Variable Damping Control of a Robotic Arm to Improve Trade-off between Agility and Stability and Reduce User Effort

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***Abstract*— This paper presents a variable damping controller to improve the trade-off between agility and stability in physical human-robot interaction (pHRI), while reducing user effort. Variable robotic damping, defined as a dual-sided logistic function, was determined in real time throughout a range of negative to positive values based on the user's intent of movement. To evaluate the effectiveness of the proposed controller, we performed a set of human experiments with subjects interacting with the end-effector of a 7 degree-of-freedom robot. Twelve subjects completed target reaching tasks under three robotic damping conditions: fixed positive, fixed negative, and variable damping. On average, the variable damping controller significantly shortened the rise time by 22.4% compared to the fixed positive damping. It is also important to note that the rise time in the variable damping condition was as fast as that in the fixed negative damping condition and there was no statistical difference between the two conditions. The variable damping controller significantly decreased the percentage overshoot by 49.6% and shortened the settling time by 29.0% compared to the fixed negative damping. Both the maximum and mean root-mean-squared (RMS) interaction forces were significantly lower in the variable damping condition than the other two fixed damping conditions, i.e., the variable damping controller reduced user effort. The maximum and mean RMS interaction forces were at least 17.3% and 20.3% lower than any of the fixed damping conditions, respectively. The results of this study demonstrate that humans can extract the benefits of the variable damping controller in the context of pHRI, as it significantly improves the trade-off between agility and stability and reduces user effort in comparison to fixed damping controllers.**

I. Introduction

The trade-off between agility and stability has long been an important problem in physical human-robotic interaction (pHRI) [1-4]. With wide spreading applications in areas such as rehabilitation [5], military [6, 7], and industrial robotics [8, 9], pHRI has marked its place as an important field of study. Given its dearth of potential uses, it is even more important that this trade-off between agility and stability in pHRI be improved.

Current research in pHRI has been focused on building energetically passive or dissipative robots. Largely, this is motivated by a need for safety for the human and the robot, and having an energetically passive or dissipative system guarantees coupled stability. Human safety is, and should be, the top priority when designing robotic controllers in pHRI applications; however, this need for safety causes stability to be over-engineered at the expense of agility.

A common control strategy for pHRI is the use of an impedance or admittance controller, as mechanical impedance or admittance describes the exchange of energy at the interaction port between two systems in physical contact [2, 10]. Stability can be guaranteed in this control scheme if physically coupled systems are energetically passive [5, 6]. The guarantee of stability, and thus safety, makes passivity-based approaches desirable; but in that quest for stability the conservative nature of the control scheme shackles the coupled system with agility limits that may be undesirable.

This study addresses this trade-off between agility and stability and proposes a variable damping controller, which varies robotic damping values throughout a safe range of damping values based on user intent and is centered at a specified value of damping appropriate when user intent is unknown. This controller is general enough to be used in many forms of pHRI. In this study, we apply it to a robotic arm interacting with the human arm, a commonly used setting in industrial and rehabilitation applications. At such, the safe bounds of damping are determined with knowledge of mechanical impedance of the human arm.

The objectives of this study were to introduce a variable damping controller for physically interactive robots and to investigate the agility and stability benefits a human would gain by using this control scheme vs. a typical fixed impedance/admittance control scheme. We hypothesized that humans could extract agility and stability gains by using a wider band of negative and positive damping values during a dynamic movement task. We further hypothesized that the variable damping controller could help humans operate the robot more easily with less user effort.

To test this hypothesis, we performed a set of human experiments with subjects interacting with the end-effector of a 7 degree-of-freedom (DOF) robot. Subjects completed target reaching tasks under three damping conditions: fixed positive, fixed negative, and variable damping. Statistical analysis of the dynamic responses confirmed the effectiveness of the variable damping control strategy to improve the trade-off between agility and stability, as well as to decrease user effort with this controller.

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II. Methods

A. Variable Damping Controller

Typically, an admittance controller uses a set of static impedance parameters, i.e., inertia (I), damping (B), and stiffness (K), at the interaction port between the human and the robot. The variable damping controller developed in this study, instead, varies the damping component of the impedance to change the system response based on the user's intent of movement.

