IMPROVING A USER'S HAPTIC PERCEPTUAL SENSITIVITY BY OPTIMIZING EFFECTIVE MANIPULABILITY OF A REDUNDANT USER INTERFACE

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ABSTRACT

Human perceptual sensitivity of various types of forces, *e.g.*, stiffness and friction, is important for surgeons during robotic surgeries such as needle insertion and palpation. However, force feedback from robot end-effector is usually a combination of desired and undesired force components which could have an effect on the perceptual sensitivity of the desired one. In presence of undesired forces, to improve perceptual sensitivity of desired force could benefit robotic surgical outcomes. In this paper, we investigate how users' perceptual sensitivity of friction and stiffness can be improved by taking advantage of kinematic redundancy of a user interface. Experimental results indicated that the perceptual sensitivity of both friction and stiffness can be significantly improved by maximizing the effective manipulability of the redundant user interface in its null space. The positive results provide a promising perspective to enhance surgeons' haptic perceptual ability by making use of the robot redundancy.

***Index Terms*—** Haptic Perception, Kinematic Redundancy, Effective Manipulability, Viscous Friction, Stiffness

1. INTRODUCTION

Discriminating the properties of soft tissue, such as different levels of stiffness, is important for surgeons to perform some surgical procedures like needle insertion and palpation [1, 2]. In robotic surgery, force feedback delivered to the surgeons from the robot end-effector is usually a combination of several force components including such as soft tissue stiffness and friction, robot inertia, and joint friction. In this case, the desired force, *e.g.*, tissue stiffness, could easily be affected by other undesired ones [3, 4].

This research is supported in part by the Canada Foundation for Innovation (CFI) under grants LOF 28241 and JELF 35916, in part by the Government of Alberta under grants IAE RCP-12-021 and EDT RCP-17-019-SEG, in part by the Government of Alberta's grant to Centre for Autonomous Systems in Strengthening Future Communities (RCP-19-001-MIF), in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada under grants RGPIN-2019-04662 and RGPAS-2019-00106, and in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada under grant RTI-2018-00681. *Correspondence: `mahdi.tavakoli@ualberta.ca`

In the presence of undesired forces, perceptual sensitivity of the desired one can be largely affected. For example, in surgical procedure of needle insertion, tip force is often combined with needle shaft friction and could be masked by each other [2, 5], which makes the discrimination of either of them more difficult. As a consequence, the perceptual sensitivity of the desired force will decrease as the magnitude of the undesired one increases.

Improving the perceptual sensitivity of desired force in the presence of undesired ones could be beneficial to the surgeons' performance as well as the robotic surgical system. With high haptic perceptual sensitivity, surgeons can accurately localize a lesion and judge the healthy status of target tissue [6]. For some surgeries, the haptic perceptual sensitivity could be critical. For example, in retinal microsurgery, only about 20% of events can be detected in which the tiny forces are around 7.5mN [7]. Just noticeable difference (JND) and Weber fraction (WF) are two commonly used characteristics to measure human perceptual sensitivity [8, 9].

There are some methods have been developed to enhance users' perceptual sensitivity, such as scaling force feedback and developing new tools. Scaling force feedback is a commonly used method to better meet human perceptual ability, especially in teleoperation systems [1]. Considering that the desired force is usually mixed with noises, scaling force feedback will scale all noises simultaneously. Besides, scaling force may distort users' feeling and make it unreal.

De Lorenzo *et al.* [5] introduced a new device, a robotic coaxial needle insertion assistant, to enhance human perceptual sensitivity. The device is able to separate the needle tip force and needle shaft-tissue friction force during needle insertion. With this device, the undesired forces can be filtered out, thus enhancing the perceptual sensitivity of the desired one. However, a new device cannot be easily introduced into the operating room due to various regulatory approvals that it must go through.

Kinematic redundancy has been used to improve task performance on modeled soft tissue stiffness discrimination by comparing redundant and non-redundant robot [10]. The advantage of this method is that it is making use of the intrinsic property of redundant robots, *i.e.*, having a larger effective manipulability (EM) than non-redundant robots, and without

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additional costs. Our previous work in [10] was focusing on general redundant robots. Here in this work we will narrow down to focus on one specific redundant robot and investigate how haptic perceptual sensitivity can be affected by different methods of optimization in the redundant robot's null space.

In this paper, we are considering scenarios of tangential palpation (friction discrimination) and needle insertion (stiffness discrimination) where both desired and undesired forces will be in presence. Please note that, we will not pay too much attention on the potential masking effect of the undesired force in this paper. Instead, we will focus on taking the intrinsic advantage of kinematic redundancy to investigate the following two questions,

1. How perceptual sensitivity of friction and stiffness will be affected by different methods of optimizing the effective manipulability (EM) of a redundant robot?

