Human User Impressions of Damping Methods for Singularity Handling in Human-Robot Collaboration

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Abstract

Kinematic singularity is a fundamental and well understood problem of robot manipulators, with many methods having been developed to ensure safe and robust operation in proximity to singularity. However little attention has been given to the scenario where the robot and human are working in physical contact to collaboratively perform a task. In such a scenario the feelings and impressions of the human operator should be considered when developing solutions for handling singularity.

This work presents an experimental study comparing three modes of handling kinematic singularities with respect to the impressions of the human operator. Two of the modes are based on traditional Damped-Least-Squares. The third method uses an asymmetric damping behavior proposed as being well suited for applications involving physical human-robot interaction. The three modes are tested and compared by subjects performing a mock industrial task, and feedback from the subjects analyzed to identify the preferred mode. Results indicate that the choice of method used affects the user's impressions of the interaction, and the asymmetrical damping behavior can produce a preferred interaction experience with human operators during tasks.

1 Introduction

The collaborative robot sector is growing, estimated to increase roughly tenfold between 2015 and 2020 [ABI, 2015]. As industrial robots leave the confines of cages to work alongside and in collaboration with human workers, new human-robot paradigms like that depicted in Figure 1 are anticipated to become more common. Shown 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 by the human operator via direct physical interaction with the robot, which assists the human by supporting the physical workload.

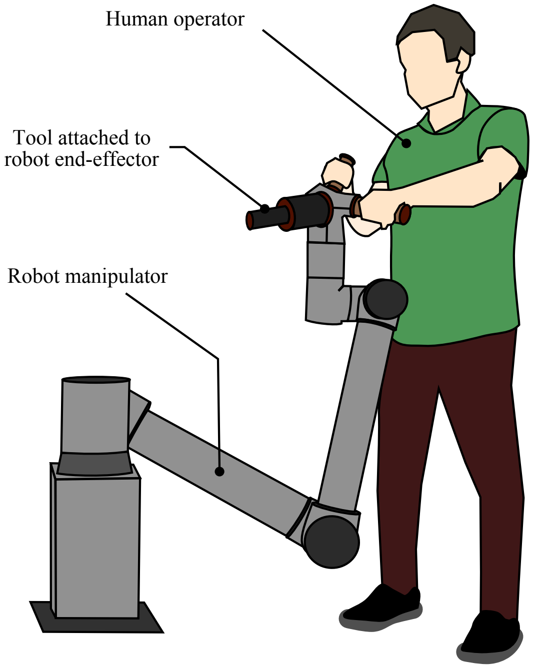


Figure 1: Example scenario showing a collaborative robot to assist human operator during an industrial task.

A challenge inherent in this human-robot collaborative paradigm is dealing with the finite workspace of the manipulator. A tool attached to the end-effector is confined to operate within the reachable workspace of the robot. Furthermore, safe and stable operation is only possible within a smaller subregion due to kinematic singularities that exist throughout the reachable workspace. Hence, and particularly for a manipulator with a small range of motion, it is likely that the human operator will at some point during a task attempt to operate the robot in close proximity to one of these singularities.

Kinematic singularity is a fundamental problem that is widely researched in robotics. 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 and resulting spatial end-effector velocity is defined as $\dot{\mathbf{x}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$ where $\dot{\mathbf{q}} \in \mathbb{R}^n$ are the joint velocities, $\dot{\mathbf{x}} \in \mathbb{R}^m$ is the spatial end-effector velocity (typically $m = 6$), and $\mathbf{J} \in \mathbb{R}^{m \times n}$ the Jacobian matrix of the manipulator. Traditional control methods actuate the joints of the manipulator to achieve a desired motion of the end-effector, thus requiring use of the Jacobian's inverse. However, in the neighbourhood of a singularity the Jacobian matrix degenerates and solutions to $\dot{\mathbf{q}} = \mathbf{J}^{-1}\dot{\mathbf{x}}$ become poorly conditioned. In mathematical terms the matrix $\mathbf{J}$ becomes singular, with its rank being less than the number of task-space dimensions m. Near singularity, motions of the end-effector require large and often unobtainable velocities at the joints, resulting in a robot behaviour that can be unpredictable and dangerous.

