Human Preferences in Using Damping to Manage Singularities During Physical Human-Robot Collaboration

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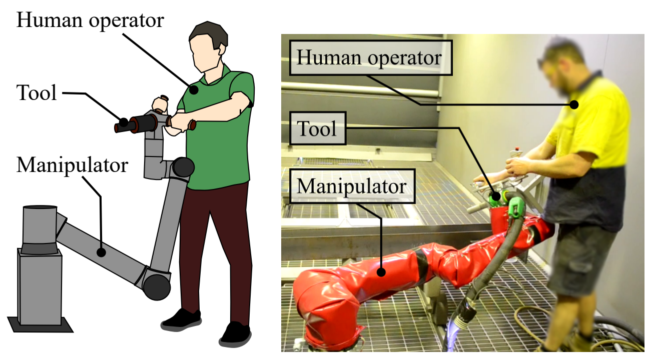
***Abstract*— When a robot manipulator approaches a kinematic singular configuration, control strategies need to be employed to ensure safe and robust operation. If this manipulator is being controlled by a human through physical human-robot collaboration, the choice of strategy for handling singularities can have a significant effect on the feelings and impressions of the user. To date the preferences of humans during physical human-robot collaboration regarding strategies for managing kinematic singularities have yet to be thoroughly explored.**

This work presents an empirical study of a damping-based strategy for handling singularities with regard to the preferences of the human operator. Two different parameters, damping rate and damping asymmetry, are tested using a double-blind A/B pairwise comparison testing protocol. Participants included two cohorts made up of the general public (n=51) and people working within a robotic research centre (n=18). In total 105 individual trials were performed. Results indicate a preference for a faster, asymmetric damping behavior that slows motions towards singularities whilst allowing for faster motions away.



(a) (b)

Fig. 1. (a) Depiction of physical human-robot collaborative (pHRC) during an industrial task. (b) Kinematic singularity causing poor robot performance during pHRC.

I. Introduction

As collaborative robot manipulators become ubiquitous in manufacturing, construction and other industries, it is anticipated that more and more robots will be used in direct physical collaboration by human workers. Depicted in Fig. 1a is a collaborative robotic manipulator working with a human operator who performs a task using a tool attached to the end-effector. Motions of the tool are controlled via direct physical interaction with the robot. Systems have been developed to provide physical assistance to humans in a variety of tasks including abrasive blasting [1], materials handling [2][3], rehabilitation [4][5][6] and others [7].

A challenge inherent in the physical human-robot collaboration (pHRC) paradigm is handling the mismatch of operational workspace. Ideally the robotic system should be capable of operating in the same workspace as the human operator in its entirety. In reality, the limited robot reach, collisions and singularities mean that the entire workspace of the worker cannot be reached. This is exacerbated in situations where the robot is fixed in location but the worker is not, as shown in Fig. 1b. Users are free to move away from the base of the manipulator, requiring the robot to work near kinematic singularity at the edge of its reachable workspace. Even before this singularity is reached, robot operation in the proximity to singularity is ill-behaved and strategies for mitigating the negative effects need to be implemented.

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It is a matter of discretion as to how robot behavior near singularity should be managed. In applications involving physical human-robot collaboration, careful consideration should be made regarding the impressions of the user. However, to date there has been a lack of studies into the perceptions and preferences of users collaborating with robots with respect to singularity handling methods. A preliminary study [8] comparing a standard Damped Least-Squares implementation with high, low and asymmetric levels of damping determined that the damping has an apparent effect on user perceptions. However, due to the small sample size (n=7) it is difficult to draw conclusions on the user preferences. This work presents results from a larger, double-blind empirical study on user preferences on damping for singularity handling during physical human-robot collaboration. The experiments included 105 trials from 69 participants, including participants from the general public (n=51) and members from a robotics research centre (n=18). A double blind study asked participants to utilize a collaborative robot, operating under an admittance-based control scheme, whilst comparing two pseudo-random damping modes that exhibited different levels of damping rate and/or asymmetry. Participants were asked to provide feedback about damping modes, describing differences between the modes, rating them with regard to particular qualities, and their preferences as to which mode they would rather use. Understanding the impressions and preferences of human users will provide insights that will lead towards improved user experience in physical human-robot interactions.

