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PASSIVE HUMAN GRASP CONTROL OF AN ACTIVE INSTRUMENTED OBJECT

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ABSTRACT

An active instrumented object was built to investigate the human ability to grasp and hold the object against gravity during rapid contractions of the object. Initial grasp force was shown to be the dominant variable that determined whether the object was held or dropped. Other factors such as the friction of the interface or the contraction velocities used (130 mm/s or higher) were not found to have a significant effect. A third order lumped parameter model of the finger was proposed and the parameters of the model corresponding to the stiffness and damping of the fingerpad and muscle together with finger mass were identified using the recorded force and displacement data. This model of the finger was shown to predict the experimental data quite well, indicating that the subjects' fingers are effectively passive during rapid haptic events that occur within 60 to 80 ms.

INTRODUCTION

Haptic interfaces are essentially computer controlled active objects with which humans interact manually for exploration and manipulation of virtual environments or teleoperated remote environments [1] (for a review, see Srinivasan, 1994). Quantitative characterization of these interactions is important for improvements in the design of the hardware and software of haptic interfaces. In this paper we describe the results of our investigations on the human ability to interact and control an active instrumented object in the context of grasping and holding it against gravity. Many of the investigations of human grasp control reported in the literature are conducted using passive objects. They also generally pertain to time scales which permit the subjects to actively control the forces exerted by the associated muscles, thereby making it difficult to separate the passive, reflexive and active behavior of the human haptic system. In the experiments described here an effort was made to exclude the possibility of active control by limiting the duration of each trial to be much less than that required for active control.

In any haptic task that involves humans actively touching the object, be it for exploration or manipulation, sensing and control of contact conditions are equally important for successful performance. Sensing is accomplished by a wide variety of tactile and kinesthetic receptors that convey rich spatial and temporal information to the central nervous system where it is processed appropriately (Srinivasan, 1994). Similarly, multiple mechanisms operating at a variety of time scales account for the control capabilities of human hands: (1) passive impedances of the fingerpads, tendons and muscles that affect contact conditions immediately; (2) short latency stretch reflexes of the muscles that op-

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erate within 30 to 40 ms after a contracting muscle is stretched suddenly (Akezawa *et al.*, 1983); (3) longer latency reflexes such as the cutaneous slip reflex which causes an increase in grasp force about 70 ms after the object begins to slip relative to the fingerpad (Johansson and Westling, 1984); (4) voluntary active control directed by supraspinal processes that requires at least 150 ms to affect contact conditions. In the experiments described in this paper, contact events that were significant for task performance occurred within 60 to 80 ms after the active object began to contract.

Quantitative investigations of the sensorimotor system of the human hand have rapidly increased over the past decade. Of particular importance is the series of studies conducted by Johansson and coworkers, recently reviewed by Johansson and Cole (1992). Using passive and active instrumented objects in a wide variety of motor performance experiments accompanied by microneurographic recordings of the afferent neural responses, they have shown that even simple human grasping and manipulation skills are accomplished by predictive feed-forward mechanisms that integrate somatosensory and visual signals with sensorimotor memory. Another recent study that is of direct relevance to the finger model proposed in this paper is that by Hajian and Howe (1994). To determine the mechanical impedance of the outstretched human index finger, these authors used an instrumented pneumatic device similar to the one we employed. In contrast to our study, it was clamped to a table and it operated with a smaller range of motion (5mm), shorter time scale (13 to 20 ms), and generally higher force ranges (2 to 20N). In spite of additional differences in the experimental design, the structure of the models and the parameter identification procedures, our results either complement or are in general agreement (except for the value of the damping ratio, as described below in the subsection on Muscle Damping) with those of Hajian and Howe (1994).

EXPERIMENTS

In order to test the limitations of the motor system of the human hand in compensating for sudden disturbances, we fabricated an "Active Instrumented Object" (Fig. 1). It mainly consisted of a pneumatic cylinder whose piston could move out (expand) or in (contract) through the operation of computer controlled valves. The range of motion was about 19mm and the velocity could be varied between 130 to 240mm/s by changing the air pressure in the cylinder through a regulator. The corresponding time required for the full contraction of the object was 80 to 150 ms. A position sensor monitored the location of the piston while two 2-axis force sensors measured the normal and shear forces applied by a subject's fingerpads on two circular plates when the object was held in a pinch grasp. The plate surfaces were either polished aluminium or covered with sandpaper depending on the experiment. The weight of the object that needed to be supported by the subjects was kept constant at 2.6 N.

