Effects of Velocity on Human Force Control

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Abstract

Although many robots and haptic interfaces are of the impedance type, admittance-type devices offer distinct advantages, such as high damping and stiffness display, particularly in applications requiring precise motion control. This study seeks to quantify human force control limitations in admittance control systems, where robot velocity is controlled to be proportional to the force applied by a human operator. Measurements of human force control in both admittance- and velocity-controlled scenarios were used to quantify force control precision, as well as to find a threshold over which a human cannot control a constant force and determine if that threshold depends on admittance gain or velocity. Experimental results show that robot velocity, not admittance, determines force control precision. Thus, velocities in admittance control systems should be limited to ensure that human force inputs remain precise.

1. Introduction

Haptic interfaces, teleoperators, cooperative robots, and autonomous robots that fall in the class of admittance control devices operate by scaling an input force and outputting a displacement or velocity [13]. This is described by the high-level control law:

$$v = k f. \tag{1}$$

This control law is sometimes referred to as proportional-velocity control. The force that the human applies to the robot, f, is scaled by an admittance gain, k, which produces an output velocity, v. This creates a damped behavior. A low-level controller, such as a proportional-derivative controller, then servos the (typically) nonbackdrivable robot or haptic device to the desired velocity. This control law allows the human to operate at the machine's level of motion accuracy by requiring that certain force levels be met in order to generate motion.

Admittance control systems have a variety of applications, including robot-assisted minimally invasive surgery, virtual reality, and rehabilitation. The Johns Hopkins University Steady-Hand Robot [12] employs admittance control laws to produce smooth motion of a tool based on an applied force from the user. Computer-integrated surgical systems like the Steady-Hand Robot have the potential to improve accuracy and precision in surgical maneuvers, thereby decreasing cost and harm to the patient. Admittance control haptic devices with high stiffness and force resolution, such as the HapticMaster, can be used in virtual design and assembly tasks [13]. In rehabilitation, admittance control devices can help users move their limbs by using the admittance gain to amplify small applied forces [3].

A great challenge for admittance control systems is to make them perform intuitively for the user. For example, a human-machine collaborative system (HMCS) that requires knowledge of how and when to assist a human operator [9] needs to consider the limits of human force control precision in order to discriminate between when the user wants to change the system admittance and when the user's force is simply varying within the normal range of human force control precision.

The purpose of the experiments presented in this paper is to study the human ability to control a constant force with only haptic feedback, (1) under admittance control and (2) when the robot is moving at a constant velocity. More specifically, we seek to find a threshold over which a human cannot control a constant force, and determine whether that threshold occurs at a certain admittance gain or a certain velocity (which are directly related through Equation 1). This threshold could be used as an upper bound in human-machine systems that require the operator to maintain precise control of applied forces. Estimates of human force control precision as related to admittance gains and velocities are important to the design and application of admittance-controlled haptic interfaces.

In proportional-velocity control (Equation 1), the applied human force is typically considered to be an exogenous input that is not affected directly by the motion of the system. However, in general, the human operator must be considered in the feedback loop for stability analysis [1,4]. Thus, this research also has the potential to simplify stability analysis of human-robot systems by finding conditions under which the human does indeed act as an external force.

1.1. Prior Work

Some previous research has examined human force control precision with purely haptic feedback, but only for isometric forces. For force control precision in exerting normal forces, Srinivasan and Chen [11] found an 11-15% mean absolute error for the index finger in extension. Jones found a coefficient of variance (standard deviation divided by mean) of up to 15% for finger flexion forces of 2-4 N [6] and 12% averaged across finger (2-6 N) and elbow (4-30 N) flexion forces [7]. These results lead to the conclusion that humans can control a constant force on a stationary target.

Force control is directly related to human force perception and discrimination, but experimental results (for purely haptic feedback) show that error in force control is higher than that for force discrimination. A recent experiment found a 10% just noticeable difference (JND) for a target force of 2.25 N, with only haptic feedback [2]. Srinivasan and Chen [11] attributed the higher error in force control precision in their experiment to the increased difficulty in control versus discrimination and the challenge of memorizing and recreating a target force.

Very little research has considered the precision of human force control on moving objects. However, Jandura and Srinivasan [5] analyzed human torque control on a device governed by the angular equivalent of Equation 1. Users in that experiment were asked to maintain a constant angular velocity, which required application of a constant torque.

2. Methods

We conducted two experiments, one where the robot moves under the admittance control law of Equation 1, and one where the robot moves at a constant velocity that is independent of the force applied.