User intent is measured by the product of velocity ($\dot{x}$) and acceleration ($\ddot{x}$), $\dot{x}\ddot{x}$. This quantity is a scaled measure of the change in kinetic energy of the system. Thus when $\dot{x}\ddot{x} > 0$ the user intends to initiate and accelerate the motion and lower robotic damping (b_r) is desirable to enhance agility and yield a faster system response; conversely, when $\dot{x}\ddot{x} < 0$ the user intends to decelerate and end the motion and higher b_r is desirable to assist stabilization.

Robotic damping was calculated in real time using a dual-sided logistic function to allow the b_r to smoothly vary in the range of $[b_{lb} + b_c,\ b_{ub} + b_c]$ as shown in (1):

$$b_r = \begin{cases} -b_{lb} + \dfrac{2b_{lb}}{1 + e^{-k_p \dot{x}\ddot{x}}} + b_c, & \dot{x}\ddot{x} \geq 0 \\ b_{ub} - \dfrac{2b_{ub}}{1 + e^{-k_n \dot{x}\ddot{x}}} + b_c, & \dot{x}\ddot{x} < 0 \end{cases} \quad (1)$$

where $b_{lb} < 0$ and $b_{ub} > 0$ are the lower and upper bounds of b_r, respectively. The constant b_c is a center damping value, which is achieved when user intent is zero ($\dot{x}\ddot{x} = 0$). The constants k_p and k_n are tuning parameters, which determine how quickly robotic damping varies from $[b_{lb} + b_c,\ b_c]$ and $[b_c,\ b_{ub} + b_c]$, respectively. To accommodate speed variability across subjects, these constants are calculated using (2)

$$k_p = -\frac{\ln\left(\frac{1-s}{1+s}\right)}{(\dot{x}\ddot{x})_{\max}}, \qquad k_n = -\frac{\ln\left(\frac{1+s}{1-s}\right)}{(\dot{x}\ddot{x})_{\min}} \quad (2)$$

where the constant s is a sensitivity measure. In this study, $s = 0.95$. $(\dot{x}\ddot{x})_{\max}$ and $(\dot{x}\ddot{x})_{\min}$ imply the maximum and minimum value of $\dot{x}\ddot{x}$ during normal movement. With the selected sensitivity value, b_r will be $0.95b_{lb} + b_c$ at $\dot{x}\ddot{x} = (\dot{x}\ddot{x})_{\max}$. Similarly, b_r will be $0.95b_{ub} + b_c$ at $\dot{x}\ddot{x} = (\dot{x}\ddot{x})_{\min}$.

B. Variable Damping Controller Simulations

To display how the variable damping controller varies damping during movement, we provide a simulation to demonstrate the benefits of variable damping on stability and agility and improvements over a single variable damping function [11]. The controller acts on a target reaching movement following a minimum jerk trajectory (Eq. (3); Fig. 1A).

