Human Velocity Control of Admittance-Type Robotic Devices With Scaled Visual Feedback of Device Motion

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***Abstract*—An admittance-type robotic manipulator is a nonbackdrivable device whose motion is controlled to move in response to a user-applied force, typically with velocity proportional to force. This study characterizes the ability of ten human subjects to accurately and precisely control the velocity of such a device, using force applied by the index finger, as the user is provided visual feedback of device motion and a target velocity on a display. The admittance, the velocity, and the visualization scale factor are varied in a full factorial design, with parameter levels representative of microsurgery/micromanipulation tasks. The results indicate that: visual scaling has no effect, for the levels tested; low velocity at high admittance results in reduced precision and accuracy; high velocity at low admittance results in reduced accuracy; and an admittance-dependent velocity exists at which accuracy is maximized. The results suggest that gain scheduling will result in improved performance.**

***Index Terms*—Admittance control, haptic interface, physical human–robot interaction, proportional-velocity control.**

I. Introduction

TASKS that are too unstructured to be fully automated can be performed using robotic manipulators that are directly controlled by a human operator. For tasks requiring high precision, such as microsurgery or micromanipulation, admittance-type robotic devices can be used in either cooperative-manipulation or telemanipulation paradigms. Admittance-type devices contain substantial gearing and inertia such that they appear nonbackdrivable to a human operator and to disturbances from relatively soft environments. Admittance-type devices can be used to stably render high inertia and damping and implement effectively rigid systems, which is difficult to do using backdrivable impedance-type devices. The Johns Hopkins University Steady-Hand Robot is an admittance-type manipulator that is used to improve precision in microsurgical tasks by reducing the tremor in the human's hand [1], [2]. The University of Utah Active Handrest is an admittance-type device that moves intuitively to support the user's hand and enable fine motor control within a large workspace [3], [4]. The HapticMASTER from FCS Robotics is a commercial admittance-type haptic interface [5].

Admittance-type robots are controlled using a method in which the user interacts directly with a force sensor mounted to the robot, and the robot is computer controlled to move in response to the applied force. A common type of admittance control is proportional-velocity control, where the admittance of the system reduces to a simple gain, k_a, making the velocity of the robot, V, linearly proportional to the applied force F

$$V = k_a F. \tag{1}$$

This control law theoretically behaves like a massless viscous damper, with damping inversely proportional to k_a. In practice, a low-level velocity servo controller is designed to have a fast time response relative to voluntary human movement, which when combined with the compliance of the soft tissue of the operator's hand renders inertial effects imperceptible.

The admittance gain k_a is tuned to adjust the dynamics of the device. A high gain results in a responsive system that can feel out of control because the resultant velocity seems disproportionately high compared with the applied force. A low gain results in a sluggish or even fatiguing user experience because attaining desired velocities may require relatively high force. The undesirable limiting cases of both high and low gains suggests that there may be an optimal gain for a given task. In this paper, we characterize optimality in terms of a user's ability to control the velocity of the device. We quantify velocity control in terms of accuracy and precision: "accurate" velocity control refers to the ability to achieve a given desired velocity in a time-averaged sense, regardless of the variance in the velocity about the mean; "precise" velocity control refers to the ability to minimize the variance in the velocity (i.e., to hold a steady velocity), regardless of the mean.

There are tasks for which both accurate and precise velocity control by the human operator is important. For example, during the surgical insertion of cochlear-implant electrode arrays, there is substantial variation in the insertion method across surgeons, but there is evidence that the insertion should be done at a

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slow and steady speed (although there is still some debate about exactly what that speed should be) [6], [7].

In other cases, we may wish to implement a kind of gain scheduling, where low values of k_a are used for precision tasks and higher values of k_a are used when the operator intends to move quickly (either detected automatically or switched manually), and it would be valuable to know what values of k_a lead to the best performance in each of the regimes. For example, the cooperative-manipulation retinal microsurgery system in [2] is capped to move slower than 6 mm/s, which may be appropriate for delicate surgical tasks; however, in a recent study by our group involving a telemanipulated retinal microsurgery system that was also limited to 6 mm/s, the surgeons indicated that they would prefer to be able to move faster during certain instrument repositioning tasks [8].

Even position-servoing tasks with visual feedback involve motions across some distance, which the operator is inclined to accomplish in some desired period of time, which naturally leads to a desired range of velocities that the operator will attempt to command during a given positioning task. It would be desirable to be able to translate task specifications given in terms of distances and completion time into a specification in terms of typical velocities, and then use that information to determine appropriate values for k_a.

Some researchers have attempted to deviate from the linear control law (1) in an attempt to improve performance. Duchaine and Gosselin [9] proposed an adaptive damping term that uses the time derivative in the applied force to measure the intention of the human operator (although their paper describes "impedance control," evidence indicates that it is the type of admittance control of interest here). Expressed in our terminology, the adaptive admittance they used is

$$k_a = \left(c - \alpha \dot{F}\right)^{-1} \tag{2}$$

where c is a baseline damping term, and α is a tuning parameter. A small study (also including virtual inertia) indicated that, for a task navigating a manipulator through a labyrinth, the adaptive admittance controller reduced completion time and the number of collisions. Fehlberg *et al.* [3] experimented with a quadratic control law

$$V = k_a |F| F. \tag{3}$$

They ultimately returned to the linear control law in (1) because they observed no better performance resulting from the quadratic control law in (3) and also found that their implementation of (3) felt active and unstable at higher velocities. However, they indicated that (3) may have merit for tasks in which fast repositioning is desirable between precision tasks. Both of the studies described above attempted to find a natural way to implement low admittance (i.e., high damping) during precision tasks and enable high admittance when fast movements are intended by the human operator.