II. Managing Singularity in pHRC

Kinematic singularity is a fundamental problem with robotic manipulators. It causes a degree of freedom to be lost, and can negatively affect the ability of a robot to perform tasks. For a manipulator with joint coordinates $\mathbf{q} \in \mathbb{R}^n$, the relationship between velocity at the joints $\dot{\mathbf{q}} \in \mathbb{R}^n$ and the resulting spatial end-effector velocity $\dot{\mathbf{x}} \in \mathbb{R}^m$ (typically $m = 6$) is defined as $\dot{\mathbf{x}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$. Matrix $\mathbf{J} \in \mathbb{R}^{m\times n}$ the Jacobian matrix of the manipulator.

Traditional control methods actuate the joints of the manipulator to achieve a desired motion of the end-effector, requiring solutions to the relationship $\dot{\mathbf{q}} = \mathbf{J}^{-1}\dot{\mathbf{x}}$. However, when a manipulator is in the neighborhood of a singularity, the inverse of the Jacobian matrix degenerates and solutions become poorly conditioned. Near singularity, motions of the end-effector require large and often unobtainable velocities at the joints, resulting in a robot behavior that can be unpredictable and dangerous. Force-based control methods, such as admittance or impedance control, are typically used when physical interaction with humans or the environment is required. Admittance control regulates robot motions with respect to measured force interactions, and hence suffers from the same limitations when near kinematic singularity. Impedance control instead regulates the manipulator force output with respect to its motion. Near kinematic singularity, the force regulation capability of manipulators are impeded.

Several methods for achieving robust robotic behavior in the proximity of singularities have been proposed [9][10]. Traditional pick and place tasks can simply avoid singular configurations during the path planning stage. Such offline methods do not suit pHRC where robot motions are computed in real-time based on physical interaction with the user. Online methods include using the Jacobian Transpose method and Damped Least Squared. The Jacobian Transpose method [11][12] switches from using $\mathbf{J}^{-1}$ to $\mathbf{J}^T$ to compute the motion, which is analogous to a force applied to the end-effector guiding the robot towards a goal pose. Damped Least-Squares (DLS) [13][14] is a method that sacrifices exactness of the inverse Jacobian solution to produce an alternative Jacobian inverse that remains well-conditioned, even near singularity. It achieves this by minimizing the norm of the residual tracking error combined with a term relating to the magnitude of the joint velocities.

Traditional methods for handling singularities like those previously mentioned are typically evaluated on their ability to maintain stability whilst simultaneously maintaining trajectory-tracking performance. Human interaction, in particular how the physical interaction feels to the human user and their perception of the experience, is not considered. These traditional methods are still commonly used in pHRC applications despite not being developed with human interaction in mind. In [4] an approach for operating a PUMA 560 manipulator near singularity during rehabilitation tasks is presented. The robot switches between DLS or the Jacobaian Transpose method depending on the region it is operated in. In [15] a method for providing a human operator with haptic feedback about the kinematic condition of a robotic manipulator during tele-operation is investigated. DLS was utilized to ensure stable operation near singularity, as well as haptic feedback forces that guided the user away from singularity.

More recently there has been research into singularity handling methods specifically developed for pHRC applications. In [16] a method based on virtual Cartesian constraints that prevent the user guiding a manipulator into poor performing configurations, such as singularities, is proposed. These repulsive forces are integrated into an admittance-based control which successfully guided users away from singular configurations. Work by [17] showed positive results in experiments using an algorithm that aims to reduce the burden of users having to be mindful of robot limitations such as joint limits, collisions and singularities. These aforementioned methods suggest that the interaction between robot and human can be improved by developing human-centric singularity handling methods. However, to date, few studies have performed trials to test how such methods are perceived and preferred by human operators during collaborative robot tasks.