Many methods for achieving robust robotic behaviour in the proximity of singularities have been proposed [Deo and Walker, 1995][Oetomo and Ang Jr, 2009]. One approach is to simply ensure the robot maintains suitable distance to singular configurations during the path planning stage. Although straightforward, this method can be challenging for singularities such as *wrist-lock* that can occur throughout the entire workspace [Chiaverini *et al.*, 2008]. Other downsides are that the usable region within the workspace can be significantly reduced, and since it relies on preplanned paths it is not suited for applications such as pHRI where robot motions are continually re-planned in real-time. The Jacobian Transpose method [Balestrino *et al.*, 1984][Wolovich and Elliott, 1984] switches from using the inverse of the Jacobian to its transpose to compute the motion. This is analogous to using a force applied to the end-effector to guide the robot towards a goal pose. Damped Least-Squares (DLS) [Nakamura and Hanafusa, 1986][Wampler, 1986] is a widely adopted approach which sacrifices exactness of the inverse kinematic solution to produce a modified Jacobian matrix that remains well-conditioned near singularity. DLS obtains feasible joint velocities by minimizing the norm of the residual tracking error combined with a term relating to the magnitude of the joint velocities.

Conventional singularity handling methods like those previously mentioned are typically developed and evaluated with a focus 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 as it is nonexistent in traditional applications. Despite being developed without human interaction in mind, these traditional methods are still commonly used in pHRI applications. The work in [Sharifi *et al.*, 2013] presented a singularity-free approach for operating a PUMA 560 manipulator during rehabilitation tasks. The workspace was divided into regions based on proximity to singularity, and the control mode switched depending on what region the robot operated in. In the neighbourhood of singularity DLS was implemented, and when very close to singularity the Jacobian Transpose method was used. Work in [Maneewarn and Hannaford, 1999] investigated a method for providing a human operator with haptic feedback relating to the kinematic condition of a robotic manipulator during tele-operation tasks. The proposed method defined a boundary surface surrounding the singular configuration. When this boundary was crossed, haptic feedback forces were fed to the operator to raise awareness of the singularity and guide them away from it. DLS was also utilized to ensure stable operation near singularity.

Recently there has been research into singularity handling methods developed specifically for applications involving pHRI. The work by [Dimeas *et al.*, 2016] proposed a method that implements virtual Cartesian constraints to prevent the operator from guiding the manipulator to low-performance configurations such as singularities. A repulsive force away from singular configurations is integrated into an admittance-based control and was successful in guiding the operator away from singularities. Other work by [Campeau-Lecours and Gosselin, 2016] presented an algorithm with the aim of reducing the burden on human operators to be mindful of robot limitations such as singularities, collisions and joint limits, and was shown to achieve positive results in experiments. A framework presented in [Carmichael *et al.*, 2017] combined several features including a variation of DLS with an exponentially shaped damping profile and an asymmetric damping scheme to achieve behavior suitable for pHRI in proximity to 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.

In this work we empirically analyze singularity handling methods from the perspective of the human operator. The methods used for comparison include two based on conventional implementations of DLS, and one using a novel asymmetric implementation proposed in [Carmichael *et al.*, 2017]. Experiments are conducted with human subjects using a collaborative robot to perform an imitated industrial task. Based on user feedback we evaluate the subjective impressions and benefits of asymmetric damping. General impressions from the human users provide insights that could potentially lead towards improved experiences during human-robot interactions.