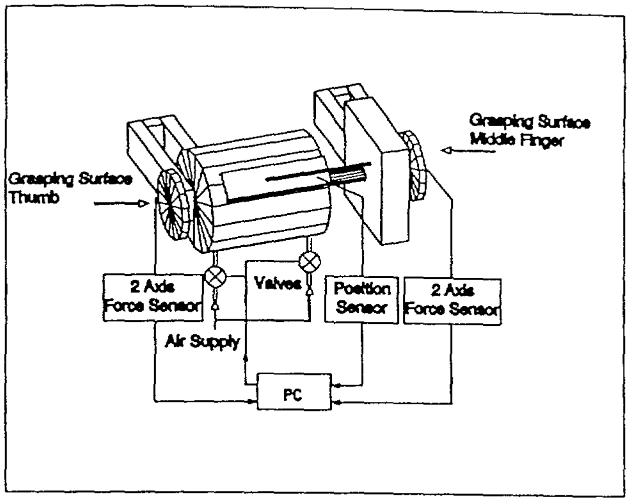

FIGURE 1: Schematic diagram of the Active Instrumented Object

The subjects were instructed to lift and hold the active object in air by squeezing the circular plates in a pinch grasp between their thumb and middle fingerpads and to avoid dropping it as much as possible. A visual display on a computer monitor indicated the initial force of grasp the subjects were required to apply. The subject could see both the object and the computer monitor, but had to focus on the monitor display to succeed in initiating the motion of the object. When subjects achieved and maintained a preprogrammed force equally with both the fingerpads for 25 ms, after an additional random time-delay of 0 to 25 ms the object contracted suddenly with a preprogrammed velocity. From the time the subject achieved the preprogrammed force to the time of initiation of contraction of the object, the subject had to maintain the force applied by each finger to be within ± 5 mN deviation, in order for the object to contract. The position of the piston and the force applied by each fingerpad of the subject were digitized and recorded at a sampling rate of 4 kHz.

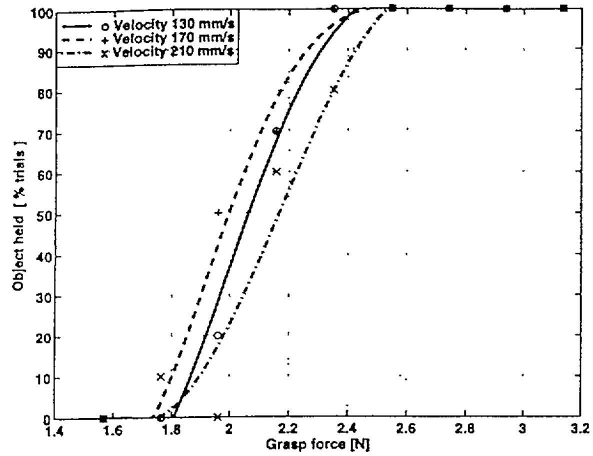

FIGURE 2: Effect of contraction velocity on subject A's performance with polished aluminium. For each value of the contraction velocity, a polynomial is fitted to the datapoints corresponding to the nine initial grasp force levels. It is observed that the effect of contraction velocity is minimal in the tested ranges of velocities and initial grasp force levels.

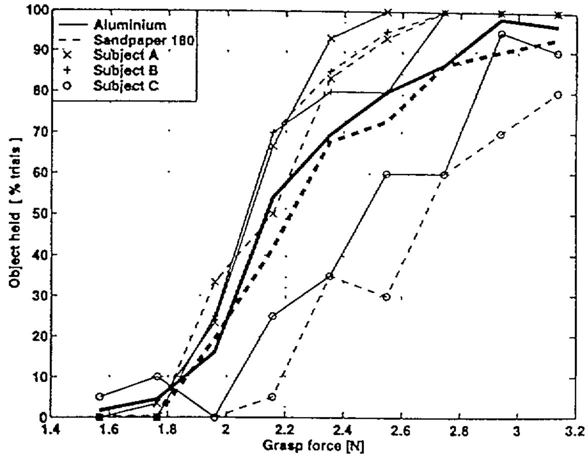

FIGURE 3: The effect of friction condition on subjects' performance. The thin lines are for each subject, mean taken over two contraction velocities (170 and 210 mm/s). The thicker lines are means over all subjects for the two friction conditions. It is observed that the effect of friction condition is minimal.