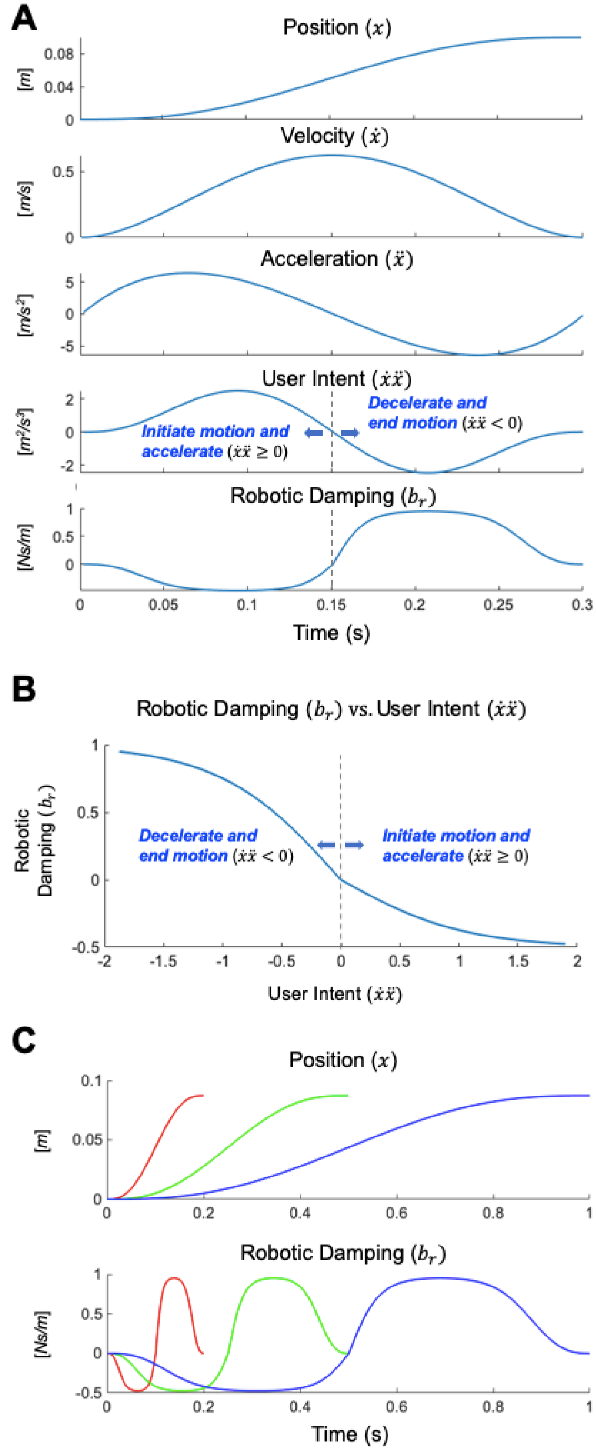

Fig. 1. A: Variable damping controller simulation for the movement following a minimum jerk trajectory. **B:** Direct relationship between robotic damping and user's intent of movement. **C:** Simulation of the variable damping controller over a wide range of movement durations (Red: $t_d = 200\ ms$, green: $t_d = 500\ ms$, blue: $t_d = 1000\ ms$).

$$x = x_{\text{target}}\left[10\left(\frac{t}{t_d}\right)^3 - 15\left(\frac{t}{t_d}\right)^4 + 6\left(\frac{t}{t_d}\right)^5\right] \quad (3)$$

In the simulation, $x_{\text{target}} = 0.1$ m, the sensitivity measure $s = 0.95$, the center of damping $b_c = 0$ Nm/s, and the lower and upper damping bounds were $b_{lb} = -0.5$ Nm/s, $b_{ub} = +1.0$ Nm/s, respectively.

The simulation shows positive velocity throughout, while acceleration is positive for the first half of the movement and negative for the second half of the movement. While the acceleration is positive, user intent $\dot{x}\ddot{x}$ is positive and consequently robotic damping decreases, which aids in agility. Conversely, in the second half of the simulation, acceleration and user intent are negative, and variable damping increases to aid in deceleration and stability (Fig. 1A). The direct relationship between robotic damping and user's intent of movement is also provided (Fig. 1B).

We also provide a simulation to show how the variable damping controller utilizes the full range of damping no matter the speed of movement. The movement duration (t_d) is changed while all other parameters remain the same as in the first simulation (Fig. 1C).

C. Experimental Protocol

To quantify the effectiveness of a variable damping controller on agility and stability in the context of upper-body pHRI, we performed a set of target reaching human experiments using variable damping and fixed damping admittance controllers integrated in a 7-DOF robotic arm (LBR iiwa R820, KUKA, Germany). A 6-axis load cell (Delta IP60, ATI Industrial Automation, NC) and a handle were fixed to the end-effector of the robot to create a port with which the human would interact.

We limited our investigation of the effects of the variable damping controller to the transverse/horizontal plane. To effectively limit motion to this plane, elements of the stiffness matrix corresponding to non-transverse plane directions were set extremely high (10^6 N/m). In the directions of the transverse plane, stiffness was set to 0 N/m, inertia to $10\,kg$, and damping was either varied as prescribed in Eqs. (1) and (2) or was fixed constant to either $b_{lb} + b_c$ or $b_{ub} + b_c$.

Twelve young, healthy subjects (age: 21-29, weight: 47-87 kg) participated in this experiment, which was approved by the Institutional Review Board of Arizona State University (STUDY00010123). All subjects provided written consent prior to participation and were not informed regarding the hypothesis.

During this experiment, a human subject was seated on a stool (Fig. 2A). A strap wrapped around their underarm attached to a vertical metal pole running along the middle of their scapula maintained their seated, upright posture. Subjects held the handle, which was connected to the end-effector of the robot, with the shoulder in ~70° of abduction, ~45° of horizontal flexion, and the elbow in ~90° of flexion. This starting posture was considered the "neutral position" for all trials. The stool was positioned so that the subject could move their arm at least 18 cm from neutral position in any direction of the transverse plane. To impose the same robot dynamics (10 kg mass and 0 N/m stiffness) to the human operator regardless of movement direction, subjects sat in two different stool positions depending on movement direction of the trials (Fig. 2B). Subjects were provided real-time visual feedback on the neutral, current, and target hand position (or the position of the end-effector) (Fig. 2C). As a safety feature, a virtual wall of 36 x 36 cm^2 was implemented around the neutral position. When displacements reached the virtual wall, the simulated damping switched to 30 Ns/m to stabilize the arm and prevent any potential injuries.