2 Method

The basis of the study is the comparison of three variations of methods for handling kinematic singularity, and how these methods differ in the minds and opinions of a human operator controlling a collaborative robot. The first two modes, referred to as M1 and M2, are typical implementations of DLS with the only difference being the level of damping utilized. In modes M1 and M2 the joint-space motion of the manipulator is calculated using the damped inverse of the Jacobian as calculated in (1). The damping coefficient λ (2) is scaled using a method similar to [Nakamura and Hanafusa, 1986] using the Jacobian's smallest singular value σ and a threshold value σ_t set to $\sigma_t = 0.25$.

$$\begin{aligned} \dot{\mathbf{q}} &= \mathbf{J}^{*}\dot{\mathbf{x}} \\ \text{where} \quad \mathbf{J}^{*} &= \mathbf{J}^{T}(\mathbf{J}\mathbf{J}^{T} + \lambda^{2}\mathbf{I})^{-1} \end{aligned} \tag{1}$$

$$\begin{aligned} &\lambda = \lambda_0 \left(1 - \frac{\sigma}{\sigma_t}\right)^2 \quad &&, \text{where} \quad \sigma < \sigma_t \\ &\lambda = 0 &&, \text{where} \quad \sigma \geq \sigma_t \end{aligned} \tag{2}$$

For mode M1 the damping is calculated with $\lambda_0 = 0.2$. This damping was selected by finding the lowest value that would allow experiments to be performed without the robot behaving erratically or repeatedly triggering a protective stop due to singularity.

For mode M2 the damping is calculated with $\lambda_0 = 0.6$ This level of damping was selected because it was high enough so there was a noticeable difference compared to mode M1, but was not heavily damped so that experiments could still be performed comfortably by participants.

For mode M3 the asymmetric principal described in [Carmichael *et al.*, 2017] is used. In this mode the coefficient λ_0 switches between two different values depending on if the manipulator is being guided towards or away from singularity. This is done using a small displacement based on the velocity command to estimate the change in the condition of the Jacobian. The damping value λ_0 is then set accordingly as either $\lambda_0 = 0.6$ if headed towards singularity, and $\lambda_0 = 0.2$ if headed away. A summary comparison of the three modes is provided in Table 1.

Table 1: Summary of the singularity handling modes

Mode	**Method for handling singularity**
M1	Equations (1) and (2) with $\lambda_0 = 0.2$
M2	Equations (1) and (2) with $\lambda_0 = 0.6$
M3	Equations (1) and (2) with $\lambda_0 = 0.6$ when moving towards singularity, and $\lambda_0 = 0.2$ when moving away from singularity

2.1 Collaborative Robot Setup

The platform used to conduct the experiments consists of a Universal Robots UR10 manipulator. As shown in Fig. 2, the robot has been fitted with a blasting nozzle to the end-effector. Also attached are two handles with trigger switches that an operator uses to control the robot, allowing them to maneuver the nozzle as desired.

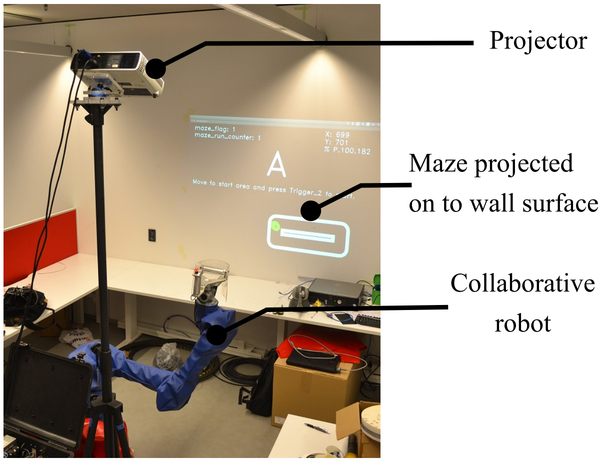


Figure 2: The UR10 manipulator used to conduct experiments.