These provided balanced data for admittance gain and velocity across all target forces, allowing an analysis of the effects of admittance gain and velocity

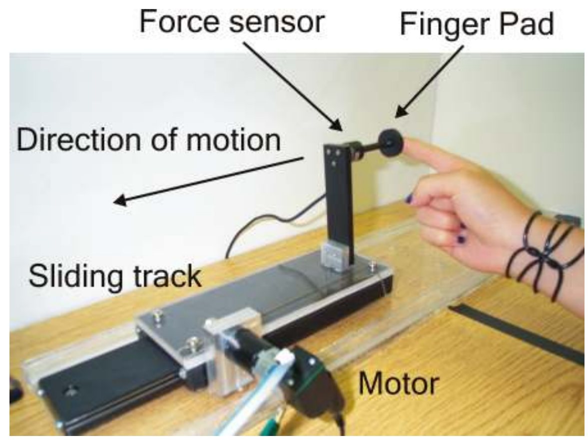

Figure 1: Experimental apparatus. A user applies force to a one-degree-of-freedom nonbackdrivable robot.

independent of one another. We hypothesize that at very low velocities and very low admittance gains, force control precision is indistinguishable between the two experiments, and the results for admittance gains in one experiment can be applied to their corresponding velocities in the other experiment through Equation 1.

Seven users (four women, three men) with ages between 19 and 28, two left-handed, five right-handed, participated in the experiments. The users did not report any neurological illness or physical injury that would impair hand function or force control ability.

The non-backdriveable, one-degree-of-freedom robot used in the experiments was composed of a linear stage driven by a Maxon A-max 22 dc motor with a 128:1 gearhead, and an ATI Nano-17 6-axis force/torque sensor mounted to the linear stage through a rigid vertical bar. The users directly interacted with a small disk (the finger pad) that is connected to the force/torque sensor through a short rod (Figure 1). The force was sampled at 500 Hz by a 16-bit A/D converter, resulting in a force resolution of 1.74 mN.

During the experiments, the users interacted with the robot attached to a low table that was hidden from view by the overhanging edge of a larger table (Figure 2). The user rested his or her right elbow on a pad, held the lower arm as straight as possible and orthogonal to the rod, and used the right index finger to press the middle of the finger pad. All users used their right hands, which does not affect the results from the left-handed users (as described in [10]). The user looked directly at a computer screen while holding his or her finger on the finger pad. Noise-canceling headphones (not shown) were used during the experiment to mask auditory cues from the motor.

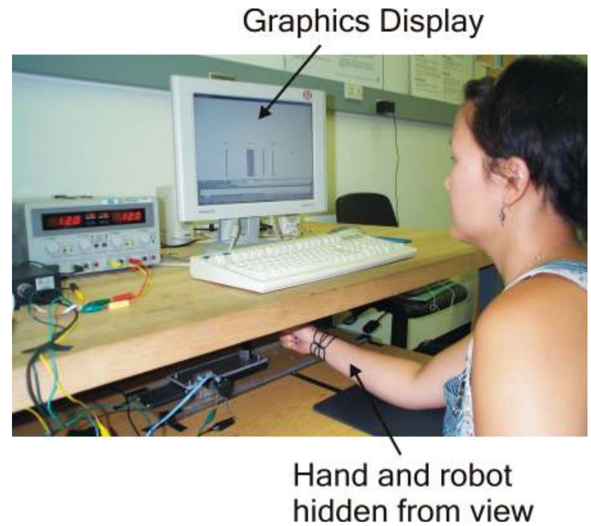

Figure 2: Experiment setup with robot, user, and graphic display.

Each user was allowed a brief practice period to interact with all of the admittance gains at whatever force levels he or she chose. The admittance gain, velocity, and force applied were displayed to the user on the computer screen. The user reported to the experimenter when he or she was ready to proceed to the next admittance gain or was finished with the practice trials.

During the experiment, the user was instructed to watch a graphic display on the computer screen that showed a stationary red line for the target force, a moving blue line for the force applied, two stationary black lines on either side of the red line to signal a force that was far "Over" or "Under" the target force (twice the target force, and 0 N, respectively), and a shaded box around the red line (Figure 3). The user was told to place and hold the blue line over the red line by adjusting the force applied. The user was not given any information about the type of control system, the admittance gain or velocity setting, or the target force box. The user was told to maintain a constant force, regardless of how the robot moved.

