic interaction.

We have neglected sensorimotor delay in our current model, which would be an important part to any competent model of human behavior. Certainly sensorimotor delay is part of the base McRuer model and could easily be incorporated into the present treatment. We have also not covered dynamic compensation, perhaps derivative compensation that has a physical equivalent in the form of a damper. We would also like to test whether our findings remain the same if we add a damping (and/or a stiffness) term to our plant model which currently only consists of a mass term. Finally, our model formulation only applies to reference tracking for moving targets as presented in [4], [5] but we believe it can easily be modified to cover point-to-point movements. Either optimal control approaches or relationships between the information-theoretic basis of Fitt's law [18], [19] and its control-theoretic counterparts could possibly be used as starting points.

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