Interaction forces between the human operator and the robot are measured by a 6-axis force-torque sensor (ATI Mini45) mounted between the handles and the end-effector. Force measurements control the manipulator using the admittance based control scheme shown in Fig. 3. The measured force-torque wrench $\mathbf{f}_s$ is transformed into the tool-frame by matrix $\mathbf{A}$ and then multiplied by admittance gain matrix $\mathbf{K}_A$ to produce a task-space velocity command $\dot{\mathbf{x}}$. This velocity is transformed into a joint command using (1) with damping depending on the singularity handling mode (M1, M2 or M3) being utilized, then sent to the UR10 controller. An additional damping term $\mathbf{f}_D$ is used to improve system stability.

A visual projection system imitates an industrial activity akin to grit-blasting. On a large wall in front of the platform a cursor is displayed where the nozzle is being pointed, and a virtual activity implemented to create the

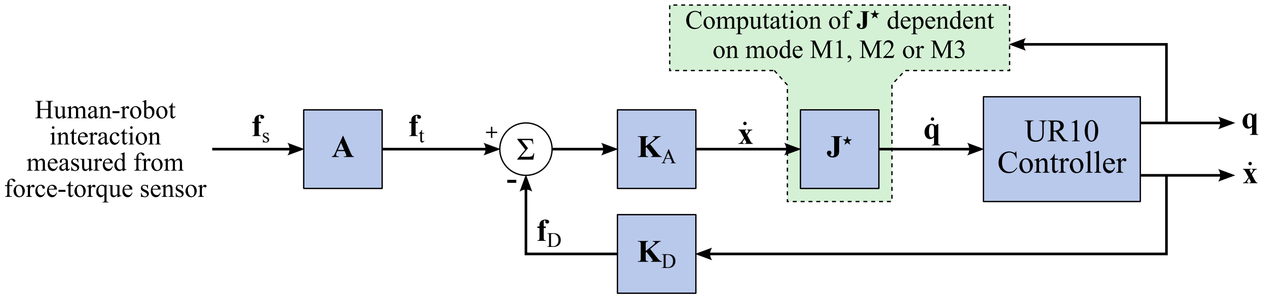


Figure 3: Admittance control for the experimental platform. The measured interaction forces between human operator and the robot are used to generate task-space velocity commands $\dot{\mathbf{x}}$. The task-space velocity is transformed into joint-space commands using the Jacobian matrix inverted depending on the singularity handling method (M1, M2 or M3) being analyzed.

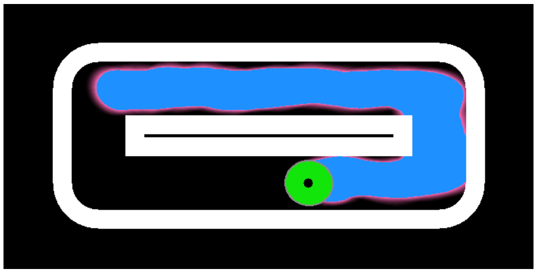
sensation that the robot is being used to blast or paint the surface. Two triggers on the handles independently enable motion of the robot and turn on/off the virtual blasting, enhancing the immersion of the activity.

As an operator *blasts* the wall, a blasting path behind the cursor is produced which only forms a solid color when moving at an appropriately slow speed. Additionally the perpendicularity of the nozzle to the wall is visualized by the cursor transitioning from a circle to an ellipse, and the color transitioning from green to red as the nozzle becomes less perpendicular. This visual feedback shown in Fig. 4 encourages the operator to perform the task in a certain manner as explained in the next section.