The experiments were conducted at nine values of preprogrammed initial grasp forces between 1.6 to 3.2 N at 0.2 N intervals and at three preprogrammed velocities of contraction (130, 170 and 240 mm/s). Three subjects were tested with 10 trials for each initial grasp force. In separate sessions, the contraction velocity and the frictional condition of the circular plates were varied. The change in frictional conditions was achieved by having polished aluminium or sand paper (grit size 180) as the grasping surfaces of the object.

RESULTS

The results show that the initial grasp force was a dominant factor that governed the ability of subjects to maintain the grasp when the active object contracted suddenly (Figs. 2 and 3).

When initial grasp force was less than 1.8 N, the subjects dropped the object in all the trials, whereas they held it in increasing number of trials as the grasp force increased. A plot of the percentage of trials that resulted in a successful hold versus initial grasp force values resulted in an S-shaped curve as shown. No significant difference in performance was observed for different velocities of contraction (Fig. 2) or between Aluminium and sand paper surfaces (Fig. 3). In fact, the differences in the S-shaped curves for the three subjects exceeded the differences in the curves for the two friction surfaces for each subject.

The recorded grasp forces and piston displacement traces are shown in Fig. 4 for all subjects and initial grasp forces when the contraction velocity was 170mm/s and the circular plate surfaces were polished aluminium. These traces show the approximate symmetry between the forces applied by each fingerpad and a remarkable consistency in the shape of the force traces for all the subjects and initial grasp forces. Also, the velocity is shown to be approximately constant, except for the initial 20 ms after the piston began to move. To examine the differences in the force traces when the object is held or dropped, three selected traces for one subject are shown in Fig. 5. At a high initial force of 3.2 N, the object was held all through the trial as indicated by the non-zero forces in the solid trace. At the intermediate initial force of 2.2 N, the forces were non-zero, but the small and rapid variations in the force exerted by the thumb at around 80ms indicates that there was a small slip which was not catastrophic. At the lowest initial force of 1.6 N, the object first started to slip under the middle finger at around 40 ms, which was accompanied by slip under the thumb at about 60 ms, and subsequently the object was dropped.

A LUMPED PARAMETER MODEL OF THE HUMAN FINGERS

The recorded force and the displacement trajec-

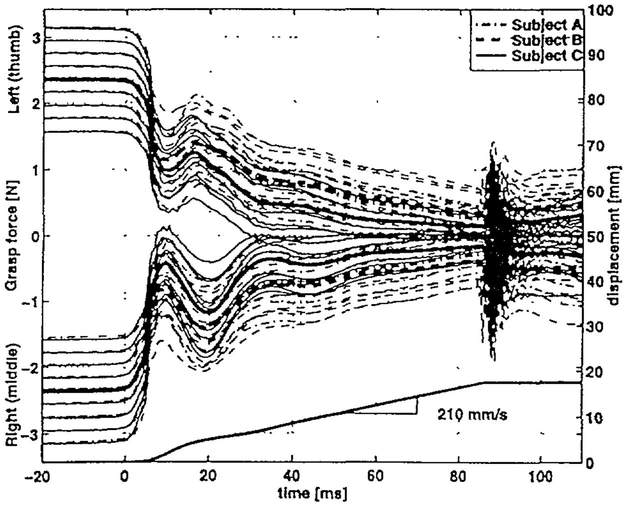

FIGURE 4: Comparison of grasp force traces for polished aluminium, at a mean velocity of 210 mm/s. The thin lines are means of 10 trials for each initial grasp force and subject; the thick lines are means over all grasp forces for each subject. Time $t = 0$ indicates the onset of contraction. At $t = 90$ ms the piston reaches the end of its travel causing the force transients shown.