A. Related Work in Force Control

Since an admittance-type device moves at a velocity proportional to the force applied on its force sensor, velocity control of an admittance-type device is related to the operator's ability to control manual forces. A number of studies have characterized isometric force control (i.e., on a static sensor). Some of these studies have demonstrated that visual feedback of applied force leads to an improvement in force control over haptic feedback alone [10], [11]. This suggests that the results of force-control experiments in which visual feedback of force was provided may not directly translate to the velocity control of admittance-type devices in which direct visual feedback of force is not provided. Allin *et al.* [12] characterized the just noticeable difference (JND) during force application; for the index finger, it is 10% with a base force of 2.25 N. The force JND quantifies human ability to continuously detect a change in force application, and likely accounts for some of the variability that may be detected by the force sensor on the admittance-type device. Lederman *et al.* [13] studied force control when the hand moved tangentially to the normal direction of force application and found that the tangential movement effected force control in the normal direction. This suggests that results from studies of isometric force control may have limited applicability to the case of admittance-type devices, due to the very presence of movement.

Hamilton *et al.* [14] showed that variability, or noise, is unavoidable during voluntary muscle contraction and that the coefficient of variation of force (defined as the standard deviation in force normalized by mean force) is high for very low forces and decreases as force increases. There is evidence that the decreased force variability results in part from the increased number of motor units activated in the muscle to attain higher forces, resulting in an effective averaging of the noise in individual motor units [14], [15]. These results suggest that precise velocity control of an admittance-type device may be relatively poor in cases in which forces are very low.

Studies that characterize human force control on moving objects, rather than characterizing isometric forces, are more directly relevant to admittance-type devices. Wu *et al.* [16] studied the effects of k_a and V on human force control when interacting with an admittance-type device operated under two regimes: the control law (1), and the device moving with a constant velocity. Force measurements were recorded as test subjects attempted to apply a constant force on the device with their index fingertip as the device moved away. Wu *et al.* concluded that velocity, not admittance gain, has the largest effect on human force control. However, we hypothesized that the results of [16] were potentially biased in two ways due to the nature of the experimental design: First, the 50% of the data collected while the device was operated with constant velocity may not have been representative of performance under admittance control, since the controller was turned ON once the subject reached a desired force, creating large accelerations that may have affected the results. Second, experiments were conducted without visual feedback, which required the subject to remember the desired force throughout the trial.

In [17], we reinvestigated the results of [16]. Human force control under the control law (1) was directly compared to isometric force control (i.e., with $k_a = 0$, so the device does not move). Using the same robotic device used in this paper, subjects' force control was evaluated for a range of admittance gains and forces. Subjects attempted to maintain a constant force on the device by visually servoing their applied force to a target force using a force meter displayed on a computer monitor. The device moved according to (1) and motion began naturally from the first application of force. We found that the nominal force was the most influential factor in determining the precision of the subject's force control. We found that force precision was poor for low nominal forces, which correlates with the observations of [14] and [15] that muscle motor control decreases for decreased force levels. We found that the admittance gain k_a was the second most influential factor in determining force-control precision. We found that when the admittance gain is set sufficiently low, force-control precision is similar to the isometric case, and thus, the device's motion has no effect on the user's innate force-control ability.

B. Contribution of This Work

The goal of the experiment presented in this paper is to further quantify performance with the control law (1) under different operating conditions. Whereas our previous experiment [17] was primarily concerned with subjects' ability to control their manually applied force on an admittance-type device, the present study is primarily concerned with subjects' ability to control the velocity of the device. Since this study is focused on velocity control rather than force control, subjects are provided a visual target velocity and visual feedback of the device's motion, rather than a visual force meter as used in [17]. This makes the present experiment more relevant to actual manipulation tasks, since users do not typically see force levels on a force meter in real-world applications.

This study also explicitly considers the scaling factor that describes the relationship between the actual motion of the device and the corresponding motion visually observed (e.g., on a monitor or in a microscope), since many applications that require a high degree of precision also require magnification of the workspace. The experiment is conducted to determine the effects of admittance gain, velocity, and scale factor on human velocity control, quantified by two metrics: the first quantifies subjects' ability to maintain the correct mean velocity (i.e., accuracy), and the second quantifies subjects' ability to maintain a constant velocity (i.e., precision). The subject is given an intuitive visual indication of a target velocity, and visual feedback of the scaled motion of the device. Although visual feedback of device motion could be considered a confounding factor in an experiment intended to characterize human force control, visual feedback of motion is present in the actual microsurgery/micromanipulation systems of interest.

The results of the experiment indicate a number of facts about velocity control of admittance-type devices, some that challenge our intuition. First, we find velocity-control relative accuracy and relative precision (i.e., normalized by the nominal absolute velocity) both deteriorate as either velocity or applied force become very low. Second, we find that an admittance-gain-dependent velocity exists at which relative accuracy is maximized. Finally, we find that the visual scaling factor has no effect on velocity control, for the range of levels tested. The results will be valuable in the design of admittance-type systems, particularly those implementing gain scheduling, which wish to strike a balance between precision and efficiency.

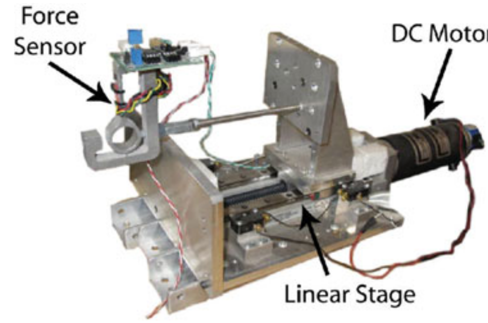


Fig. 1. One-degree-of-freedom admittance-type device used in this study.