A. The Exponentially Damped Least Squared Method

In this work we utilize the framework presented in [18]. It combines several features including a variation of DLS with an exponentially-shaped damping profile and an asymmetric damping strategy to achieve behavior suitable for pHRC in proximity to singularities. The Jacobian is decomposed using Singular Value Decomposition into $\mathbf{J} = \mathbf{U\Sigma V}^T$ with $\mathbf{U} \in \mathbb{R}^{m\times m}$ and $\mathbf{V} \in \mathbb{R}^{n\times n}$ both orthonormal matrices, and $\mathbf{\Sigma} \in \mathbb{R}^{m\times n}$ diagonal containing the singular values $(\sigma_1, \sigma_2, \cdots, \sigma_m)$ of the Jacobian matrix. Inverting $\mathbf{J}$ requires inverting $\mathbf{\Sigma}$ which degenerates as singular values approach zero. To manage this, an exponential function is used to shape the reciprocal of the singular values, maintaining numerical integrity. This shaping is done using (1) where σ_0 and σ_1 define the sharpness of the damping, and β is a small parameter close to zero ($\beta = 0.02$ is suggested).

$$s(\sigma_i|\bar{\sigma}_0, \bar{\sigma}_1) = \begin{cases} 1-\beta^{\left[\frac{\sigma_i - \bar{\sigma}_0}{\bar{\sigma}_1 - \bar{\sigma}_0}\right]}, & \text{if } \sigma_i > \bar{\sigma}_0 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Using the shaping function $s(\sigma_i)$ to shape the reciprocal of the singular values, the Exponentially Damped Least Squares (EDLS) Jacobian inverse $\mathbf{J}^\star = \mathbf{V\Sigma}^\star\mathbf{U}^T$ with $\mathbf{\Sigma}^\star_{ii} = s(\sigma_i)/\sigma_i$ is calculated. Readers are directed towards [18] for a comprehensive explanation of the framework.

By setting the parameters $\bar{\sigma}_0$ and $\bar{\sigma}_1$ appropriately, different damping behaviors can be achieved. The speed at which the damping kicks in as a singularity is approached, referred to as the *Damping Rate*, is tuned by how far apart the values are. Having them similar in value will result in a sharp transition, whereas having them far apart will result in the damping coming into effect gradually.

The framework also proposes using an asymmetric behavior with more damping being applied when approaching singularity versus moving away. This is achieved by having two sets of damping parameters, $\{\bar{\sigma}_{a0}, \bar{\sigma}_{a1}\}$ and $\{\bar{\sigma}_{b0}, \bar{\sigma}_{b1}\}$ which are switched between according to if the robot is moving towards or away from singularity.

III. Experimental Method

A collaborative robot with the EDLS framework implemented was used to evaluate user damping preferences during pHRC. This section presents the experimental method used for this evaluation.

A. Experiment Design

User interactions with the robot were evaluated with regards to two different aspects: *damping rate* and *damping asymmetry*.

1) Damping Rate: The damping rate refers to how fast the damping slows down the motions of the robot when a singular configuration is approached, and is set by the difference between the $\bar{\sigma}_0 - \bar{\sigma}_1$ values in the shaping function (1). Two different damping rates are compared:

- *Fast damping rate:* $\bar{\sigma}_1 - \bar{\sigma}_0 = 0.1$
- *Slow damping rate:* $\bar{\sigma}_1 - \bar{\sigma}_0 = 0.2$

The smaller 0.1 difference in the *fast* rate results in a sudden onset of damping when a singularity is approached. The value of 0.1 was chosen as it was not too small to be alarming to the user. The larger 0.2 value in the *slow* rate results is a gentler damping change. This value was chosen as it was not too large as to cause frustration, and produced a subtle yet noticeable difference between the two settings.

2) Damping Asymmetry: We measure the asymmetry by comparing the difference in the $\bar{\sigma}_0$ values in both sets. If they are identical then we say that the damping is symmetric. Subscripts a and b are used to denote the $\{\bar{\sigma}_0, \bar{\sigma}_1\}$ sets corresponding to moving away from, and towards singularity, respectively.

Three different levels of asymmetry are compared:

- *No asymmetry:* $\bar{\sigma}_{a0} = \bar{\sigma}_{b0}$
- *Small asymmetry:* $\bar{\sigma}_{a0} = \bar{\sigma}_{b0} - 0.025$
- *Large asymmetry:* $\bar{\sigma}_{a0} = \bar{\sigma}_{b0} - 0.1$

The value of 0.1 for large asymmetric damping was chosen as this is the existing value being used with the collaborative robot and had come about from lengthy tests and trials. The small value of damping was chosen to be 25% of the large asymmetric value. Only asymmetry that increases damping towards singularity (i.e. $\bar{\sigma}_{a0} < \bar{\sigma}_{b0}$) was considered. The opposite results in a *stuck* sensation that is unfavorable to the user.