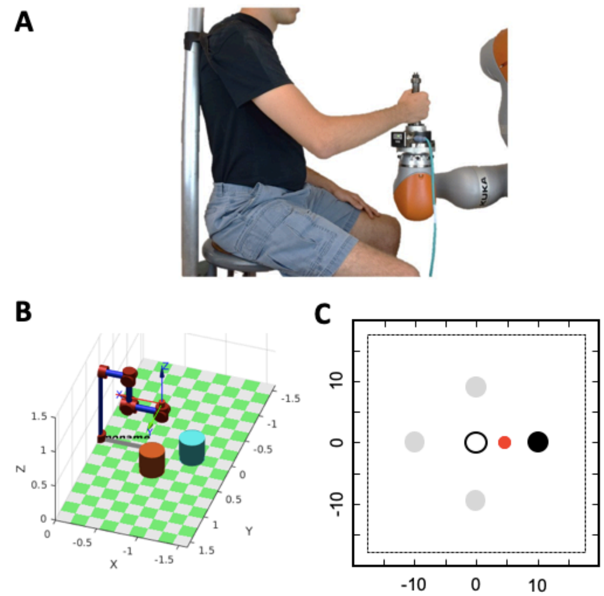

Fig. 2. A: Experimental Setup. **B:** Sitting positions. Cyan cylinder: stool position for left/right trials. Orange cylinder: stool position for forward/backward trials. Robot principally moved in the global Y axis as pictured. **C:** Real-time visual feedback for target reaching tasks. Hollow black circle: neutral position, solid red circle: current hand position, solid black circle: target, gray circles: target locations (10 cm from the neutral position). Only one target will be presented for each trial. Dotted box: virtual wall of 36 x 36 cm^2.

Each experiment consisted of a series of target reaching trials from the neutral position to a target position 10 cm forward, backward, left, or right in the transverse plane. The subjects were instructed to reach the target as quickly as possible, while staying stable. The trial duration started when the target moved away from the neutral position and lasted until 2 seconds after the subject first came within 0.5 cm of the target. Once a trial concluded, the target returned to the neutral position. The subject then moved back to the neutral position, and a new trial started at a randomized interval between 0.5-1.5 seconds. Within blocks, trial movements were randomized either forward and backward, or left and right.

Trials were spread evenly across three damping conditions: variable, fixed positive, and fixed negative damping. Variable damping bounds were set at $b_{lb} = -20$ Nm/s and $b_{ub} = +60$ Nm/s with $b_c = 0$ Nm/s. The lower bound of damping was determined based on data from a sister study in our lab, which tested the lower damping bounds that humans could stabilize subject to a perturbation at different points in the workspace around their body. An environment with this level of negative damping was shown to be safe as subjects stabilized perturbations throughout the workspace at this level of damping without prior practice. During the positive damping trials, $b_r = b_{ub} = +60$ Nm/s and during negative damping trials, $b_r = b_{lb} = -20$ Nm/s.

Each subject completed 15 blocks of 10 trials in the left/right direction, followed by 15 blocks of 10 trials in the forward/backward direction. The 15 blocks were split