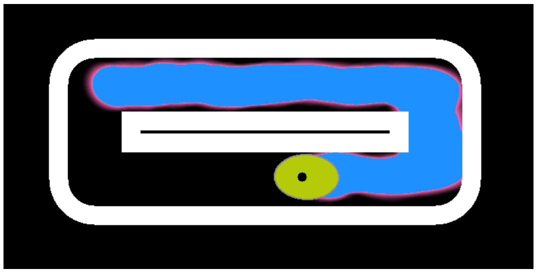
2.2 Experimental protocol

A challenge in this study was to devise an experimental protocol that would adequately and fairly compare the singularity methods being tested. Since the aim is to obtain feedback from how the robot feels and behaves near singularity this means that the tasks performed should encourage the singularity to be approached. However it is also undesirable to enforce significant constraints to the task, e.g. an exact motion which must be followed, as it is desirable that the task be executed in a genuine manner. Additionally we did not want to explicitly instruct the operator to head towards the singularity, but rather have them reach the singularity themselves. What is required is a task that indirectly encourages the operator to move the robot towards singularity whilst allowing them to do so with an appropriate amount of freedom.

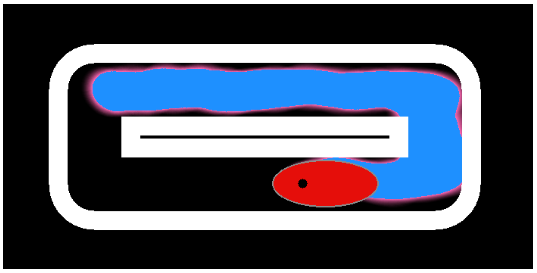
To satisfy these requirements a task based on a maze was created. Operators are instructed to complete a single clockwise lap starting from the top-left corner of the maze. They are also instructed that the blasting path should be a solid color (which regulates the speed of the motion), and that the nozzle should remain perpendicu-



(a) Nozzle perpendicular to maze



(b) Nozzle at small angle to maze



(c) Nozzle with large angle to maze

Figure 4: simulated skew of the blasting nozzle.

lar to the surface. Visual cues, such as the blasting path color and the cursor skewing when not perpendicular to the wall, provide feedback to the operator. The maze itself is a simple rectangle designed so that to reach the right hand side with the nozzle kept perpendicular to the wall requires the manipulator to be stretched and *elbow-lock* singularity to be reached. This arrangement requires that the nozzle be tilted off-perpendicular in order to complete the maze, however this is not communicated with subjects before tasks are performed. It was found that this arrangement successfully encouraged subjects to repeatedly and consistently reach the singularity, whilst not explicitly asking them to do so and maintaining flexibility in how the task is executed.

Another challenge in the protocol is how to obtain feedback from subjects. The different modes (M1, M2, M3) produce different feelings to the user during the task, however the differences can be subtle and require many repeated attempts before a comparison is made. To simplify this it was decided to conduct the experiment using a pairwise comparison approach. Subjects are asked to compare two modes, explained to them always an A and B, and answer questions about how they compare as they perform the blasting maze activity. This reduces the experiment to a number of side-by-side comparisons which can be repeated for all combinations of M1, M2 and M3.

Seven subjects, all healthy males under 30, volunteered to participate in the experiment. Approval was obtained from UTS Human Research Ethics Committee (ETH150038). Each subject performed the maze repeatedly whilst performing pairwise comparisons of the singularity handling modes. Modes were not referred to by name (M1, M2 M3) but simply as either A or B, allocated randomly and unknown to the subject. For each pairwise comparison subjects were allowed to switch between A and B repeatedly until they felt they could answer the questions asked.

In total each pairwise comparison (M1-M2, M1-M3, M2-M3) was repeated twice by all subjects. For each pairwise comparison the following six questions were asked:

Q1: Which method was the smoothest to use?

Q2: Which method was the most responsive?

Q3: Which method required the most force to use?

Q4: Which method felt like you were in control the most?

Q5: Which method was the least frustrating to use?

Q6: Which method felt safest to use?

Questions Q1 to Q3 were considered to be less subjective as they relate to characteristics of robot motion that can to a degree be quantified. For these questions subjects were asked to rank A and B as either A≫B, A>B, A=B, B>A, or B≫A.

Questions Q4 to Q6 are considered much more subjective. Characteristics such as how much in control, how frustrated, and how safe do you feel are far more qualitative. For these questions subjects were asked to rank A and B and either A>B, A=B, or B>A.