3) Damping Settings: Six different robot settings based on the two damping rates (Fast vs Slow) and the three levels of asymmetry (None, Small, Large) were created, listed in Table I. Fig. 2 plots the shaped reciprocal singular value for the six settings. In all settings, the parameter $\bar{\sigma}_{b0}$ was set to 0.25 as this kept the collaborative robot a suitable distance away from singularity and allowed experiments to be performed without erratic behaviors due to singularity.

TABLE I
Damping settings and pairwise comparisons performed

Setting	#1	#2	#3	#4	#5	#6
Rate	Fast	Fast	Fast	Slow	Slow	Slow
Asymmetry	None	Small	Large	None	Small	Large
$\bar{\sigma}_{a0}$	0.250	0.225	0.150	0.250	0.225	0.150
$\bar{\sigma}_{a1}$	0.350	0.325	0.250	0.450	0.425	0.350
$\bar{\sigma}_{b0}$	0.250	0.250	0.250	0.250	0.250	0.250
$\bar{\sigma}_{b1}$	0.350	0.350	0.350	0.450	0.450	0.450
Trial #1	B	A				
Trial #2					B	A
Trial #3		B	A			
Trial #4			B		A	
Trial #5	B				A	
Trial #6	B			A		
Trial #7		B				A
Trial #8		B		A		
Trial #9	B					A
Trial #10				B		A
Trial #11			B			A
Trial #12				B	A	
Trial #13	B		A			
Trial #14			B	A		
Trial #15		B			A	

B. Experimental Procedure

The experimental procedure was designed taking into account the number of variables and concerns about participant fatigue. It was considered that asking participants to test and rank all six settings was not a suitable approach due to the subtlety in the differences between them. Instead, the experiment would assign two pseudo-random settings, labeled as A and B, for the participant to compare. Given the 6 different settings being evaluated, all pairwise combinations results in 15 A-B comparisons to be evaluated. A randomized sequence of pair-wise combinations was created, shown in Table I. Starting at trial #1, participants would compare two settings which were referred to as A and B. The next participant would continue where the previous left off, ensuring all combinations would be tested. After 15 trials were performed, the experiment would return to the A-B settings used for trial #1 and the sequence would repeat.

Experiments were performed at the University of Technology Sydney (UTS). Participants were first introduced to the robot, ensuring that the robot configuration and the standing position of the participant were similar between trials. Instructions for controlling the robot were given. It was explained that the robot was used by pressing enabling triggers located on handles on the end-effector, and with the triggers pressed the tool would follow their hand motions. Participants were instructed to use the robot to get familiar with its operation. As participants began to use the robot, instructions for the experiment were provided with technical terms avoided.

It was explained to participants that as the robot is moved outwards (away from the base, to the participant's left) and the arm becomes fully stretched, the robot needs to slow down and eventually stop. When it is moved back in (towards the base) it will speed up. It was then explained that we are