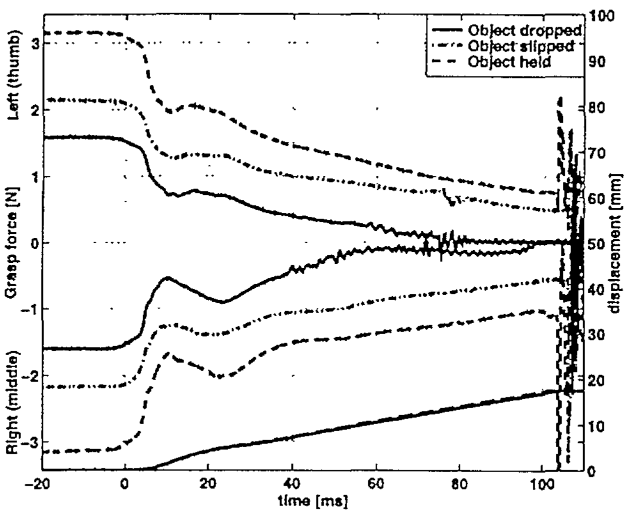

FIGURE 5: Typical force traces with three different resulting grasp behavior of Subject B; contraction velocity = 170 mm/s, sandpaper friction conditions. Time $t = 0$ indicates onset of contraction.

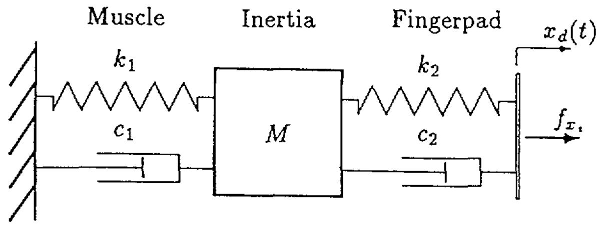

FIGURE 6: Schematic diagram of third order mass-spring-damper model of finger.

tories were analyzed to gain an insight into the nature of the underlying mechanisms that give rise to the observed shape of the force trajectories. The first goal was to understand the general shape of the trajectories, i.e. the pronounced dip and subsequent maxima in the grip force vs. time trajectories. The first version of the model represented the finger as a first-order spring-damper system that is suddenly released from compression following the measured displacement-time trajectories. This formulation could only partially explain the observed behavior and a more complicated model was therefore analyzed.

As the displacement and force measurements were colocated and we wanted to include the effects of inertia, the simplest model that would be able to describe the shape of the trajectories and still be physically plausible and identifiable using the available signals was a third order model shown schematically in Figure 6. In this model, we specify the muscle (k_1 and c_1) and the fingerpad (k_2 and c_2) as separate spring-damper systems with the finger inertia modeled as a mass (M) between them.

Using the Laplace transform to express the system as a transfer function between the displacement, x_d, and grip force f_{x_i} we obtain

$$
\begin{aligned}
x_d(s) &= \frac{Ms^2 + (c_1 + c_2)s + k_1 + k_2}{(c_2 s + k_2)(Ms^2 + c_1 s + k_1)} f_{x_i}(s) \\
&= \frac{1}{c_2} \frac{s^2 + (c_1 + c_2)/Ms + (k_1 + k_2)/M}{(s + k_2/c_2)(s^2 + c_1/Ms + k_1/M)} f_{x_i}(s) \\
&= \gamma \frac{s^2 + 2(\xi_1\omega_1 + \xi_2\omega_2)s + \omega_1^2 + \omega_2^2}{(s + k_2/c_2)(s^2 + 2\xi_1\omega_1 s + \omega_1^2)} f_{x_i}(s) \qquad (1)
\end{aligned}
$$

where $i = 1$ for the thumb and $i = 2$ for the middle finger.