II. Method

A. Subjects

The experiment is performed by ten (six males, four females) right-handed subjects. Subjects were recruited from the University of Utah student population, with approval of the institutional review board. Subjects' ages range from 18 to 40. They had normal touch sensation and normal (corrected) vision, by self-report. Subjects were not compensated for their participation.

B. Apparatus

The one-degree-of-freedom admittance-type device used for this experiment, shown in Fig. 1, is the same device used in [17]. It comprises a lead-screw-driven linear stage (Servo Systems Co. MLPS-4-10) driven by a DC motor (Servo Systems Co. 23MDC-LCSS) with an optical encoder mounted to the shaft. The lead screw has a pitch of 12.7 mm and the encoder resolution is 4000 counts/rev after quadrature, which translates to a linear resolution of 3 μm for the linear stage. The subject interacts with the device using an index finger. The custom strain-gauge-based force sensor has a sensitivity of 0.7 mN per bit. After digital low-pass filtering (described below), the standard deviation of the force signal is approximately 4 mN, with a peak noise of approximately 10 mN. The force sensor is mounted on the linear stage using a rigid rod. A Sensoray 626 DAQ card is used for data acquisition and digital control. It has a 16-bit ADC that is used to read force data, and a 14-bit DAC that is used to command voltage to the current amplifier (Advanced Motion Control 12A8) used to power the DC motor, which is powered by a 24-V linear power supply. The gain of the amplifier is 0.25 A/V. Force readings are sampled at 1 kHz. Software was developed in C++ using the CHAI 3D library.

A low-level velocity-servo controller is implemented to make the device appear like the idealized control law (1) to the human operator. The proportional-derivative-plus-feedforward controller that is implemented is shown in Fig. 2. Unit-DC-gain digital low-pass filters G_1, G_2, and G_3 with time constants

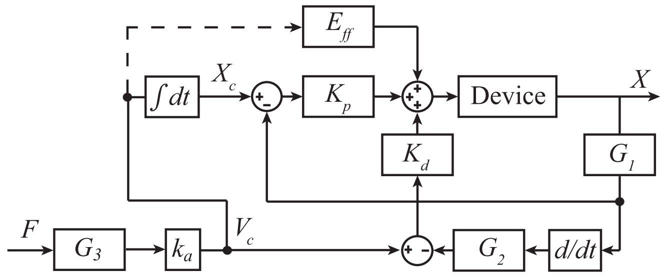


Fig. 2. Low-level control system of the admittance-type device.

$\tau_1 = 1$ ms, $\tau_2 = 16$ ms, and $\tau_3 = 8$ ms are used to reduce quantization error and noise. The proportional gain is set at $K_p = 30$ V/mm and derivative gain at $K_d = 0.1$ (V·s)/mm for the majority of the experiments. The proportional gain is increased to $K_p = 60$ V/mm for low velocities of 0.2 mm/s and below to improve tracking. Nambi *et al.* [17] empirically found that these gain values give minimal tracking error for sinusoidal position trajectories with amplitude and frequency of interest here. The controller gains are automatically adjusted according to the target velocity in each trial and are held constant for a given trial. The feedforward model for the device was experimentally derived in [17] and is given by the voltage

$$E_{\text{ff}} = 0.06V_c + 2.2(1 - e^{(-3.3V_c)}) \tag{4}$$

where V_c is the commanded velocity. This feedforward model is a smooth function that approximates Coulomb-plus-viscous friction. The inputs for the system are calculated as

$$V_c(n) = k_a F(n) \tag{5}$$

$$X_c(n+1) = X_c(n) + V_c(n)\Delta t \tag{6}$$

where $F(n)$ is the force applied by the user at sample n, $X_c(n)$ is the commanded position of the device, which is found by numerically integrating the desired velocity, and Δt is the sampling time of the control system (1 ms). Nambi *et al.*[17] found that the controlled device is capable of tracking signals at frequencies below 7 Hz (44 rad/s), with amplitudes of interest, with negligible attenuation and phase lag.

Visual feedback is provided to the subject on a 0.5-m computer screen placed at a distance of 0.7 m from the user, as shown in Fig. 3. Graphics are displayed at 30 Hz. Fig. 4 shows an annotated screen capture of the visual feedback that is shown to the subject. The visual target velocity is displayed as a continuous stream of white squares that move across the screen from right to left at a constant velocity. A colored sphere, rendered in front of the stream of squares, represents the scaled position of the device. The best size and shape for the graphics that were streamed across the visual display were determined in pilot testing, with the goals of inducing a sensation of the stream moving with constant velocity and avoiding preferential positions of the sphere relative to the squares.

C. Design

A full-factorial repeated-measures design is used. Three factors are considered: the scale S, the desired velocity V_d, and the admittance-gain k_a. The scale factor is defined such that if the robotic device moves at a rate of 1 mm/s, the colored sphere moves across the screen at S mm/s.

The range of admittance gains and velocities used in this experiment were selected based on the results reported in [17]. The levels for V_d considered here are 0.1, 0.4, 0.7, and 1.0 mm/s. The levels for k_a considered here are 0.1, 0.4, 0.7, and 1.0 mm/(N·s). The desired velocity V_d is the velocity of the robotic device, not the scaled velocity displayed on the screen. The force values required at each combination of V_d and k_a are determined by (1) and are shown in Table I.