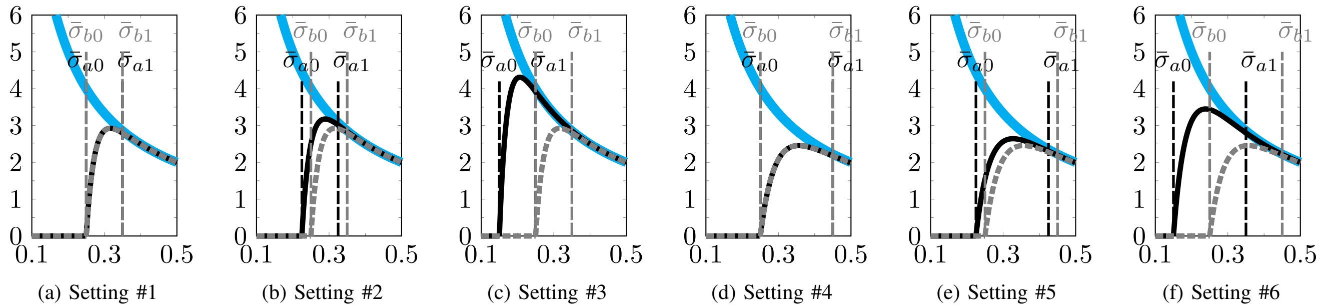

Fig. 2. Plots of the shaped reciprocal singular values $s(\sigma)/\sigma$ (vertical axis) versus σ (horizontal axis) for the six settings evaluated. The blue line represents the reciprocal singular value with zero damping, i.e $1/\sigma$. The solid black curve corresponds to moving away from singularity, parameterized by $\{\bar{\sigma}_{a0}, \bar{\sigma}_{a1}\}$. The dashed grey curve corresponds to moving towards singularity, parameterized by $\{\bar{\sigma}_{b0}, \bar{\sigma}_{b1}\}$.

interested in how the robot behaves in these last few inches of movement. It was also explained that the A/B toggle switch mounted on the end-effector allowed them to switch between two different modes that may change the way the system behaves. Participants were then invited to move the robot as far to the left as they can until it stops, and then move it back in, as many times as they wish and changing the mode (A/B) as often as desired.

As participants moved the robot to and from the edge of its reachable workspace, switching between modes A and B, they were asked questions from a questionnaire. Verbal responses were written down by the experimenter while the participant continued to evaluate the robot.

During each trial the following five questions were asked:

Q1: Which mode is the smoothest to use?
Q2: Which mode is the most responsive?
Q3: Which mode feels like you are in control the most?
Q4: Which mode is the least frustrating to use?
Q5: Which mode feels safest to use?

For each question, participants were asked to compare modes A and B on a five point scale:

- $A \gg B$: A much more than B
- $A > B$: A a little more than B
- $A = B$: A and B about the same
- $A < B$: B a little more than A
- $A \ll B$: B a lot more than A

After comparing A and B with regard to the 5 questions, participants were then asked, all things considered, which mode would they choose. Possible options were A, B or either (i.e. same, or no preference one way or the other). Finally, participants were asked to describe how both A and B felt with their descriptions of both modes recorded.

C. Recruitment

Experiments with two different cohorts were performed. One experiment was held during an Open Day at the University of Technology Sydney. The robot was on display with signs set up inviting members of the public to be part of the experiment. Being wary of participant time, volunteers were asked to perform a single pseudo-randomized trial each. During the day 51 individuals participated in the experiment.

The experiment was repeated with a second cohort made up of members from the UTS Centre for Autonomous Systems. This cohort was comprised of mostly engineers, research support staff and higher degree research students in the field of robotics. As this cohort were readily available, experiments were preformed over several days. Participants in this cohort were asked to perform three trials, each comparing different damping settings. These trials are similarly pseudo-randomized and assumed to be statistically independent. In this cohort 18 participants and a total of 54 trials were performed.

In total, the experiments included 69 participants and 105 trials. Experiments were conducted under UTS Human Research Ethics Committee approval (ETH18-3029).

D. Collaborative Robot Setup

Experiments were conducted using the ANBOT, a collaborative robotic system designed to assist workers performing industrial abrasive blasting [1]. The system consists of a Universal Robots UR10 manipulator fitted with a blasting nozzle to the end-effector. Also on the end-effector are two handles with trigger switches that an operator uses to maneuver the nozzle as desired. A toggle switch mounted on the end-effector allowed the user to switch between the A-B damping settings as desired. This could be toggled at any time during the trials at the discretion of the user.

Force measurements from a 6-axis force-torque sensor (ATI Mini45) mounted between the handles and the end-effector control the manipulator using the admittance based control scheme. Desired velocity of the tool is transformed into joint commands using EDLS Jacobian inverse which is calculated based on the damping setting being utilized. For a detailed description of the admittance control implementation, readers are directed to [18].

IV. Results

During the experiments with the general public, it was observed that some participants did not engage with the experimental protocol as desired. This is attributed to the novelty of interacting with a robot distracting participants from following the protocol as instructed. For example, some participants would not extend the arm outwards until it would stop. Eight participants were labelled as not following protocol, and their results excluded from the following analysis.