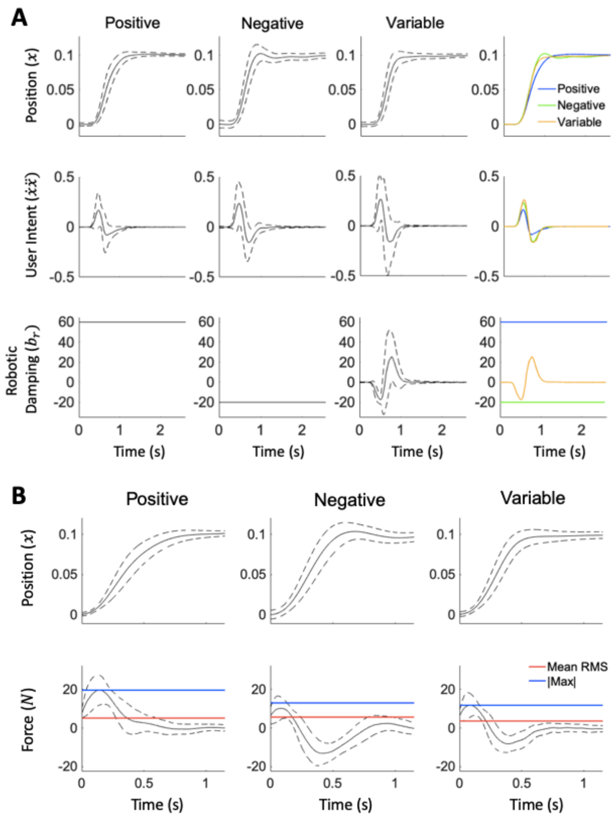

Fig. 3. A: Comparisons of position response, user intent, and robotic damping in three experimental conditions. Blue: positive damping, green: negative damping, orange: variable damping. **B:** Comparisons of interaction forces in three experimental conditions. (Top): position response, (Bottom): measured interaction force (black), maximum interaction force (blue), mean RMS interaction force (red). Solid and dotted lines denote the mean and mean +/- 1SD of all trials. Responses for the left movement trials of a representative subject are shown.

evenly between positive, negative, and variable damping. Within a given block of 10 trials, the sequence of left/right or forward/backward trials were randomized. In total, each subject completed 300 trials, 25 for each forward, backward, left, and right movements in each of the three damping conditions. The order of the blocks with different damping conditions was randomized and not communicated to the subject.

Prior to trials in each direction, subjects completed two blocks of 10 trials with a zero damping environment to gather velocity and acceleration data during normal movement, specifically, $(\dot{x}\ddot{x})_{\max}$ and $(\dot{x}\ddot{x})_{\min}$, and to tune the constants k_p and k_n for each subject. Once initial estimates of k_p and k_n were found, the subjects completed two more blocks of 10 trials under the variable damping condition to gather data to refine the tuning parameters and familiarize the subjects with the experimental setup and environments. Including the additional preliminary trials, the entire experiment took approximately 2 hours for a subject to complete.

D. Data Analysis

In this experiment, we sought to quantify the effects of a variable damping controller using 3 performance measures: agility, stability, and user effort. Rise time, defined as the time to reach 90% of the steady-state value, was used as the measure of agility in this study. Percentage overshoot (%OS), defined as the amount that the response overshoots the steady-state value as a percentage of the steady-state value, was used as the measure of stability. Settling time, defined as the time to reach and stay within $\pm 5\%$ of the final value, was also used as the stability measure. Lastly, maximum and mean root-mean-squared (RMS) forces at the interaction port were used to quantify the user effort. The mean RMS interaction force was calculated from the beginning to the end of movement.

During data analysis, all position data through a trial was averaged. Any trials that contained any position data for any time outside of mean ± 3 standard deviation (SD) was considered outlier data and discarded from any further analysis. According to this criterion, we rejected 9.2% of the total trials.

Our central hypothesis was that the variable damping control strategy would improve the trade-off between agility and stability as well as decrease the user effort. In particular, the rise time for agility would be significantly faster during interaction with the variable damping controller than the fixed positive damping controller in all four movement directions. The %OS and settling time for stability would be significantly lower during interaction with the variable damping controller than the fixed negative damping. The maximum and mean RMS interaction forces for the user effort would be significantly lower during interaction with the variable damping controller than the other two fixed damping controllers.

To test this hypothesis, we performed one-way repeated measures ANOVA with damping condition as the within subject factor, separately for each metric and for each direction of movement. The ANOVA analysis was followed by pairwise comparisons with Bonferroni correction. All statistical tests were made using the SPSS statistical package at a significance level of $p < 0.05$.

III. Results

The effects of the three damping-defined environments were consistent across all subjects. Positive damping (+60 Ns/m) was more stable than negative damping (-20 Ns/m), while negative damping demonstrated a faster system response. Variable damping ($[-20, +60]$ Ns/m), which aimed to demonstrate the stability of positive damping and the agility of negative damping, showed it could balance the trade-off between stability and agility, while decreasing the user effort compared to either fixed damping condition. Results of a representative subject for the left movement direction are shown in Fig. 3. These responses were consistent across all four movement directions (forward, backward, left, and right) and all subjects.