System Identification

The identification method used that gave the best results was the ARMAX model (Ljung, 1987) where the model used is formulated in discrete time and of the form

$$A(q)y(t) = B(q)u(t - n_k) + C(q)e(t)$$

where A, B and C are polynomial in the delay operator q^{-1}:

$$\begin{aligned} A(q) &= 1 + a_1 q^{-1} + a_2 q^{-2} + a_3 q^{-3} \\ B(q) &= b_0 + b_1 q^{-1} + b_2 q^{-2} \\ C(q) &= 1 + c_1 q^{-1} \end{aligned}$$

To implement the method we used the *Matlab System Identification Toolbox* and applied the algorithm to the first 50ms of data after contraction, with a sampling interval of 250 μs. The identified discrete time system was then converted to continuous time system by assuming a zero-order-hold on the input. The parameters of the transfer function in Eq. (1) are calculated as follows:

The model parameters can all be obtained if the poles, the high frequency gain (γ) and the zeroth order term ($\omega_1^2 + \omega_2^2$) in the numerator polynomial are known, i.e.

1. Gain $\gamma = \dfrac{1}{c_2}$ determines c_2.
2. Real pole $-\dfrac{k_2}{c_2}$ determines k_2.
3. Imaginary poles $-\xi_1\omega_1 \pm j\omega_1\sqrt{1-\xi_1^2}$ determine ω_1, ξ_1.
4. Numerator term $b_0 = \omega_1^2 + \omega_2^2$ gives $m = \dfrac{k_2}{b_0 - \omega_1^2}$.

Note that we do not need to know the zeros, which simplifies the identification task significantly. The identified parameters are shown in Figures 7-9, and Table 1.

Inertia As is to be expected the inertia or effective mass parameter (M) does not vary considerably with load, surface conditions or contraction velocity (Fig. 7). Further, it did not vary much between subjects and was 0.02-0.04 kg for the middle finger and 0.015-0.03 kg for thumb, which indicates that the larger length of the middle finger contributes to higher moment of inertia and higher effective mass. These results agree reasonable well with results obtained by Hajian and Howe (1994) for the index finger ($M \simeq 0.02kg$).

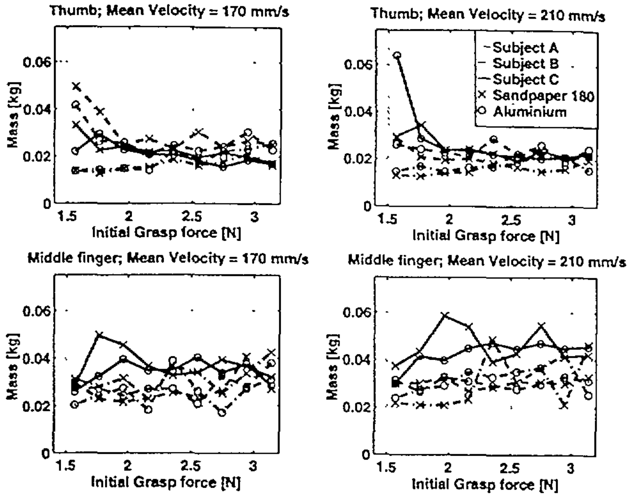

FIGURE 7: Identified finger masses.

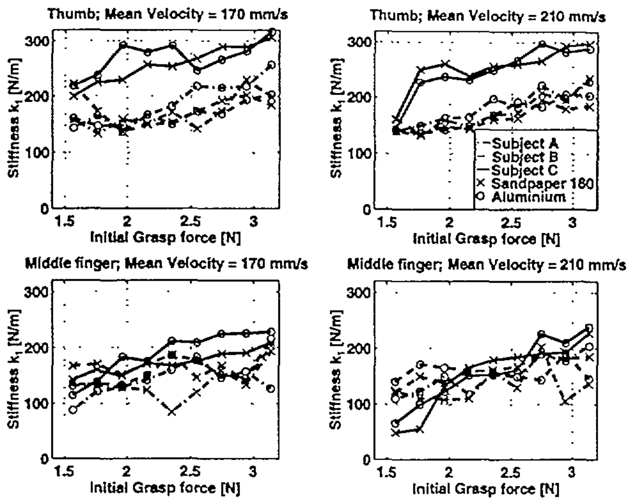

FIGURE 8: Identified finger stiffnesses.

Muscle Stiffness The muscle stiffness (k_1) shows the most interesting variations as it varies with subjects as well as with initial grip force (Fig. 8).