When the user held his or her applied force line within the shaded target box for three seconds, indicating that he or she was holding a "constant" force, the graphic display was turned off and data recording commenced. Under the assumption that the human can maintain a constant force on a stationary robot with only haptic feedback, this data provided a baseline case. After two seconds, the robot began to move to the left, away from the user's hand, using either a desired admittance gain or velocity, depending on the experiment. In both experiments, the robot accelerated to the commanded velocity almost

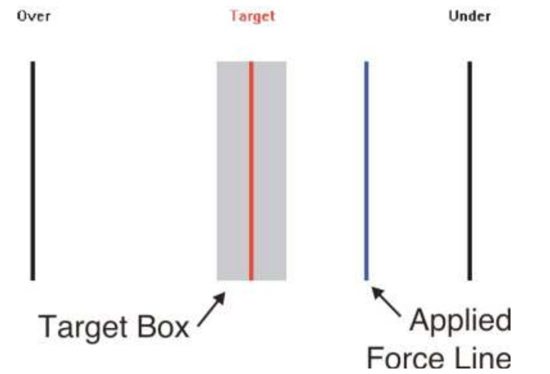

Figure 3: Graphic display shown on computer screen to users at the beginning of each trial.

Table 1: Experiment Configurations

Velocity Experiment	Admittance Control Experiment
7 users	7 users
2 trials per configuration	2 trials per configuration
f = 0.5, 1, 2, 3 N	f = 0.5, 1, 2, 3 N
v = 0, 1, 4, 7, 10, 13, 16, 20, 30 mm/s	k = 0, 0.5, 1, 2, 3, 4, 5, 7, 10 mm/Ns

instantaneously. After another two seconds, the robot stopped moving, data stopped recording, and text appeared on the screen to signal the end of the trial.

The target box was set at ±15% of the target force, slightly higher than the 10% JND [2], to ensure that it was actually possible for the user to hold a "constant" force for three seconds. The values of the admittance gain k and velocity v were chosen from the results of preliminary experiments to ensure that the threshold discussed in Section 1 would be found. The target force values were chosen to give a range of forces that might be used in light pushing tasks, while not exceeding human limits of force discrimination [6]. The admittance gain, velocity, and force values used in the experiment are shown in Table 1. Each user performed two trials for each of the 36 randomized configurations (4 forces for each of the 9 k values or 4 forces for each of the 9 velocity values in Table 1), with the order of presentation of configurations also randomized.

3. Results/Discussion

As our first metric for force control precision, we used the standard deviation of the force data for the portion of the trial when the robot was moving at a constant velocity or under admittance control (the

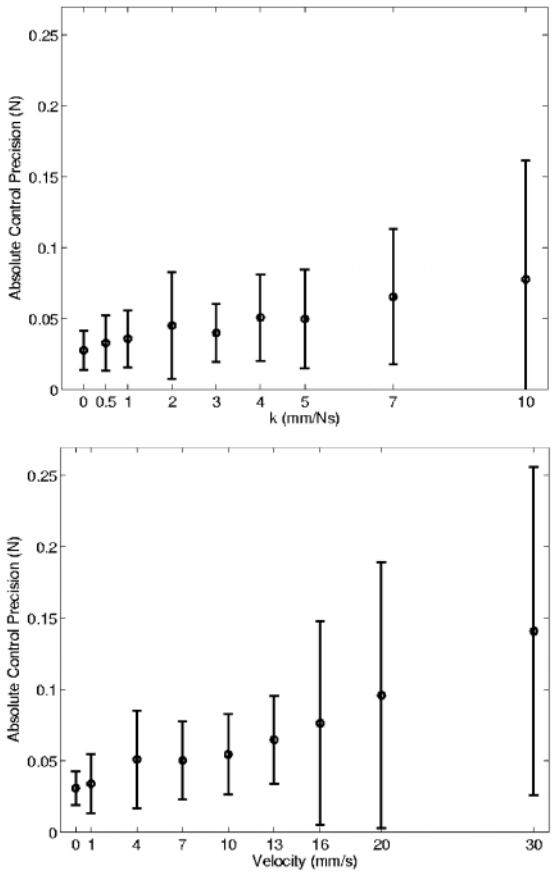

Figure 4: Absolute control precision across all users and trials for the admittance control and constant velocity experiments. Lower values indicate better precision.

second half of the data). Figure 4 shows this metric, which we refer to as the absolute control precision (averaged over all users, configurations and trials). This metric gives an absolute measure of force control precision for different velocities or admittance gains. Note that a low value of this metric indicates good precision. Both the admittance and velocity experiment plots show strong upward trends in the absolute control precision metric and an accompanying increase in standard deviation in the metric.