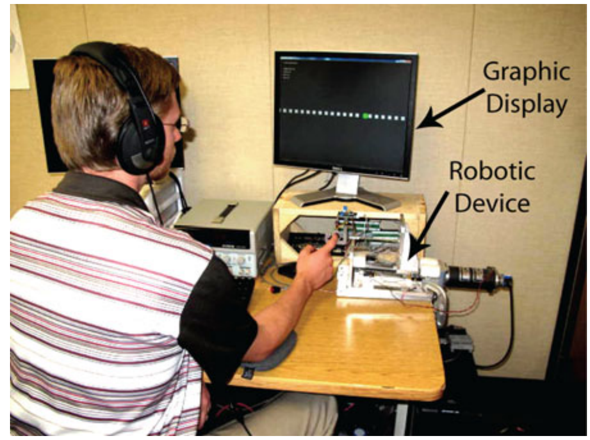


Fig. 3. Experimental setup, consisting of an admittance-type robotic device and a computer monitor. The subject interacts with the device using his index finger, as his elbow rests on a pad that is freely repositioned on the table. The subject wears headphones playing white noise.

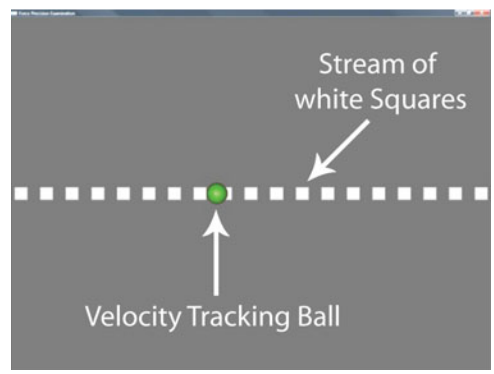


Fig. 4. Annotated screen shot of the experiment provided to the test subject. The desired velocity was indicated by a stream of white squares moving from right to left. The scaled location of the device was indicated with a sphere whose color (red, yellow, green) indicated the state of the experiment.

TABLE I
TARGET FORCE LEVEL (N) FOR EACH COMBINATION OF V_d AND k_a

		k_a (mm/(N·s))			
		0.1	0.4	0.7	1.0
V_d (mm/s)	0.1	1.0	0.25	0.14	0.1
	0.4	4.0	1.0	0.57	0.4
	0.7	7.0	1.75	1.0	0.7
	1.0	10	2.5	1.43	1.0

The levels of S used here are 30, 45, 60, and 75. The range of scale levels was selected in pilot testing such that the motion of the sphere is visually perceivable for the slowest velocities considered, and such that the sphere does not move off the screen for the fastest velocities considered, during a 4.5-s trial. With V_d spanning 0.1–1.0 mm/s, and S spanning 30–75, the velocities displayed to the screen span 3–75 mm/s.

Every combination of k_a, V_d, and S is tested in a randomized block, resulting in 64 trials per block. Each block is repeated four times, sequentially, with a different random ordering each time, making a total of 256 trials in the complete experiment, with the four repetitions of a given combination distributed roughly equally throughout the experiment.

To test all models described in this study, we used a mixed-effect analysis of variance (ANOVA) model with a maximum likelihood estimator in SPSS 19 (SPSS Mixed), which parallels a mixed-factor ANOVA. This enables us to simultaneously account for effects within trials, within subjects, and between trials and subjects for proper estimation. The key differences between this method and a standard ANOVA model are due to the estimation procedure that allows for more complex model testing by implementing an asymptotically correct estimation procedure (rather than the finite sample assumptions of the standard mixed-factor ANOVA). For ease of use, all results are reported akin to a mixed-factor ANOVA and all independent variables were treated as categories. In every case, conventional significance was determined at $\alpha = 0.05$, two tailed.

D. Procedure

The subject rests their right elbow on the table and uses their right index finger to apply a force to the left, which is also the direction of motion for both the device and the visual target velocity, as shown in Fig. 3. The subject is instructed to match the velocity of the colored sphere to the velocity of the stream of white squares by applying a force on the force sensor. White noise is played through headphones to eliminate audio feedback of the device and other distractions.

Before the experiment begins, the subject is required to practice with the device for at least five minutes. The subject manually sets the k_a, V_d, and S values to levels within the range of values being tested, enabling the subjects to become familiar with the device under the full spectrum of conditions.

During the experiment, at the beginning of a trial the subject is given no information about k_a or the required force; only the change in the velocity of the white squares across the screen can be perceived. Device motion and data recording for the trial begin when the subject applies a force on the sensor of 12 mN, which is 20% higher than the peak noise observed in the filtered force signal. The force required to trigger the device is so low that it does not affect the user's ability to control the device (i.e., there is no sensation of sticking at the beginning of a trial). Each trial lasts 4.5 s, but only the last 2 s is considered in the data analysis; the first 2.5 s is eliminated to account for the ramp-up time required for the subject to attain a specified velocity (it was determined in pilot testing that this was sufficient). The trial begins with a yellow sphere on the right edge of the screen. When sufficient force is applied to begin the trial, the sphere turns green and remains green for the duration of the trial. At the end of a trial, the sphere turns red, at which point the subject removes their finger and the device moves back to its starting position. The force sensor is zeroed to account for any drift before the sphere turns yellow again, indicating that the subject should reinsert their finger to begin the next trial. In the event that a subject's performance is potentially affected by a special circumstance, the subject is permitted to reattempt the trial. The subject is allowed to rest at any time during the experiment. The experiment lasts between 45 and 60 min for each subject.