3 Results

To assess the overall performance of each singularity handling mode from the pairwise comparisons a Bradley-Terry model is used [Caron and Doucet, 2012]. The results from this analysis give each mode a performance measure ranging from 0 to 1, with all three summing up to unity. Figure 5 shows the output of the Bradley-Terry model for all the subject data combined with respect to each of the six questions. Some interesting observations can be made.

For *Q2: Which mode is the most responsive*, subjects ranked M1 and most responsive, M2 and the least responsive, and M3 in between. This aligns with the amount of damping that each mode applies to the robot and supports the notions that large damping negatively affects the responsiveness of the interaction.

For *Q3: Which mode required the most force*, the feedback is the opposite of Q2 with mode M2 ranking the highest, M1 lowest and M3 again in between. Again this aligns with the damping factors applied, with higher damping requiring the operator to apply more force to achieve the equivalent motion.

For *Q1: Which mode was the smoothest to use*, the feedback did not seem to align with the degree of damping applied. Before the study it was anticipated that M2 might be ranked as the smoothest due to its consistently large amount of damping ensuring no erratic motions of the robot. Unexpectedly it was instead ranked the worst. Subjects commented during the experiment that the large damping experienced when trying to move away from the singularity tended to interfere with their desired motions. It is hypothesized that this may have contributed to the negative score that this mode received.

The remaining questions Q3-Q6 are somewhat more subjective and were noticeably more difficult for subjects to answer. These three questions are also more tailored towards the operator's impressions of the robot rather than behavioral characteristics. Due to this, subjects tended to spend much more time comparing the modes before providing their feedback. Across questions Q3-Q6 mode M1 fared the worst. This is attributed to the low amount of damping causing the singularities to be reached and negatively affecting the perceptions of the subjects. Between modes M2 and M3 the

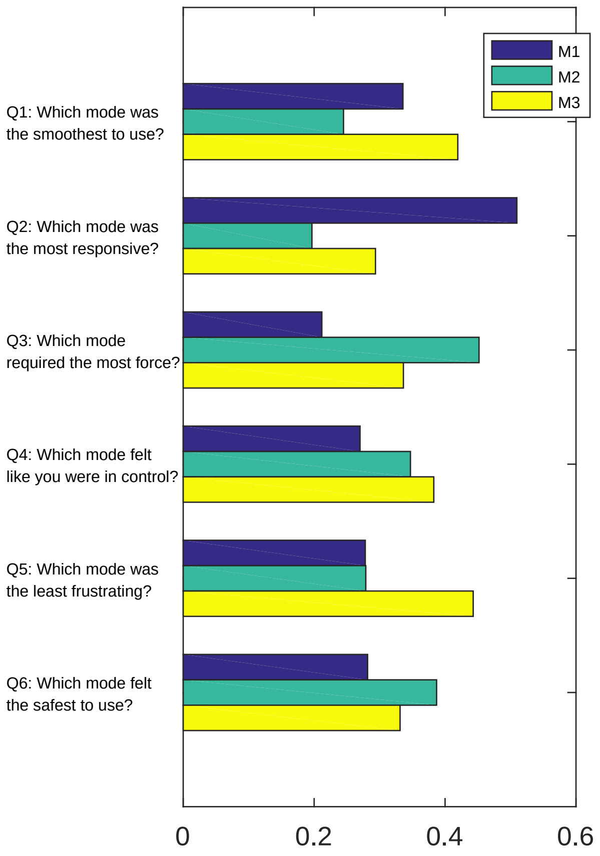


Figure 5: Results from the experiments comparing the three singularity handling models M1, M2, M3. Mode M1 had constant damping with $\lambda_0 = 0.2$. Mode M2 had constant damping with $\lambda_0 = 0.6$. Mode M3 utilised asymmetric damping with λ_0 switching between 0.2 and 0.6. Results are calculated using a Bradley-Terry model and organized by questions Q1-Q6.

biggest difference was noted in Q5 with M3 being ranked much less frustrating than M2. This is attributed to the large damping sensation that subjects felt when trying to move away from the singularity using mode M2. Despite this, M2 was ranked as feeling the safest suggesting that a heavily damped response invokes a sensation of reliability or predictability which may be preferable in certain scenarios.