2. Is there any trade-off effect on the haptic perceptual sensitivity when optimizing the EM to be isotropic?

Our hypotheses are that, the perceptual sensitivity of both friction and stiffness can be improved by maximizing the EM along the movement direction, and there is a trade-off effect for isotropic condition.

The remaining part of this paper is organized as follows: Section 2 describes the methods in detail including apparatus, cost function and control law, participants and experimental conditions. Section 3 presents experimental results and discussions. Section 4 remarks on our conclusions.

2. METHODS

2.1. Apparatus

A custom 4-degree-of-freedom (DOF) redundant planar haptic device including two robots, as shown in Figure 1, was employed in our experiments. The first base robot was a 2-DOF planar Rehabilitation robot (Quanser Inc., Markham, ON, Canada) while the second one came from a PHANToM 1.5A (Geomagic Inc., Morrisville, NC, USA). The 4-DOF robot was controlled via interface of MATLAB/Simulink (R2017a, MathWorks Inc., Natick, MA, USA) with Quarc real-time control software (Quanser Inc., Markham, ON, Canada). The control rate of the experiment was 1000 Hz.

2.2. Cost function and control law

The effective manipulability (EM), denoted as ρ in Eqn.(1), is commonly used to describe robot manipulability along a specified movement direction. Here we took it as our cost function to optimize the EM along a specified direction u via the internal motion of the redundant robot in its null space.

$$\rho = (u^T (JJ^T)^{-1} u)^{-1/2} \tag{1}$$

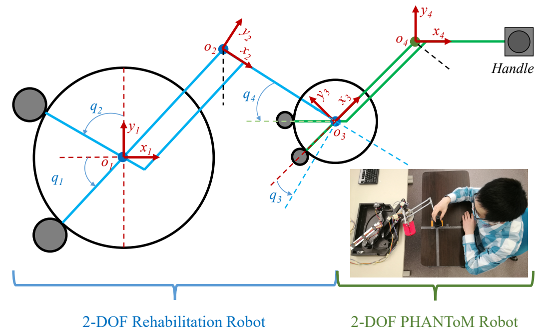


Fig. 1: Sketch of the 4-DOF robot and experimental scenario.

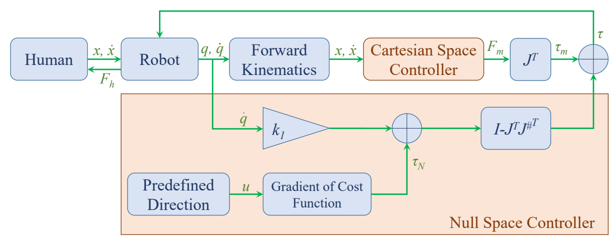


Fig. 2: Control diagram for the 4-DOF robot.

where J is the Jacobian matrix of the 4-DOF robot, and u is the specified movement direction. The velocity manipulability ellipsoid $M = JJ^T$ is included inside Eqn.(1).

The control diagram for the 4-DOF robot is shown in Figure 2, in which the null space controller [11] is defined by

$$\tau = J^T F_m + (I - J^T J^{\#^T})(\tau_N - k_1 \dot{q}) \tag{2}$$

where τ is the joint torque vector for generating the robot end-effector force F_m, and τ_N is related to the gradient of the cost function Eqn.(1) which will be projected into the robot null space by a projector $(I - J^T J^{\#^T})$. The parameter of k_1 is a suitable positive constant damping gain for stabilizing the system while $J^{\#}$ is the generalized inverse Jacobian.

The Cartesian space controller for the primary task was modeled as a spring-damper model, *i.e.*, a virtual wall with friction, as follows

$$F_m = k_D(\dot{x}_d - \dot{x}) + k_P(x_d - x) \tag{3}$$

where k_P is the spring coefficient, k_D is the damping coefficient, x and $\dot{x}$ are the real-time end-effector position and velocity respectively, while x_d and $\dot{x}_d$ are the desired end-effector position and velocity respectively. In this paper, we modeled the tissue friction as viscous damping and modeled the tissue stiffness as spring stiffness. By tuning the damping coefficient k_D and the spring coefficient k_P, the tissue friction and stiffness can be adjusted respectively.