E. Measures

In order to characterize human velocity control, performance is quantified in terms of accuracy and precision. Accuracy is a measure of a subject's ability to match the mean velocity with the desired velocity, regardless of the variation about the mean. Accuracy of a given trial is quantified in this study by the difference between the mean velocity μ and the desired velocity V_d, normalized by the desired velocity, resulting in a normalized error relative to the desired velocity

$$E_d = \frac{\mu - V_d}{V_d}. \quad (7)$$

Precision is a measure of a subject's ability to minimize the variance in velocity about the mean (i.e., to maintain a constant velocity). The coefficient of variation of velocity, C_v, quantifies precision of a given trial in terms of the standard deviation of velocity, σ, normalized by the mean velocity

$$C_v = \frac{\sigma}{\mu}. \quad (8)$$

Both [11] and [17] use a metric similar to C_v to quantify variation, but formulated in terms of force rather than velocity.

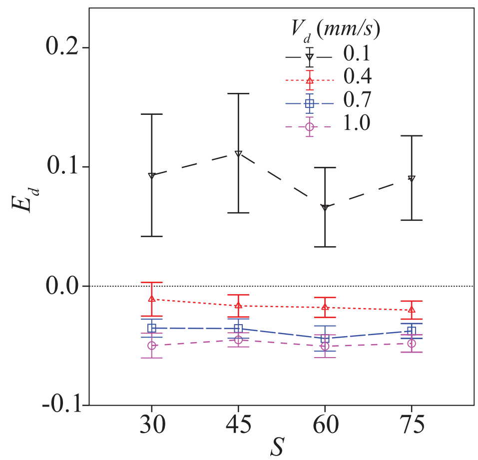
Strictly speaking, E_d and C_v characterize relative accuracy and precision, as opposed to absolute accuracy and precision. However, for brevity, we will simply use the terms "accuracy" and "precision" throughout this paper.

III. RESULTS

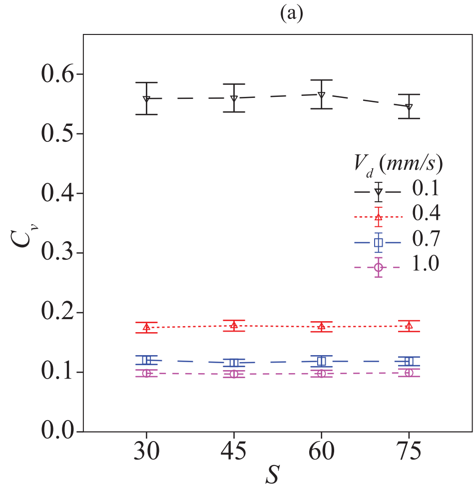
A. Scale

Fig. 5 shows the experimental results for each metric for the complete dataset. The general lack of dependence on the scaling factor, S, is immediately evident, indicating that velocity control performance is not dependent on scaling factor, at least for the range of scaling factors here. ANOVA confirms that the effect of S is not significant ($F(3,2487) = 1.262$, $p = 0.286$) in a model of E_d that includes S, k_a, and V_d, and their interactions. The effect of S is not significant ($F(3,2486) = 0.373$, $p = 0.773$) in a model of C_v that includes S, k_a, and V_d, and their interactions.

For subsequent sections that characterize accuracy and precision, S is not considered in the statistical analyses, and the data collected under the four different scaling values simply act to increase the total number of data points gathered at each of the combinations of k_a and V_d.



(a)



(b)

Fig. 5. Experimental results for (a) normalized error E_d and (b) coefficient of variation C_v for different levels of scaling factor S. The means with 95% confidence intervals shown at each combination of S and V_d include all values of k_a, subjects, and trials.

B. Accuracy

The metric E_d is a measure of how accurately a subject can track a desired velocity. In a model of E_d that includes k_a, V_d, and the k_a-by-V_d interaction, the effect of V_d is significant ($F(3{,}2535) = 127.503$, $p < 0.001$), as is the effect of k_a ($F(3{,}2535) = 21.683$, $p < 0.001$), as is the interaction ($F(9{,}2535) = 8.035$, $p < 0.001$).

Fig. 6(a) and (b) shows the relationship between E_d, V_d, and k_a. E_d is a signed metric that is sensitive to the direction of the error in accuracy, meaning that E_d can differentiate if the subject errs by moving too quickly or too slowly; $E_d = 0$ would indicate perfect accuracy. On average, subjects move faster than the desired velocity when the desired velocity is very slow, and slower than the desired velocity once it is sufficiently fast. The results suggest that there is a small range of velocities that are most accurately tracked, even over a large range of admittance gains and applied forces (and the full range of scale factors), and that for some velocities, subjects will always tend to lead or lag the desired velocity regardless of the admittance gain. These results are seen in spite of the fact that the subjects are presented with visual feedback indicating the mismatch between actual and desired velocity.

We find that accuracy is poorest at a combination of the lowest V_d and the highest k_a, which correspond to the smallest applied force (0.1 N). This poorest-accuracy combination aside, we find nearly equally poor accuracy at the next-smallest applied force values (with low V_d and high k_a) as we do at the highest applied force value (10 N), which occurs at a combination of the highest V_d and lowest k_a. These results suggest that there is a range of forces, neither too low nor too high, at which subjects have the most accurate control of the device's velocity. The results also suggest that there is a small range of velocities where velocity-control accuracy is maximized. In some situations, it may be desirable to set the admittance gain such that operators tend to err by moving too slowly rather than too quickly. Setting the admittance gain k_a of the device such that operators tend to move too slowly could reduce the risk of inadvertently overshooting a target. However, this would require knowledge of the typical velocities that would be used for a given task.

The variation of E_d about the mean between trials is another useful indicator of velocity-control accuracy because it quantifies the unpredictability in accuracy for any given trial. Even in the case of a mean $E_d \approx 0$ it quantifies the typical inaccuracy in any given trial as opposed to the nearly perfect accuracy of the trials in the aggregate. We observe that the variance in E_d is correlated with the mean value of E_d. Thus the results for accuracy can be interpreted both in terms of the average and in terms of repeatability.