For some quickly moving trials in both experiments, a sharp drop in force occurs for approximately 0.5 seconds after the robot begins to move. (A typical example of this behavior is shown in Figure 5.) That portion of data was removed from each trial before calculating the absolute control precision. This could be due to the effects of robot acceleration or a period of human adaptation, but further research is needed to determine what exactly causes this loss of force control. It may also be desirable to find trends in

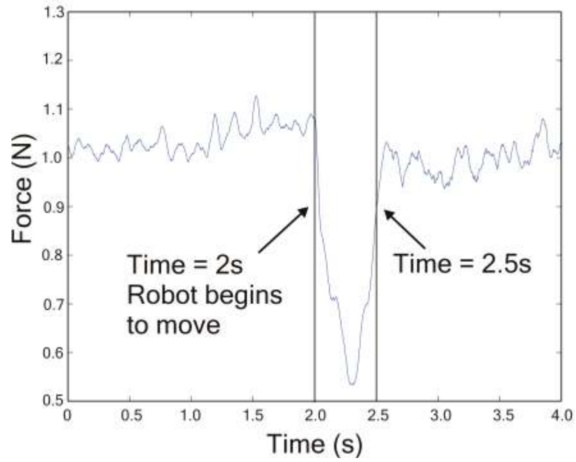

Figure 5: Sample Data. Force control precision is drastically lost around time = 2s, when the robot first begins to move and recovered approximately 0.5 seconds later.

the magnitude of the drop in applied force and the significance of and trends in the time interval of this occurrence.

Although the target force levels are balanced across admittance gain and velocity values, it is possible that the mean force level affects control precision. To address this, we also considered the coefficient of variance. Our experiment, unlike those of [6,7,11], calculated the coefficient of variance by dividing the standard deviation in the force data by the mean of that data, not the target force, to avoid assumptions about the user's performance. This metric tends to remove the effects on precision that come with increasing force, which could occur even for isometric forces. This metric was calculated using the same portion of the data used to calculate the previous metric.

We found relatively low values for coefficients of variance: 2-6% for the admittance experiment and 2-12% for the velocity experiment. The coefficients of variance for the isometric cases of $k = 0$ and $v = 0$ can be compared directly to previous work. Our coefficients of variance are significantly lower than those found in previous work, which can probably be attributed to differences in trial lengths. Jones used a 120-second trial [6,7], and Srinivasan and Chen used 14-second trials [11]. Our trials were significantly shorter, and this could explain the increase in precision.

In order to quantitatively discriminate whether velocity or admittance gain directly affects force control, and to determine at what threshold value the force control precision is worse (in a statistically significant sense) than the isometric case, an analysis

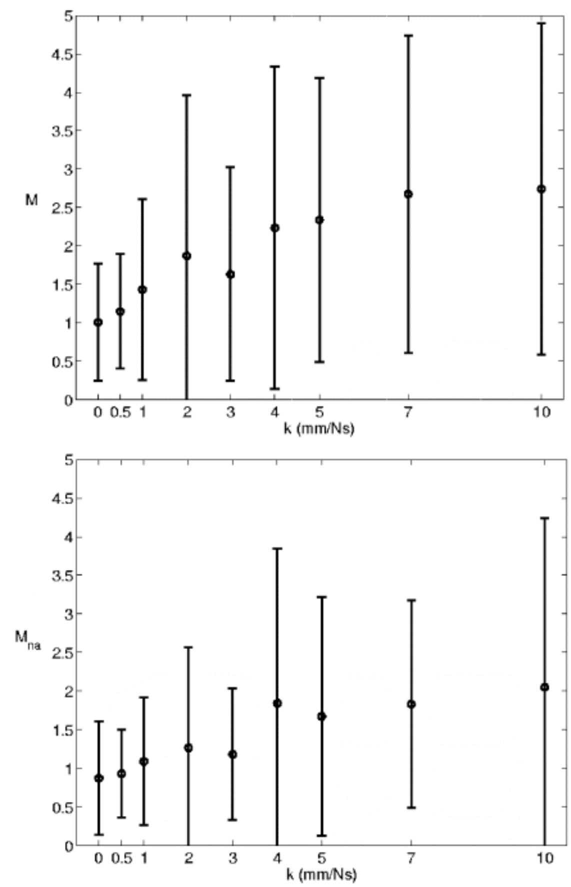

Figure 6: ANOVA metrics for the admittance experiment.