A. Symmetric versus Asymmetric Damping

Of the different A/B combinations listed in Table I, only #10 and #13 directly compared large asymmetry with no asymmetry, with the same damping rates. These combinations were evaluated 14 times during the study.

Fig. 3 shows the results of Q6 about which mode they prefer. In 11 out of these 14 trials (78.6%) users preferred the large asymmetric setting over the symmetric setting. Two participants (14.3%) preferred symmetric damping, and 1 participant did not have a preference.

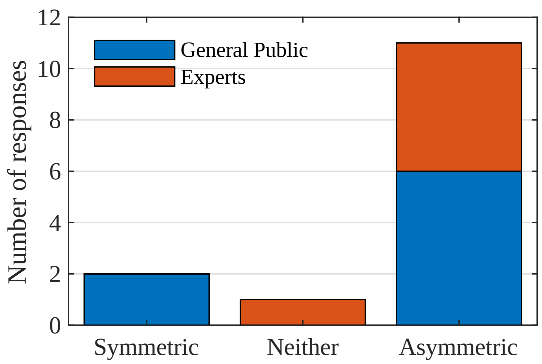

Fig. 3. Participant preferences when comparing large asymmetry versus no asymmetry. In these comparisons, both A and B modes had the same level of damping rate.

B. Fast versus Slow Damping Rate

Of the 15 different A/B combinations listed in Table I, three of them (#6, #11, #15) directly compared slow and fast damping rates, with the same level of asymmetry. These combinations were evaluated 20 times during the study.

Fig. 4 shows the results of Q6 when asked which mode they prefer overall. In 15 trials (75%) users preferred the mode with fast damping rate, and 3 trials (15%) users preferred the mode with slow damping rate. Two participants did not have a preference.

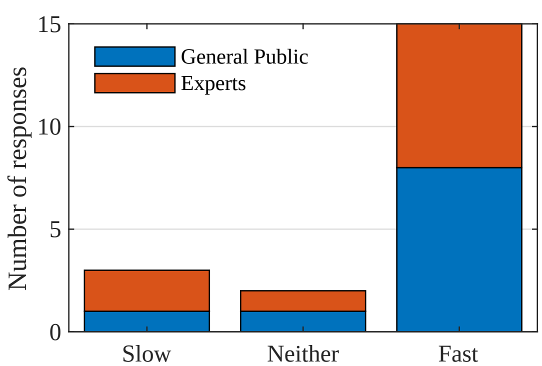

Fig. 4. Participant preferences when comparing fast versus slow damping rate. In these comparisons, both A and B modes had the same level of asymmetry.

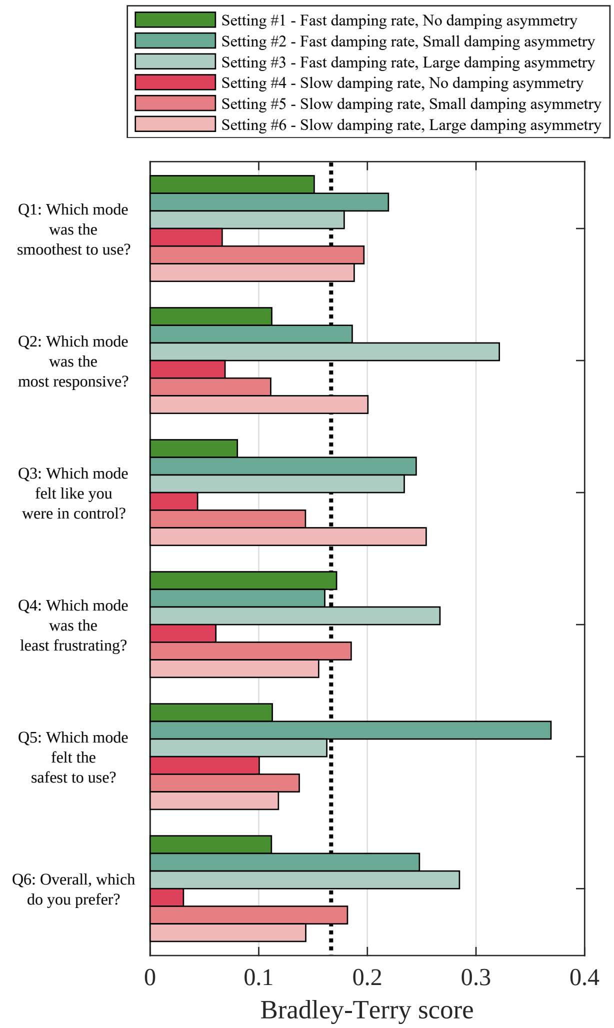

Fig. 5. Results from the experiments comparing the size damping settings across all pair-wise comparisons. Results are calculated using a Bradley-Terry model and organized by questions Q1-Q6.