C. Precision

The metric C_v quantifies the variation in a subject's velocity relative to a mean velocity, regardless of the accuracy of the mean. Precision quantifies the subject's ability to maintain a constant velocity. In a model of C_v that includes k_a, V_d, and the k_a-by-V_d interaction, the effect of V_d is significant ($F(3{,}2534) = 5032.753$, $p < 0.001$), as is the effect of k_a ($F(3{,}2534) = 116.888$, $p < 0.001$), as is the interaction ($F(9{,}2534) = 15.929$, $p < 0.001$).

Fig. 6(c) and (d) shows the relationship between C_v, V_d, and k_a. A C_v value of zero would indicate perfect precision. We find that C_v for the lowest velocity level is substantially higher than that of all other velocity levels, and similar to accuracy, we observe the poorest precision at this lowest velocity. As V_d increases, C_v decreases asymptotically for all k_a levels. The most significant reduction in C_v occurs when increasing V_d from 0.1 to 0.4 mm/s. At low values of V_d the precision is more sensitive to changes in V_d than it is to changes in k_a, and at higher values of V_d the effect of V_d and k_a on precision become comparable.

It can be seen that the best precision occurs at a combination of the highest V_d and the lowest k_a, which corresponds to the largest applied force. In addition, the precision is insensitive to small changes in either V_d or k_a in this case. However, note that this combination of parameters that results in the highest precision was found to result in relatively large E_d.

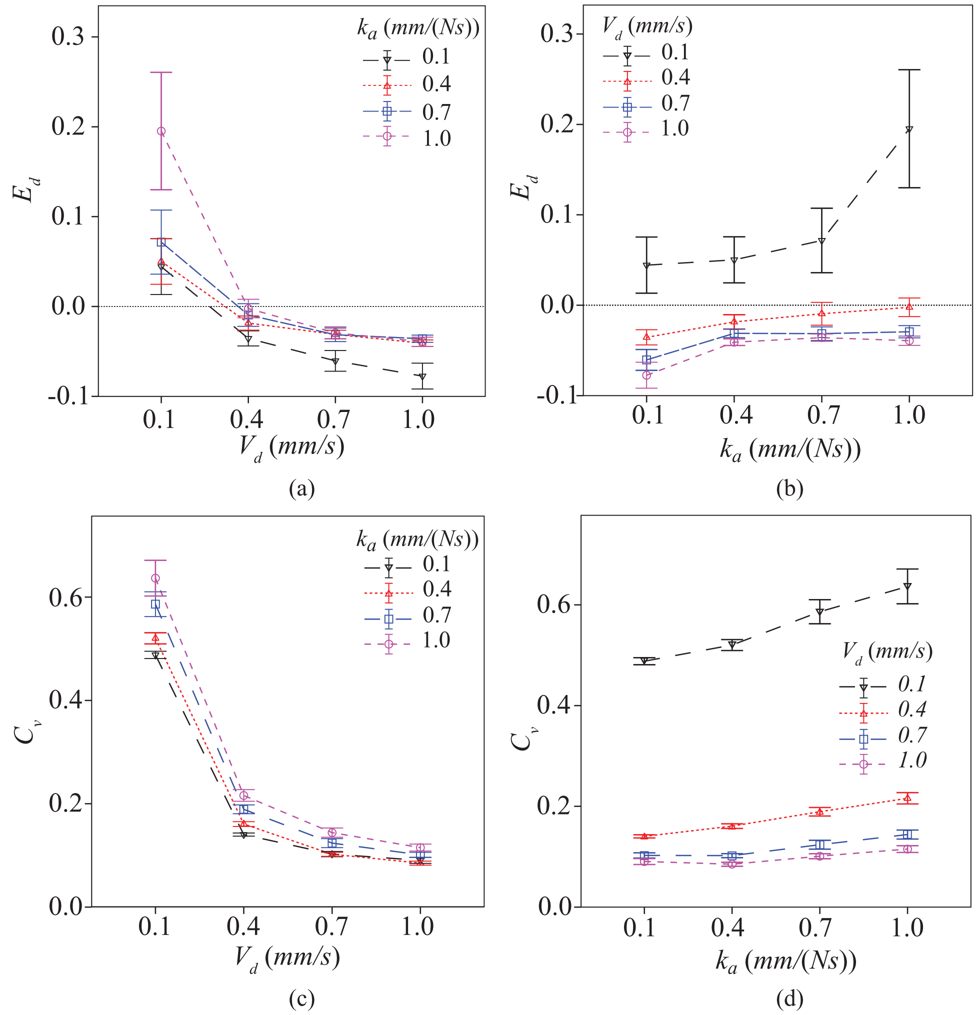


Fig. 6. Experimental results (means with 95% confidence intervals) including all scale values, subjects, and trials. (a) Normalized error E_d across all levels of V_d at different levels of k_a. (b) E_d across all levels of k_a at different levels of V_d. (c) Coefficient of variation C_v across all levels of V_d at different levels of k_a. (d) C_v across all levels of k_a at different levels of V_d.

IV. Discussion

We observe that velocity-control precision naturally improves with an increase in velocity, independent of other factors. Precision is poorest at low velocities, and at those low velocities, precision is poorest at the highest admittance gains. We observe that velocity-control accuracy is worst at combinations of low velocity and high admittance gain, which is in agreement with the results for precision. We observe that the next-worst results for accuracy are at combinations of high velocity and low admittance gain. Synthesizing our results, we can make some basic recommendations for the design of admittance-type micromanipulation systems: For improved accuracy and precision, commanding low velocities with high admittance gains should be avoided. For improved accuracy, commanding high velocities with low admittance gains should be avoided. These results may seem intuitive, but they directly challenge the commonly used static linear control law in (1). Finally, the choice of the admittance gain is not sensitive to the choice of the visual scaling factor. We elaborate on these recommendations below.