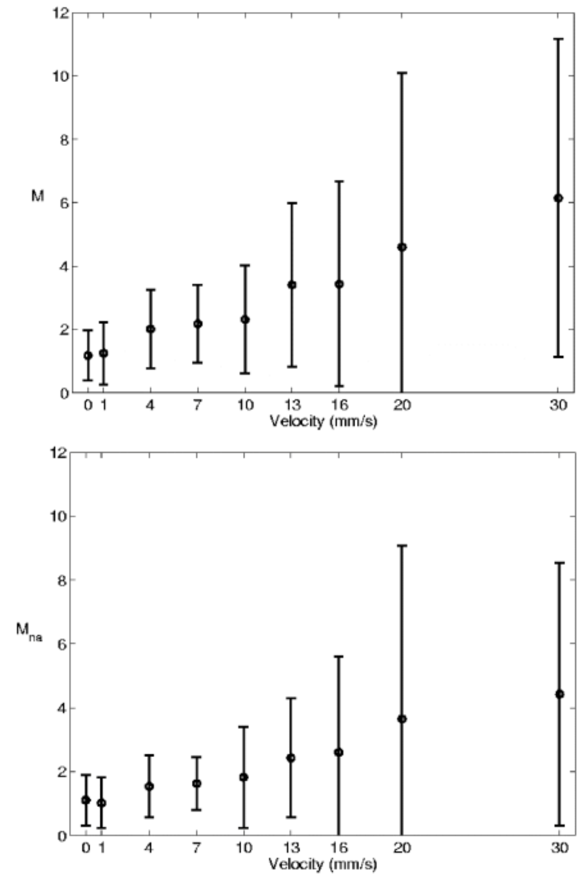

Figure 7: ANOVA metrics for the velocity experiment.

of variance (ANOVA) mixed-effects model [8] was used to analyze both experiments' data for the metric:

$$M = \sigma_2 / \sigma_1, \quad (2)$$

where σ_2 gives the standard deviation of the second half of the trial and σ_1 gives the standard deviation of the first half of the trial, and for the metric:

$$M_{na} = \sigma_{2,na} / \sigma_1, \quad (3)$$

where $\sigma_{2,na}$ gives the standard deviation of the second half of the trial without considering the effects of acceleration (that is, without the 0.5 seconds of transitional data described in Figure 5).

These metrics normalize the absolute control precision of the constant velocity or admittance control part of each trial by the absolute control precision of the stationary (isometric) part, which is the baseline case. These standard deviation ratio metrics were chosen to explicitly compare the force control precision when moving versus the isometric force precision of the same applied force *for the same trial*. In choosing these metrics, we hope to largely eliminate the direct effect of force level in the analysis to follow.

In the ANOVA for the admittance control experiment (Figure 6), F-tests show that the variables k, f, and *user* all have a main effect on the metrics M and M_{na}, and that k and *user* also have an interaction effect on M ($p < 0.05$). A Scheffe test [8] shows which values of k had significantly different results from the baseline case of $k = 0$ (stationary robot). Those were $k = 4, 5, 7, 10$ for M and $k = 10$ for M_{na} ($p < 0.05$).

The F-test for the velocity experiment shows that the variables v and *user* have a main effect on both metrics, and that f and *user* also have an interaction effect on both metrics. The Scheffe test shows which values of velocity gave significantly different results from the baseline case of $v = 0$ (stationary robot). Those were $v = 13, 16, 20, 30$ for M, and $v = 20, 30$ for M_{na} (Figure 7).

The F-tests for the admittance control experiment showed a main effect of force while the F-test for the velocity experiment did not. We explicitly chose the two metrics to eliminate the effects of force level, so, due to the admittance control law of Equation 1, a main effect of force in the admittance experiment is evidence of the influence of velocity.

In fact, when we consider the group means for each of the four force levels, there is a strong upward trend in both metrics with an increase in force level. A main effect of force in the velocity experiment would point to the importance of the equivalent "*k*" value. The fact that force did not have a main effect in the velocity experiment confirms that velocity, and not the admittance gain, is the determining factor affecting non-isometric force control precision.