C. Ranking using Bradley-Terry model

To rank the preferences of all damping settings a Bradley-Terry pairwise comparison model is used [19]. The results from this analysis give each setting a normalized ranking measure ranging from 0 to 1, with all six settings summing up to unity. The Bradley-Terry model was applied to the entire cohort with respect to each of the six questions asked. If the result was either A≫B or A>B, then this would be counted as a single win for A over B in the Bradley-Terry model, vice versa for B winning over A, and A = B treated as a tie. The results are shown in Fig. 5 with the vertical dotted line representing the average score to allow above and below average rankings to be easily identified.

For *Q1: Which mode was the smoothest to use*, results indicate that Setting #2 was most preferred. This is followed by #5, #6 and #3 which were all ranked above average. Notable was #4 (slow rate, no asymmetry) which was ranked noticeably lower than the rest.

For *Q2: Which mode is the most responsive*, results indicate that Setting #3 (fast rate, large asymmetry) was ranked highest by a large margin. Notable was #4 (slow rate, no asymmetry) with the opposite settings to #3 was ranked the lowest.

For *Q3: Which mode felt like you were in control*, the results indicate that setting #6 was preferred, closely followed by #2 and #3. Both settings with no asymmetry (#4 & #1) were ranked the lowest.

For *Q4: Which mode was the least frustrating*, the results indicate that setting #3 (fast rate, large asymmetry) was preferred. Notable was #4 (slow rate, no asymmetry) which was ranked noticeably lower than the rest.

For *Q5: Which mode felt the safest to use*, the results indicate that setting #2 (fast rate, small asymmetry) was considered the safest. The remaining settings were all below average, but not too dissimilar to each other.

When asked *Q6: Overall, which do you prefer*, the results showed a preference for setting #3 (large asymmetry, fast damping rate) followed by #2 (small asymmetry, fast damping rate). Both settings with no asymmetry were the lowest ranked, with setting #4 (no asymmetry, slow rate) ranked significantly lower than the rest.

V. Discussion

It is clear from the results, in particular the responses to Question 6, that participants had a strong preference towards using the robot with the large asymmetric damping and fast damping rate. This agrees with past preliminary results that also indicated that asymmetric damping is a favorable characteristic that improves behavior near singularity [8].

Verbal feedback provided interesting insights into the impressions and feelings of participants during the trials. When asked why participants chose one setting over another, reasons such as *smoother*, *lighter*, *more responsive* and *requires less force* were often cited. When describing settings that were not preferred, reasons such as *slower*, *harder to move*, *more abrupt*, *heavier*, *sluggish*, *more resistance* and *laggy* were used.

Despite the overall preference for faster damping rate with large asymmetry, there were interesting differences in how certain settings were interpreted. Some participants preferred the fast damping rate, stating that it required less force to use. This interpretation makes physical sense as the faster damping rate requires increased force to be applied by the user only when the robot is closer to singularity. Conversely, some participants preferred the slower damping rate. One stated that it lets them *feel the edge [of the workspace] before you get to it*. Another said the slower damping rate let them *slow down more gradually, which I like*, and that the fast damping rate was *too sudden*. Likewise, differences in opinions were received regarding the asymmetric damping. One participant who favored the asymmetric damping said that it *follows you more*, whereas the symmetric damping *slows down a lot more when coming back [away from singularity]*. Another participant who was from the expert cohort said directly about the asymmetric damping that it was *easier to leave singularity*. In contrast, one participant from the general public who favored the symmetric damping described it as having a *small "stop" when you go back in [away from singularity]*. This highlights that there is unlikely a one-size-fits-all approach, and versatility in how collaborative systems behave can be beneficial.