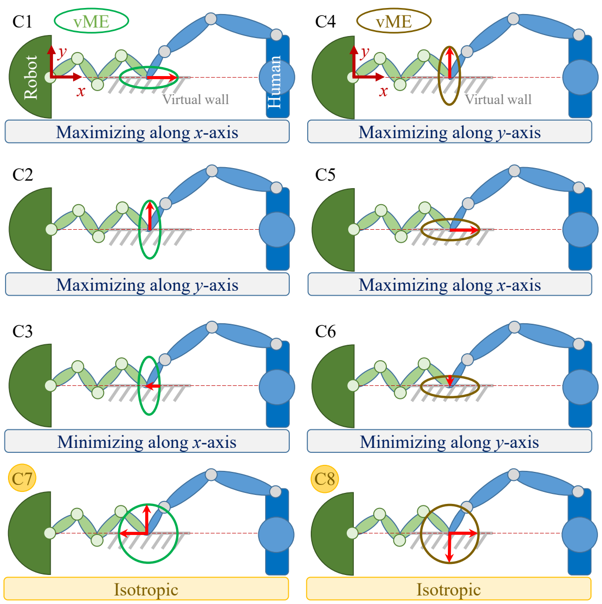


Fig. 3: Illustration of experimental conditions (top view). The red arrows represent the optimization directions. vME, means velocity manipulability ellipsoid.

2.3. Participants and experimental conditions

Six participants were employed for the experiments. The experiments were approved by the Health Research Ethics Board (HREB) at University of Alberta under study ID MS3_Pro00057919. Please note that, due to the COVID-19 pandemic, all experiments involving human subjects were suspended at University of Alberta, therefore all participants were played by the first author.

In total of three experiments including eight conditions (C1~C8) were designed as shown in Figure 3, and different conditions indicated different optimization methods. Experiment-1 (C1,C2,C3) was friction discrimination task where the directions of friction and stiffness were orthogonal to each other as illustrated in Figure 4. Experiment-2 (C4,C5,C6) was stiffness discrimination task where the directions of friction and stiffness were parallel to each other. Experiment-3 (C7,C8) included two isotropic conditions which can be viewed as the extended condition for Experiment-1 and Experiment-2 respectively.

Based on two alternative forced choice (2AFC) method [12, 13], in each trial of all experiments, participants were required to discriminate two stimuli (one reference and one comparison, sequentially and randomly presented), then answered a predefined question of *"whether the second tissue friction/stiffness is higher than the first one?"* by typing in number 1 ("yes") or number 0 ("no"). Nine friction/stiffness levels yielded 90 trials in total (9 *pair* × 10 *repetition*) for each condition each participant.

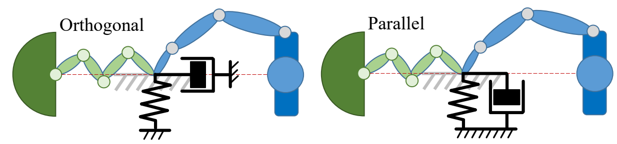
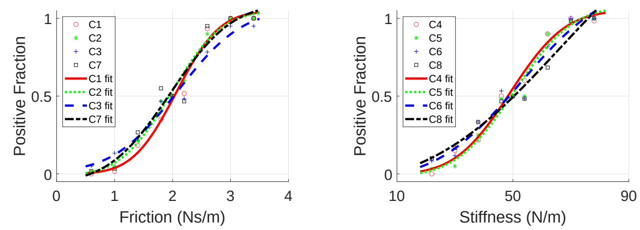


Fig. 4: Illustration of relative directions between stiffness and friction. "Orthogonal" is for friction discrimination task while "Parallel" is for stiffness discrimination task.



(a) Friction (b) Stiffness

Fig. 5: Positive fraction with respect to friction and stiffness.

3. RESULTS AND DISCUSSIONS

3.1. Performance metrics

For all experiments, we employed the just noticeable difference (JND) and the Weber Fraction (WF) as our major human performance metrics. The JND describes the minimum differences that have to be made between the comparison stimulus and the reference stimulus in order to perceive a noticeable change for the human. The WF describes the percentage difference in stimulus strength with respect to the reference stimulus that is just noticeable [10].

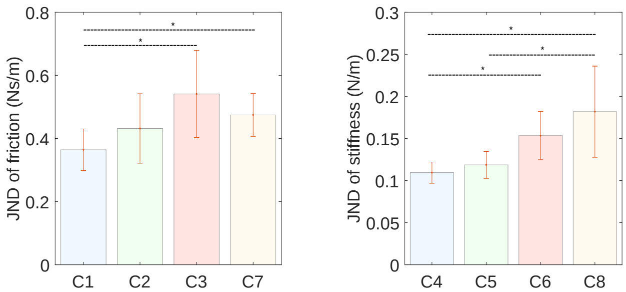
Using method of Weibull function [10, 14], the fitted psychometric functions based on all pooled data were obtained and shown in Figure 5. The JND and WF were calculated using commonly used method [8] and listed in Table 1.