As well as recording the subject feedback, statistics of how often the manipulator got stuck into singularity were recorded. The manipulator got stuck in elbow-lock singularity a total of 11 times during the pairwise comparison tests, every instance was when the M1 mode was being used. This makes sense as this mode produces the least damping of the three and hence has the least resistance against approaching singularity. For all pairwise comparisons that included M1 as one of the modes, the robot got stuck in singularity at some point during the pairwise test 39% of the time. This would require the operator to halt the task and the robot to be reset, leaving the operator with a negative impression and explaining why it fared poorly in the feedback for questions Q4-Q6.

4 Discussion

When asked about general characteristics of the interaction such as the smoothness, responsiveness and force requirement (Q1, Q2 and Q3), there was general agreement across the subjects which aligned well with the damping used in each of the modes. This demonstrates that the methods used to handle kinematic singularity have a perceivable effect on the human operating the robot. Human-robot interaction may be improved by developing new methods for handling kinematic singularity that has characteristics favorable to the human operator.

An interesting finding was that there was no clear consensus on the preferred singularity handling mode. When asked questions relating to controllability, frustration and safety (Q4, Q5 and Q6) the responses were more varied and subjective. To some subjects the sensation of a slow and highly damped movement was preferred as this gave them a higher sense of control. To others this felt too restrictive, preferring the ability to perform fast and nimble motions. A consequence of this result is the indication that there is no one-size-fits-all approach to how the robot should behave. It is likely that there are several factors affecting an individual's preferences regarding human-robot physical interaction. More experienced users who are comfortable with the robot may prefer a faster nimble response that allows them to perform tasks without feeling restricted, where as novice users yet to be comfortable with the robot may prefer a slower, more predictable behavior. It is also likely that the task being performed would have an influence on the perceptions of the human operator.

Outcomes from this study have several implications for continued research in this area. The results highlight that when evaluating the user feeling and impressions during human-robot interaction, asking subjects *which mode feels the best* may not be adequate as the factors that constitute the best feeling are likely subject specific. More insights in future studies may be obtained by collecting quantitative data (e,g, interaction force, speed, jerk) along with the subject's qualitative feedback for comparison. The pairwise method used for comparing different modes was found to be well suited for this kind of study. When qualitatively comparing control modes, trying to rank them can be difficult as often the differences are subtle and nuanced. It is for this reason we employed the pairwise comparison tests so that modes would be compared side-by-side with the aim of obtaining a better and fairer comparison. Tools such as a Bradley-Terry model [Caron and Doucet, 2012] can then be used to form a ranking of all the modes based on their pairwise comparisons. An advantage of this approach is that it can be scaled to include larger numbers of modes, allowing future studies to include more variations within the analysis.

5 Conclusion

In this paper we presented a study comparing three different modes for handling kinematic singularity during collaborative human-robot tasks. Two of the modes were based on conventional damped least-squares, and the third one using a novel asymmetrical variant that was proposed as being well suited for physical human-robot interaction. Experiments with 7 subjects compared the three modes and provided feedback with regards to how it felt to use and the perceptions of the user.

Trends between the modes and behavioral feedback, such as robot responsiveness, were observed and related back to how the damping was implemented. Less consistent was feedback about characteristics relating to user impressions on controllability, frustration and safety. Overall it was observed that in human-robot physical interaction, methods of handling singularities have an effect on the perceptions of the user which indicates that improvements may be obtained by developing singularity handling methods specifically with the user in mind.

Acknowledgments

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