First, damping condition had a significant effect on the rise time ($p < 0.001$; Fig. 4). Pairwise comparisons further demonstrated that the rise time in the variable damping condition was significantly faster than that in the positive

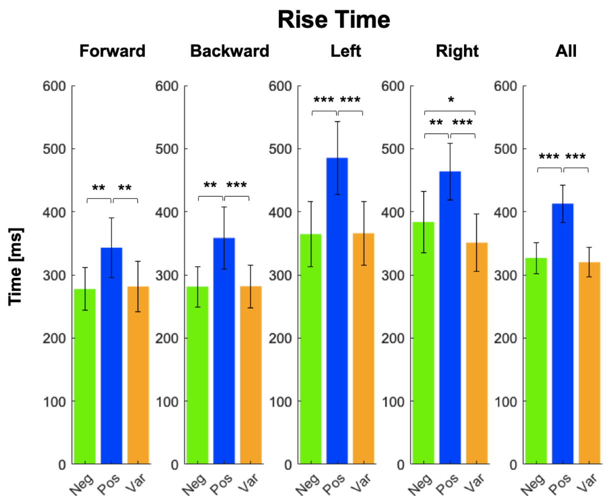

Fig. 4. Comparisons of group results on the rise time in three different experimental conditions. Green: negative, blue: positive, orange: variable. The same color codes are used in all subsequent figures. Bars and error bars denote the means and 95% confidence intervals. Asterisks denote statistically difference for pairwise comparison: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

damping condition in all four movement directions (p = 0.001 for forward and $p < 0.001$ for all other 3 directions). When averaged across all movement directions, the rise time in the variable damping condition was 22.4% faster than in the positive damping condition ($p < 0.001$).

The rise time in the variable damping condition was not statistically different from that in the negative damping condition in three of the four directions (forward, backward, and left) and 8.5% faster than the negative condition in the right direction (p = 0.04). When averaged across all movement directions, there was no statistical difference between the two damping conditions (p = 0.63).

Second, damping condition had a significant effect on the %OS ($p < 0.001$), which is the other side of the agility-stability trade-off (Fig. 5). When the fixed damping conditions were compared, for every subject, positive damping had less overshoot than negative damping. Positive damping overshoot averages ranged from 3.7% to 4.8%, whereas negative damping overshoot averages ranged from 11.2% to 16.0% depending on the direction. The %OS for variable damping was always somewhere in the middle; its averages ranged from 5.3% to 7.2% depending on the direction.

Pairwise comparisons showed that the %OS in the variable damping condition was significantly lower than that in the negative damping condition in all directions, except the forward direction (p = 0.06). While statistical significance was not reached, the forward direction also showed the same trend. When averaged across all movement directions, the %OS in the variable damping condition was 49.6% lower than in the negative damping condition ($p <$ 0.001).

Comparisons with the positive damping condition showed statistical difference only in the forward and backward directions, but there was no significant difference

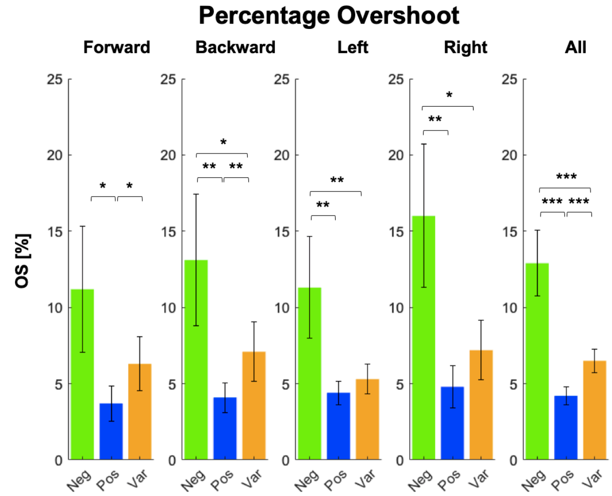

Fig. 5. Comparisons of group results on the percentage overshoot (%OS) in three different experimental conditions.