TABLE II

Instances of "No Preference" responses for questions asked

Question	Public	Experts	Total
Q1: Which is smoothest to use?	22.2%	17.3%	19.6%
Q2: Which is most responsive?	31.1%	11.5%	20.6%
Q3: Which are you most in control?	35.6%	15.4%	24.7%
Q4: Which is the least frustrating?	46.7%	13.5%	28.9%
Q5: Which feels safest to use?	77.8%	59.6%	68.0%
Q6: Overall, which do you prefer?	8.9%	9.6%	9.3%

Some questions were more challenging for participants to make a preference. Safety had the highest instance of no preference being made (i.e. A=B), with 77.8% of the general public and 59.6% of experts responding with no preference. Next was the question about frustration, with 46.7% of the general public and 13.5% of experts responding with no preference. The instances of no preference for each question are listed in Table II. A trend is observed that as questions were asked from Q1 to Q5, the instance of no preference increased. Questions were ordered purposely from what the authors considered were less subjective to more subjective. It is speculated that the reason for the increasing rates of no preference answers is due to participants not having an explicit criterion for the questions. When answering about safety, participants often asked what was meant by safety, or what made the robot safe. In these cases participants were told that it was up to their own interpretation. Comparing the two cohorts, experts would less frequently respond to questions with no preference. It is hypothesized that prior experience with robotics gives this cohort additional perspective and insight with which a decision can be made.

In a prior preliminary study that examined user damping preferences [8], the challenge of designing an appropriate experimental protocol was discussed. The challenge stems from wanting to have experimental data collected in a controlled and repeatable manner, whilst allowing subjects to perform experiments without constraints such that natural feedback in response to singularity can be obtained. The trials in [8] utilized a contrived task for subjects to perform. This task was specifically designed such that its completion would require the robot to reach a singular configuration. It was found that this approach did result in subjects moving the robot towards singular configurations without having to be explicitly asked. However when asking for the subject's perceptions, it was difficult to isolate effects due to the singularity, with subjects often providing feedback about other elements of the task. In this work a more direct approach was chosen. Subjects, after becoming familiarized with the system, would be asked explicitly to move the tool to the extreme of its reachable workspace, and to provide feedback on their experience. This direct method was deemed to be more appropriate for the qualitative study being performed. The downside of this approach is the variability that this introduces, with subjects able to manipulate the robot as they wish. This variability was mitigated by instructions from the experimenters on how the singularity should be reached, and ensuring consistency in the subject's relative standing position and the configuration of the robot.

The A/B pairwise method used for comparing different damping settings was found to be well suited for this study. Using tools such as the Bradley-Terry model [19], a normalized ranking of user preference can be obtained. Despite the subtle differences in robot behavior with the settings compared, preferences for fast damping rate and asymmetric damping were observed among participants. An advantage of this approach is that it can be scaled to include larger numbers of experimental variables, allowing future studies to include more variations within the analysis. Quantitative assessment was not the objective of this work, however an extension would be to use a task-based protocol and compare performance metrics such as time to completion, movement smoothness or other metrics. This would allow correlations between the quantitative task-based metrics and the qualitative user feedback to be evaluated. Future work could also explore evaluating and comparing other methods for handing singularity during physical human-robot collaboration.

VI. Conclusion

In this paper we presented an empirical study on the user preferences on damping for singularity handling during physical human-robot collaboration. The experiments included 105 trials from 69 participants comprising of the general public (n=51) and experts (n=18). The double blind study asked participants to utilize a collaborative robot whilst comparing modes with differing damping rate and/or asymmetry.

Results shows that participants had a strong preference for the faster damping rate and large damping asymmetry. Alternatively, settings with slow damping rate and no asymmetry were rated poorly. Interesting differences between public and expert cohorts were observed regarding participants being able to choose between the two settings with respect to various criteria.

Outcomes from this study have several implications for continued research in this area. The results demonstrate that the methods used for mitigating the negative effects of kinematic singularities during physical human-robot collaboration have a significant effect on the perceptions of users. Decisions made when implementing these methods should consider how the behavior of the system will be received. This motivates the need for more understanding of what factors makes these strategies favorable or unfavorable to the end user, and the development of new methods designed with the user in mind.

Acknowledgments

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