For subjects A and B it increased for both the fingers from about $120N/m$ to about $200N/m$ when the initial grip force was increased from $1.6N$ to $3.2N$ or about $50N/m$ per N of grasp force. For subject C middle finger parameter values were similar to those for subjects A and B, but the stiffness of thumb increased from about $200N/m$ to $300N/m$. This is a rate of $60N/m$ per N for the same increase in initial grasp force. The stiffness was there-

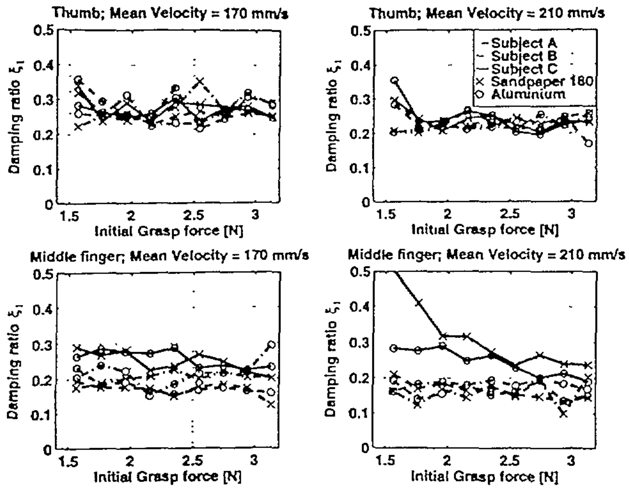

FIGURE 9: Identified finger damping ratios.

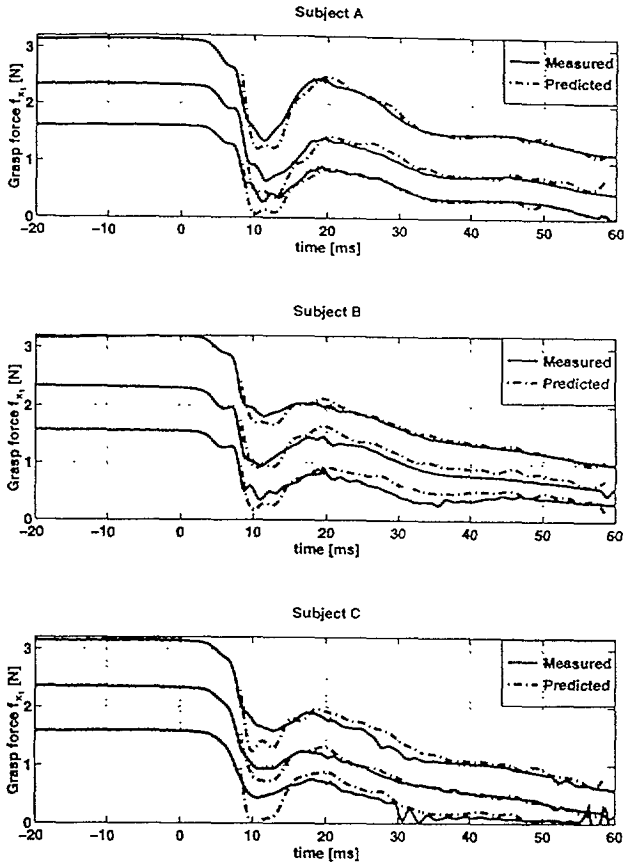

FIGURE 10: Matching of experimental data and model predictions of typical force trajectories for the three subjects. The two traces for each initial grasp force were aligned at the onset of contraction.

fore considerably higher and increased more with respect to initial grasp force for subject C. It is interesting that this mismatch in stiffness correlates with a marked difference in grasping performance (see Fig. 3). The numerical results for stiffness are consistent with ones obtained by Hajian and Howe (1994) if one extrapolates their results to lower force values and the values for the rate of increase in stiffness with load are essentially the same.