3.2. Experiment-1 & Experiment-2

In order to investigate the perceptual sensitivity of friction and stiffness, we conducted Experiment-1 and Experiment-2 respectively. Experiment-1 of friction discrimination task can be taken as a mimic scenario of tangential palpation where the directions of friction and stiffness were *orthogonal* to each other. Experiment-2 of stiffness discrimination task can be taken as a mimic scenario of needle insertion where the directions of friction and stiffness were *parallel* to each other [5].

The results of Experiment-1 & Experiment-2 were shown in Table 1 and Figure 6. For simplicity, we also included the results of Experiment-3 (C7,C8) in the same table and figure.

By comparing the three conditions of C1,C2,C3 as well as the three conditions of C4,C5,C6 respectively in Table 1 and Figure 6, we can find that maximizing the EM along the



(a) Friction (b) Stiffness

Fig. 6: JND of friction and stiffness.

Table 1: Summary of JND and WF in each condition.

Friction Task			Stiffness Task		
Cond.	JND	WF	Cond.	JND	WF
C1	0.3642	0.1819	C4	0.1094	0.2282
C2	0.4317	0.2199	C5	0.1187	0.2399
C3	0.5410	0.2767	C6	0.1534	0.3184
C7	0.4746	0.2474	C8	0.1819	0.3731

movement direction (C1/C4) will result significantly higher perceptual sensitivity of friction/stiffness (*i.e.*, lower JND and WF) than minimizing it (C3/C6) (see Table 2 for *p*-values).

For C2 (or C5), it was expected to have similar results to C3 (or C6) while different results from C1 (or C4), but that was not the case. There were no significant difference between C2 and C1 or C3 in friction discrimination task, also no significant difference between C5 and C4 or C6 in stiffness discrimination task. The reason was that they were using different cost functions for the optimization after realizing the specific cost functions, which made them be not comparable.

The results here indicated that, by maximizing the EM along the movement direction, the participants' perceptual sensitivity of both friction and stiffness can be significantly improved in terms of JND and WF.

3.3. Experiment-3: Isotropic conditions

Experiment-3 (C7,C8) included two isotropic conditions where the EM was set to be isotropic rather than maximizing/minimizing it. The goal here was to investigate whether the isotropic conditions (C7,C8) will have a trade-off effect on perceptual sensitivity when comparing to condition of maximizing (C1,C4) and minimizing (C3,C6) EM.

Table 2: Summary of *p*-values of t-test for paired-sample.

	C2	C3	C7		C5	C6	C8
C1	0.2257	0.0178*	0.0168*	C4	0.3575	0.0104*	0.0332*
C2	-	0.1603	0.4343	C5	-	0.0529	0.0291*
C3	-	-	0.3152	C6	-	-	0.4121

Note: * for significance level under 5%.

By comparing C7 with C1,C3 in the friction discrimination task in Table 1 and Figure 6, we can find that there was only significant difference for C7 with C1 but not with C3. Also, the isotropic condition (C7) seems to have a trade-off performance compared to condition of maximizing (C1) and minimizing (C3) EM in terms of numerical JND and WF.

However, this was not true for the stiffness discrimination task. The isotropic condition (C8) had the lowest sensitivity of stiffness (*i.e.*, the highest JND and WF) compared to condition of maximizing (C4) and minimizing (C6) EM in terms of numerical JND and WF. For statistical analysis, there was only significant difference for C8 with C4 but not with C6.

There was no any trace of trade-off effect for C8 even numerically like observed in C7. This could be caused by masking effect in the stiffness discrimination task since the directions of friction and stiffness were parallel to each other. However, further experiments were required before drawing any conclusion about isotropic condition and trade-off effect.

3.4. Limitations

The WF of friction obtained in our friction discrimination task was in a normal range like that shown in literature (around 0.23) [15]. But there was relatively larger difference between the WF obtained in our stiffness discrimination task (around 0.16 in the literature). This difference could be probably caused by the potential masking effect which resulted in larger values of WF and JND of stiffness in our experiment.

The main limitation of this paper was the small participants pool and potential bias since all experiments were performed by the first author. In future work, we will employ more participants to increase individual diversity and eliminate potential bias.

4. CONCLUSION

Haptic perceptual sensitivity is a beneficial factor for surgeons accurately conducting many surgical tasks like suturing and palpation. In this paper, we experimentally showed that the haptic perceptual sensitivity of friction and stiffness can be improved in terms of just noticeable difference (JND) and Weber Fraction (WF) by appropriately optimizing the effective manipulability (EM) of a redundant robot.

This paper provided a preliminary but promising result to improve haptic perceptual sensitivity by taking advantage of kinematic redundancy. In future work, we will investigate how masking effect will influence the haptic perceptual sensitivity, as well as whether the same optimization approach can also benefit the haptic perceptual sensitivity of other types of forces such as torque and inertia.

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