Inspection of Figures 6 and 7 reveals that the variance (relative to the distribution of the means) in both metrics for the admittance experiments appear much larger than those for the velocity experiment. This is more evidence supporting the idea that velocity, and not admittance gain, affects force control. In Figure 6, each value of k includes data from four different force levels (and thus four different velocities), causing the large variance in the metrics around the respective means because of the effect of velocity. The velocity levels in Figure 7 also contain four different force levels (corresponding to four different equivalent "*k*" values), but the variance is relatively much smaller.

Because the metric M considers the entire second half of the data, it includes the effects of acceleration and/or learning discussed earlier. For this reason, it is not clear if the data is truly representative of the given value of k or v, or simply the act of *switching* from k = 0 to some nonzero admittance gain, or from $v = 0$ to some nonzero constant velocity. Understanding force control during this switching may be of interest in its own right in the field of virtual fixtures [9] for operator assistance. Further research must be done to isolate and understand this phenomenon. The metric M_{na} assumes that the user has adapted to the new admittance or constant velocity situation.

"Passing" the Scheffe test is sufficient (but not necessary) for two groups of data to be significantly different from one another. In Figures 6 and 7, the metrics appear to deviate from the baseline case ($k = 0$, $v = 0$) at lower values than those found by the Scheffe tests. Therefore, while we were able to show statistically that at or above 20 mm/s (also when switching from rest to a velocity at or above 13 mm/s) the human has degraded force control over the isometric case, it is possible that the true thresholds are lower than these values. More data is needed to find the precise thresholds. Figure 7 indicates that the true threshold, where the motion of the robot first affects human force control precision, could be lower than 4 mm/s.

No significant trends could be found in user performance due to gender, handedness, or experience with haptic devices. The ANOVA described in this section was performed with the S-PLUS statistical software package.

4. Conclusions and Future Work

Based on inspection and statistical analysis of experimental data, we found that velocity, not admittance gain, determines force control precision in an admittance control system. The upper bound of human force control ability occurs at or below a velocity of 20 mm/s. An upper limit on velocity should be enforced in any teleoperated or cooperative robot system that requires the human operator to control force to the same precision as they would isometrically. This velocity limit can be implemented directly in velocity controllers, or indirectly in admittance controllers by calculating an upper bound on k based on admissible forces.

A future study could directly analyze the effects of velocity under admittance control (not constant velocity control), by creating a statistical experiment that is balanced in velocity and force (and therefore not balanced in admittance gain). Because of the large variance found between users and trials, the new experiment should contain a larger data set to statistically determine the threshold velocity value for force control. The results from our experiment could be used to justify the simplicity of the new experiment, as well as to decide which velocity levels need be considered.

The experimental method presented in this paper of switching from an admittance gain of zero to a non-zero admittance gain models techniques used in force guidance in human-machine collaborative systems with virtual fixtures. HMCS devices should apply the previously mentioned upper limits of velocity, calculated indirectly from force and admittance, to ensure that the user maintains force control during the application and release of the virtual fixture. This is especially critical in applications such as microsurgery, which requires high precision.

Human-robot systems that require a specific level of force control precision can consult the plot of absolute control precision in Figure 4. This data provides ranges of deviations from a mean force that can be expected for different k and v values, and could be used to design optimal filters, making admittance control devices move more closely to the user's intended velocity. This would increase the intuitiveness of an admittance control device.

As mentioned in Section 2, the robot accelerates almost instantaneously to the target velocity or the effective velocity that results from the control law of Equation 1, producing greater accelerations for higher velocities. Analysis of the effects of acceleration on human force control requires further research, and the results could be compared to the analysis of velocity data in this paper to determine whether velocity or acceleration causes the drastic loss and eventual recovery of force control shown in Figure 5. If the loss in force control is due to the final velocity, results from the proposed acceleration experiment would show similar reduction in force control precision over different acceleration values that result in the same final velocity. That would suggest that the human is reacting to a certain velocity, not the acceleration, during the typical 0.5-second drop in force control (Figure 5).

Once the conditions under which the human is not affected by the robot in a human-robot system are determined, this information could be used to simplify stability proofs for teleoperated and cooperative robots, by essentially taking the human "out of the loop." If an appropriate acceleration or velocity threshold is implemented on a human-robot system, under which the human can control a constant force as accurately as if the robot was not moving at all, then the human could be considered an exogenous force input, and would not need to be modeled in a stability analysis.

Finally, the coefficients of variance in this experiment were much lower than those from other experiments with longer trial lengths and probably demonstrate the true limits of human ability for force control precision. The results of an experiment to quantify this effect could reconcile this experiment's results with those of previous research and lead to a more comprehensive understanding of human force control.

Acknowledgments

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