The accuracy results indicate that there are combinations of V_d and k_a for which it is difficult for subjects to achieve the target velocity in spite of the fact that they are receiving direct visual feedback of their error in velocity. Anecdotally, we observe that combinations that result in $E_d < 0$ tend to feel fatiguing, and this may explain why subjects persistently apply too little force in spite of the observable velocity error. One could hypothesize that a reduction in k_a would always result in a monotonic improvement in velocity control, and although we do see that trend in terms of precision, we do not in terms of accuracy. Consequently, if the intended velocities for some specific application happen to fall within the undesirable range for that device, we would predict, based on our results, that the resulting system would be suboptimal in terms of the user being able to achieve the intended velocity.

In Table II, we provide the configurations that would result in perfect velocity-control accuracy (i.e., $E_d = 0$), based on a curve-fit interpolation of the data in Fig. 6(a). The curve fitting was done using MATLAB's Curve Fitting Toolbox, using a power function of the form $E_d = aV_d^b + c$, where the

TABLE II
ESTIMATED COMBINATIONS OF ADMITTANCE GAIN AND VELOCITY THAT RESULT IN PERFECT ACCURACY, DETERMINED BY FINDING ZERO CROSSINGS OF INTERPOLATED DATA IN FIG. 6(A)

k_a (mm/(N·s))	V_d (mm/s)	F (N)
0.1	0.21	2.1
0.4	0.27	0.68
0.7	0.31	0.44
1.0	0.39	0.39

The required applied force is then calculated according to (1).

parameters a, b, c were fit for each individual constant-k_a set, resulting in a smooth curve with an adjusted $R^2 > 0.99$ in each case.

In the study of Nambi *et al.* [17], when subjects were instructed to maintain a constant isometric force with their index finger for a period of 2 s, with the same body posture used in the present study, the subjects had a tendency to apply forces higher than the target force at target forces below approximately 2 N, and to apply forces lower than the target force at target forces higher than approximately 2 N, indicating that a force existed near 2 N at which the subjects could best control the applied isometric force. Nambi *et al.* [17] also reported that subjects' force-control performance while operating an admittance-type device under control law (1) with an admittance gain of $k_a = 0.1$ mm/(N·s) was indistinguishable from force-control performance recorded on the stationary sensor, but subjects' force-control performance became dissimilar from the isometric case as the admittance gain was increased. If we consider the case of $k_a = 0.1$ mm/(N·s) in Table II, we find that a force of approximately 2.1 N and the resulting velocity of approximately 0.21 mm/s would result in close-to-perfect accuracy. This result is in agreement with [17], in spite of the fact that the visual feedback in the present study is substantially different from that in [17].

In Table II, we observe an inverted relationship between force and velocity, indicating that low velocities are most accurately controlled with relatively large forces, whereas high velocities are most accurately controlled with relatively low forces. This suggests that operating near the optimal isometric force value for a particular human–robot configuration will not always be best in terms of velocity control of the robot, and smaller forces may actually be more desirable as the velocity increases. As discussed earlier, these accurate configurations anecdotally appear to correspond to those that feel neither fatiguing nor "out of control" for the human operator.

These results challenge the previously developed adaptive and nonlinear controllers described in (2) and (3), respectively, which both have an increase in force generally indicate a desire to increase the velocity. Our results suggest a different type of gain scheduling is likely to result in superior system performance—a method in which precision manipulation and responsive (i.e., fast) manipulation are accomplished with decoupled controllers. Within a given control regime, we suggest continuing to use (1) such that an increase in force results in an increase in velocity, and vice versa, in an intuitive fashion. However, the switch between control regimes (i.e., the switch between discrete values of k_a) would likely need to occur manually (e.g., using a foot pedal or button push) or by estimating the human operator's intentions without relying on the force sensor (e.g., detecting gaze).

We note that the quantitative values observed in this study may be specific to an index-finger pushing force and the posture of the subjects. However, the quantitative results should be informative for other configurations that are largely similar to ours, and the qualitative results are likely to apply more generally to other configurations of admittance-type robotic devices controlled by physical human–robot interaction.

Our study is focused on a range of relatively slow velocities (0.1–1.0 mm/s) that is appropriate for applications that require high precision, such as microsurgery and micromanipulation tasks. Muñoz *et al.* [18] asserted that humans do not have precise positioning control when the velocity of a movement exceeds a threshold velocity value (based on tasks with a computer mouse). Although there are no data to directly correlate the positioning experiment of [18] with the velocity control of our study, it is important to note that our study does not consider high-speed movements that might exceed the threshold velocity at which human performance is known to degrade. As such, the results of our experiment should not be extrapolated to high speeds.

We find that the effect of the scale factor (S) is insignificant to velocity control for the range of parameters considered. According to Muñoz *et al.* [18], human performance in positioning tasks with a computer mouse is highly dependent on the scale factor. A computer mouse is not an admittance-type device, so direct comparisons of our results to [18] should be made with caution, but it does leave open the question of whether the scale factor would have an effect on positioning tasks (as opposed to velocity-control tasks). Regardless, we provide evidence here that the user's ability to control the velocity of the device need not be considered when determining the scale factor, at least for the range of useful scale factors considered.

The results of our study apply directly to admittance-type haptic devices and cooperative manipulators, as well as to telemanipulation systems in which the master devices is admittance type. It is possible that the results may also apply to telemanipulation systems comprising an admittance-type slave and an impedance-type master connected by a virtual coupling [19] (e.g., the retinal-surgery system in [8]). However, such extensions should be made with caution, as the virtual compliance binding the master to the slave and serving as the virtual force sensor, if not sufficiently stiff, will lead to a fundamentally different haptic experience.