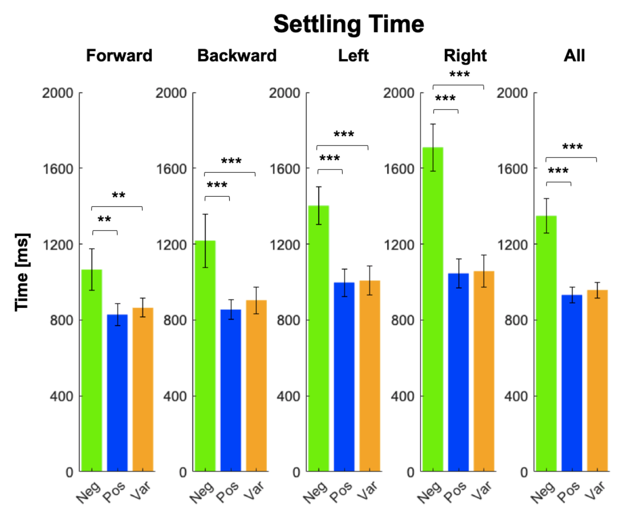

Fig. 6. Comparisons of group results on the settling time in three different experimental conditions.

in the left and right directions. However, when averaged across all movement directions, the %OS in the variable damping condition was significantly higher than in the positive damping condition ($p < 0.001$).

Third, damping condition also had a significant effect on the settling time ($p < 0.001$), which is another stability measure (Fig. 6). Pairwise comparisons further demonstrated that the settling time in the variable damping condition was significantly faster than that in the negative damping condition in all four movement directions (p = 0.002 for forward and $p < 0.001$ for other 3 directions). When averaged across all movement directions, the settling time in the variable damping condition was 29.0% faster than in the negative damping condition ($p < 0.001$).

The settling time in the variable damping condition was not statistically different from that in the positive damping condition in all four directions. When averaged across all movement directions, there was no statistical difference between the two damping conditions (p = 0.17).

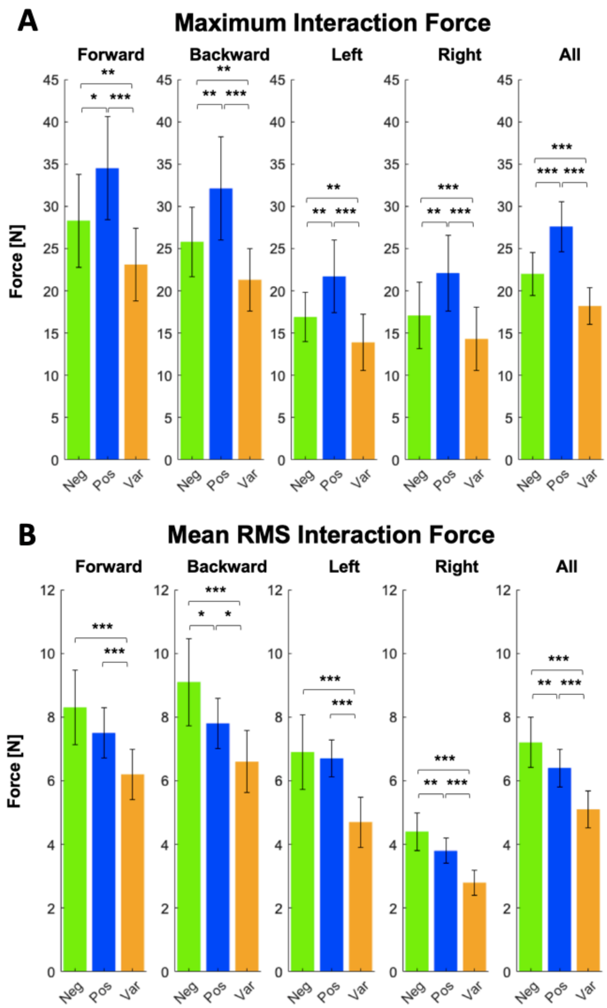

Fig. 7. Comparisons of group results on interaction forces in three different experimental conditions. **A**: maximum interaction force, **B**: mean RMS interaction force.

Lastly, damping condition also had a significant effect on the user effort ($p < 0.001$), measured by the maximum and mean RMS interaction forces (Fig. 7). In all movement directions, both forces were consistently lower in the variable damping condition than the other two fixed damping conditions, i.e., the variable damping controller significantly reduced the user effort.

In all directions, positive damping showed the greatest maximum interaction force, followed by negative damping, and variable damping had the least maximum interaction force. When averaged across all movement directions, the maximum force for the variable damping controller was 17.3% less than the negative controller ($p < 0.001$) and 34.1 % less than the positive damping controller ($p < 0.001$).

Mean RMS interaction force ordered from greatest to least had a different order, but the same conclusion can be made: the variable damping controller was easiest to use with the lowest user effort. In all directions, negative damping showed the greatest mean RMS interaction force, followed by positive damping, and variable damping had the least mean RMS interaction force. When averaged across all movement directions, the mean RMS interaction force for the variable damping controller was 29.2% less than the negative controller ($p < 0.001$) and 20.3% less than the positive damping controller ($p < 0.001$).