Muscle Damping Muscle damping coefficient (c_1) does not vary noticeably with loading or subjects although muscles of subjects A and B appear to have lower damping ($0.8 - 1.0 Ns/m$) than the ones of subject C ($\sim 1.2 Ns/m$). The variance in the data is however too large to make this difference significant. The resulting damping ratio (ξ_1) for all the subjects is $0.2 - 0.3$ (Fig. 9), which indicates an underdamped system. Similar results were obtained by Hunter and Kearney (1982) when investigating the ankle joint ($\xi_1 \simeq 0.3$) and also by Becker and Mote (1990) for a finger joint ($\xi_1 \simeq 0.2 - 0.4$). Somewhat higher values have been reported by Hajian and Howe (1994), ($\xi_1 \simeq 0.5 - 1.0$).

Fingerpad Stiffness and Damping These parameters proved to be the most difficult to identify, partially because the compressed fingerpad is much stiffer than the muscles and the frequencies needed to identify it are attenuated by the complex poles. The fingerpad is also highly nonlinear. Together, these factors make the identification of these parameters difficult and considerable variance was observed in the results. The stiffness was observed to be about $10^4 N/m$ which agrees resonably well with results obtained using static indentations (Gulati, 1995). The damping coefficient was found to be about $2-6 Ns/m$. Neither fingerpad stiffness nor fingerpad damping seemed to vary between subjects or initial grip force. The significance of this result is however unclear because of the difficulties mentioned above.

Model Predictions

Using the parameters obtained through the sys-

TABLE 1: Identified values of fingerpad parameters (median values across grasp force levels).

Subject:	Stiffness k_2	Damping c_2
A	2-5 10^4 N/m	$2-9$ Ns/m
B	1-7 10^4 N/m	$1-11$ Ns/m
C	1-9 10^4 N/m	$1-8$ Ns/m

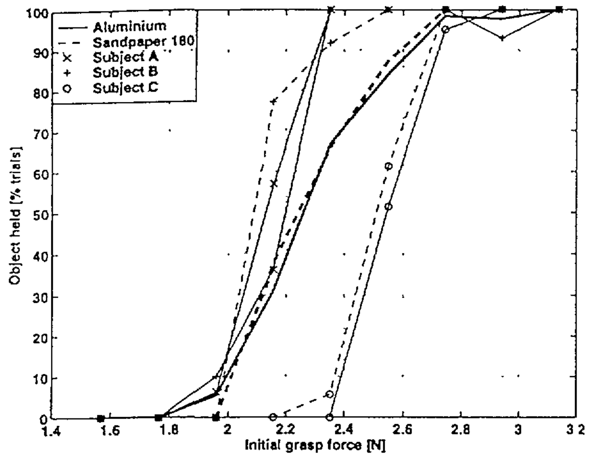

FIGURE 11: Model predictions of subject performance.

tem identification calculations, we investigated how well the model could predict the observed grasp force trajectories as well as the grasping performance of each subject.

Grasp Force Trajectories As the prediction of grasp force trajectories from piston displacement data effectively involves differentiation of the position signal, the resulting predictions contain considerable high frequency noise. To minimize the effects of the noise we filtered the results using a Butterworth low-pass filter with a cutoff frequency of 800 Hz. Several predicted trajectories for each subjects are compared with actual trajectories in Fig. 10 and the agreement is generally acceptable.

Grasp Performance Prediction To investigate if we could use the model to predict the observed grasping performance we tried the simple criterion that the object would be dropped if the grasp force level was below certain value at a fixed point in time. The results did not appear to depend much on the time point chosen and Figure 11 shows the results when the criterion force value was 1.5 N at t = 45 ms. Comparing these results with Fig. 3, we note that the agreement is quite good. This indicates that a passive model of the finger along with very simple grasping criteria can describe the observed grasping behavior to sufficient precision.

CONCLUSIONS

Within the ranges of forces and velocities used in the experiment, the main observation was that in spite of grasp force variations over time among subjects, the dominant variable in determining grasping performance of all the subjects was the initial grasp force. Other variables such as piston contraction velocity and friction conditions had only minor effects. Further, the experimental data has been shown to fit a third order mass-spring-damper model for the fingers, thus confirming that the subjects' fingers effectively acted as passive dynamic systems. This model also related the grasping performance of each subject to the strategy the subject used in the stiffness modulation of the finger muscles before each trial. Furthermore, the identified parameters governing the passive dynamic properties of the fingers provide a starting point for more complex models which account for the active nature of the finger muscles.

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