One could question if the results for velocity-control precision C_v in this study are conflated by the effect of noise from the force sensor, which becomes relatively more important at low nominal force levels. However, a simple calculation using the values provided reveals that the portion of C_v due to force-sensor noise in our study is an order of magnitude smaller than the values reported in Fig. 6(c) and (d).

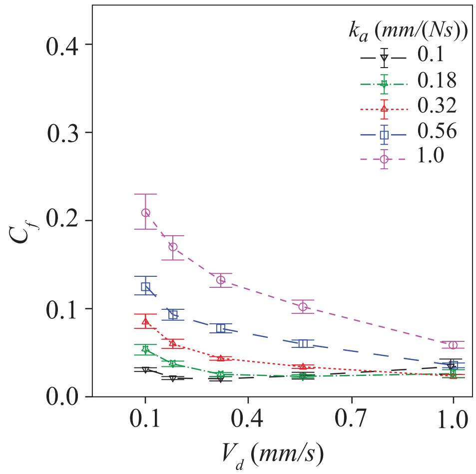


Fig. 7. Coefficient of variation of force C_f (means with 95% confidence intervals), including all subjects and trials, from the experimental data of [17], but shown in terms of C_f rather than the original force metric used in [17]. The lowest and highest values of velocity (V_d) and admittance gain (k_a) are the same in both experiments.

One could also question if the high values of C_v (i.e., poor velocity-control precision) at the lowest velocity tested in our study might be due to the rendered velocity being difficult to see, either due to pixel resolution (i.e., movement of the rendered stream appears intermittent rather than continuous) or due to visual acuity (i.e., the motion is too small to see). To explore the above hypotheses, we can again compare the results of the present study with the results of [17]. In that experiment—in which the same device was used to evaluate force-control ability over the same range of velocities, admittance gains, and applied forces—subjects were shown an indication of applied force on a continuous horizontal force scale, where the target force was shown in the center of the screen and the scale was set to display 0–200% of the target force. Because of the way that visual feedback was provided to subjects (force rather than device motion), the experiment of [17] did not suffer from the potential low-velocity problems of the present study being considered here. If either of the low-velocity hypotheses above (i.e., pixel-quantization effects or low mean rendered velocity) are the primary reason for the high C_v at $V_d = 0.1$ mm/s, then the effect should not be observed in the results of [17]. Fig. 7 shows the coefficient of variation in force (C_f) from the analogous experiment of [17], with the original units converted to coefficient of variation. Note that the coefficient of variation in force and velocity can be directly compared since the admittance gain k_a will appear in either both or neither of the numerator and denominator in (8). Since the specific set of admittance gains and target velocities used in the studies are different, only the values of C_f at the lowest and highest values of admittance gain and target velocity are directly comparable. We observe that C_v in Fig. 6(c) is higher than that of C_f in Fig. 7 at $V_d = 0.1$ mm/s across values of k_a. However, we also find that C_v in Fig. 6(c) is higher than C_f in Fig. 7 by an equivalent amount at $V_d = 1$ mm/s, which is the highest velocity. From this comparison, we can draw two conclusions. First, when attempting to control a constant velocity of an admittance-type device, which corresponds to the application of a constant force, a subject can accomplish the task more precisely when provided with visual feedback of their applied force than when provided with direct observation of the movement of the device, and this appears to be true across a wide range of admittance gains and velocity values. Second, the poor precision in velocity control observed in the present study at very low velocity values appears to be primarily due to the low velocity itself, and not due to problems associated with rendering slow velocities graphically on a screen.

The equilibrium-point hypothesis provides a theory of human motor control during manipulation tasks in which the human central nervous system (CNS) generates a virtual motion trajectory of "equilibrium points" combined with control of the limb impedance about those equilibrium points [20]. This theory seamlessly handles the transition from noncontact movements to contact tasks. Researchers have explored how the various physiological sensors are weighted and utilized by the CNS in that control task. For example, in an investigation of human force and position control during the compression of an object with variable stiffness, it was shown that force sensing is weighted more by the CNS, relative to position sensing, as the stiffness of the object increases [21]. In our present study, as well as our previous study [17], which characterize force and velocity control of an object with variable damping, it seems likely that a similar type of sensor weighting would happen within the CNS, with force feedback becoming more important as damping increases (i.e., as admittance decreases), with the limiting case of the pushing task becoming isometric. This topic is left as an open problem, since the results of our study are informative at the systems level but do not delve into the human motor control underlying the results.

V. Conclusion

The study presented here characterized the ability of ten human subjects to accurately and precisely control the velocity of an admittance-type robotic device for which velocity was controlled to be proportional to applied force through an admittance gain, using force applied by the index finger, as the user was provided visual feedback of device motion and target velocity on a screen. The proportional admittance gain, the velocity, and the visualization scale factor were varied in a full factorial design, with parameter levels representative of microsurgery and micromanipulation tasks. The results indicate that: visual scaling has no effect, for the levels tested; low velocity at high admittance results in reduced precision and accuracy; high velocity at low admittance results in reduced accuracy; and an admittance-dependent velocity exists at which accuracy is maximized. Our results suggest that gain scheduling will likely result in improved system performance compared to previously proposed nonlinear and adaptive controllers. Although the quantitative values that we observed may be specific to the human–robot configuration tested, the qualitative results are likely to apply more generally.

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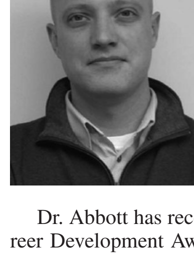

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