IV. Discussion

Impedance/admittance controllers with fixed positive damping have been a popular choice in pHRI applications largely because of the stability guaranteed by physically coupling two passive or dissipative systems. The stability of this control scheme comes at the expense of agility. The variable damping controller in this study provides an alternative control scheme which provides better agility and maintains stability, while reducing user effort. It does this by varying the damping to negative values to aid in agility and to positive values to aid in stability. When user intent indicated the user added kinetic energy to the system, the damping decreased, and conversely when the user took away kinetic energy, the damping increased. As long as the lower bound of the robotic damping range is lesser in magnitude than the positive damping of the human neuromuscular system, the coupled system is still stable.

Analysis of the response of the variable damping controller showed that it significantly improved the agility over the positive damping controller as the rise time was 22.4 % faster compared to the positive damping. It is also important to note that there was no statistical difference for the rise time between the variable and negative damping controllers. From this we can conclude the variable damping controller is at least as agile as the negative damping controller. It also showed significant improvement in stability over the fixed negative damping controller as the %OS and the settling time were about 50% and 30% of those of the negative damping controller, respectively. In addition to the improvements on the agility-stability trade-off, variable damping was also the easiest to use with the lowest user effort of all the controllers. The maximum and mean RMS interaction forces were tracked throughout the trials, and in all movement directions, it was demonstrated that the variable damping controller resulted in the least interaction forces.

Despite the positive results of this study, future research on the variable damping controller is needed in several areas. First, we performed target reaching experiments in forward, backward, left, and right directions in the transverse plane. While these movements are important "building blocks" of the normal movements, it is much simpler than arm movements during normal motor tasks. To fully validate the effectiveness of the variable damping controller, it is important to evaluate its performance for more realistic arm movements, which we will tackle in the next phase of this study. Next, there are rooms for improvement for the variable damping controller. In particular, the range of robotic damping, i.e., $[b_{lb} + b_c,\ b_{ub} + b_c]$, can be determined in a subject-specific manner. Another potential improvement would be tuning the parameters k_p and k_n adaptively throughout dynamic movement.

References

[1] W. S. Newman, "Stability and Performance Limits of Interaction Controllers," *Journal of Dynamic Systems Measurement and Control-Transactions of the Asme,* vol. 114, no. 4, pp. 563-570, Dec 1992.

[2] N. Hogan and S. P. Buerger, "Impedance and interaction control," *Robotics and Automation Handbook, New York, CRC Press,* 2005.

[3] J. E. Colgate and N. Hogan, "Robust-Control of Dynamically Interacting Systems," *International Journal of Control,* vol. 48, no. 1, pp. 65-88, Jul 1988.

[4] H. Kazerooni, "Human Robot Interaction Via the Transfer of Power and Information Signals," *Ieee Transactions on Systems Man and Cybernetics,* vol. 20, no. 2, pp. 450-463, Mar-Apr 1990.

[5] H. I. Krebs and B. Volpe, "Rehabilitation Robotics," *Handbook of Clinical Neurology, Neurological Rehabilitation,* vol. 110, no. 3rd series, pp. 283-294, 2013.

[6] Sarcos, "http://www.sarcos.com/."

[7] A. B. Zoss, H. Kazerooni, and A. Chu, "Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX)," *Ieee-Asme Transactions on Mechatronics,* vol. 11, no. 2, pp. 128-138, Apr 2006.

[8] H. Kawamoto and Y. Sankai, "Power Assist System HAL-3 for Gait Disorder Person," *In Proc. International Conference Computers Helping People with Special Needs (Lecture Note in Computer Science),* vol. 2398, pp. 196-203, 2002.

[9] C. Heyer, "Human-robot interaction and future industrial robotics applications," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taiwan, 2010, pp. 4749–4754.

[10] H. Lee and N. Hogan, "Essential considerations for design and control of human-interactive robots," in *In Proc. 2016 IEEE International Conference on Robotics and Automation (ICRA 2016)*, Stockholm, 2016, pp. 3069-3074.

[11] J. Arnold, H. Hanzlick, and H. Lee, "Variable Damping Control of the Robotic Ankle Joint to Improve Trade-off between Performance and Stability," in *IEEE International Conference on Robotics and Automation (ICRA)*, Montreal, Canada, 2019, pp. 1699-1704.