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Perception and Action in Simulated Telesurgery

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Abstract

We studied the effect of delay on perception and action in contact with a force field that emulates elastic soft tissue with a specific rigid nonlinear boundary. Such field is similar to forces exerted on a needle during teleoperated needle insertion tasks. We found that a nonlinear boundary region causes both psychometric and motor overestimation of stiffness, and that delay causes motor but not psychometric underestimation of the stiffness of this nonlinear soft tissue. In addition we show that changing the teleoperation channel gain reduces and can even cancel the motor effect of delay.

Keywords

delay; perception; action; telesurgery; needle insertion

1 Introduction

Telesurgery can substantially improve patient care as well as surgical training by providing global access to surgical specialists [1, 2]. In telesurgery the surgeon determines the motion of a remote slave robot by moving a master robot and sensing the forces reflected from the slave to the master (Fig. 1a).

Telesurgery requires transmission of information from a distance, and therefore delay is unavoidable. In the last few years, we have studied the effect of delay on perception of stiffness in linear spring like fields [3–6] and on action in contact with them [7]. Here we developed a new protocol to probe the effect on perception and action in the same experiment testing the effect of delay on a nonlinear environment which simulates needle insertion into soft tissue [8, 9]. We employed simulated telesurgery and focused on a simple teleoperation architecture which includes only delay and gains in the transmission channel (Fig. 1b) in order to highlight the effects of delay without additional control considerations [10, 11].

2 Methods

Subjects held the handle of a PHANTOM® Premium 1.5/6DOF haptic device, and looked at a screen which displayed start and target positions consistent with the haptic scene (see Fig. 2a). The haptic device exerted forces on the hand at 1 kHz and acquired its trajectory at 200 Hz. Lateral position of the hand was displayed by a line and provided subjects with partial position information, without revealing the penetration into a haptic virtual object.

In this study we wished to explore interactions with a force field that approximates the properties of biological tissue. This was, however, a simplified model, as the reaction forces were simulated to depend only on the position and direction of movement. Therefore the force $F_h(t)$ that was exerted in the x axis direction (away from the subject – see Fig. 2a) was a nonlinear function of the hand displacement $x_h(t)$, similar to the position dependent component in [9]:

$$F_e(t) = \begin{cases} x_e(t) = x_h(t - \Delta t_1) \cdot G_x & \\ 0 & x_e(t) < x_0 \\ k_{b1}(x_e(t) - x_0) + k_{b2}(x_e(t) - x_0)^2 & x_0 < x_e(t) < x_b; \dot{x}_e(t) > 0 \\ k_t(x_e(t) - x_0) & x_e(t) > x_b \\ k_t(x_e(t) - x_0) & x_0 < x_e(t) < x_b; \dot{x}_e(t) < 0 \\ F_h(t) = F_e(t - \Delta t_2) \cdot G_F & \end{cases} \quad (1)$$

where G_x, G_f are position and force gains respectively; $x_0 = 3mm$ is the position of the boundary of the field, $x_b = 20mm$ is the position of the interface between rigid nonlinear boundary and the underlying linear tissue, $x_e(t)$, $\dot{x}_e(t)$ and $F_e(t)$ are position, velocity, and force at the environment side, t_1, t_2 are the delays, k_{b1}, k_{b2} are the linear and quadratic coefficients of the nonlinear boundary stiffness, and k_t is the stiffness of the underlying linear tissue. In Fig. 2b–c the force-position trajectories of such force field with and without delay are depicted.

The target was located 67mm beyond the boundary of the field, x_0 ; the start point was located 33mm away from the boundary. Subjects were instructed to quickly reach the target and then return to the starting point. Such a “slicing” movement completed a single trial. Performance feedback was provided as written text messages (“long”, “short”, and “exact”).

The experiment consisted of four phases: (i) Null training – 20 movements in free space allowing subjects to become acquainted with the dynamics of the haptic device and with the task. (ii) Base training – 40 movements with 10 randomly ordered blocks of force fields k_t stiffness levels chosen from $k_t = 25, 35, 45, 55, 65, 75, 85, 95, 105, 115$ N/m, 4 trials in each block, allowing subjects to become acquainted with the various tissue stiffness levels that were later presented during catch trials of the experiment. (iii) Task training – 20 movements with task force field. The exact values of the parameters of task and base force fields depend on the experiment. (iv) Test – the subject was introduced to a task or base field for a number of consecutive trials (5 to 7 – randomly chosen). Since the fast slicing movement involves mostly feedforward control [12], subjects who are trained to perform slicing movement to a certain point inside the surface are expected to miss the target (overshoot/undershoot) whenever the surface properties are unexpectedly changed [7]. Thus,

following this series a catch trial was introduced in order to probe for adaptive changes in estimation [7]. We have introduced the term “motormetric” – as a contrast to “psychometric” analysis – to designate procedures based on observable motor actions for assessing the evolution of perceptual models. The catch trial was either followed by a question: “Which force field was stiffer – the current or previous?”, or by another trial similar to the training block and then the question. This provided us also with a psychometric evaluation of stiffness perception. Feedback was not provided for trials in which the subject’s response was required and for one randomly selected trial in each training block.

Experiment 1: Perception of stiffness of nonlinear tissue without delay

Seven subjects participated in this experiment. We aimed to test whether our combined motormetric and psychometric paradigm is applicable for comparing task nonlinear tissue force field (N) to base linear one sided elastic force field (L) using linear elastic force fields with different levels of stiffness as catch trials. The parameters of the experiment are specified in Table 1.

Experiment 2: Effect of delay on perception of stiffness of nonlinear tissue

Seven subjects participated in this experiment (including five subjects who participated in Exp. 1). Here we explored the effect of delay on the perception of the stiffness of nonlinear elastic force field. Since the psychometric task of comparing the stiffness of nonlinear tissue force field with linear elastic force field was difficult, we compared task delayed nonlinear (D) elastic force field and base nondelayed nonlinear (N) elastic force field. We introduced non delayed nonlinear elastic force fields with different levels of linear component of stiffness as catch trials (see Table 1).

Experiment 3: Canceling the motormetric effect of delay by use of gain

Two subjects from Exp. 2 participated in this experiment. We wished to test if it is possible to cancel the motormetric effect of delay by correctly choosing the gains of teleoperation channel, as suggested in [13]. The experiment was similar to Exp. 2, but position and force gains were changed. We used regression of the amount of overshoot in catch trial as a function of difference between the levels of linear components of stiffness between trained and catch fields to find the mean undershoot p for identical stiffness levels. To cancel the motormetric effect the position gain must be smaller than 1 such that the subject will make larger hand movements, yielding correct catch trials without delay. Thus, we calculated the position and force gains according to

$$G_x = (x_t - x_0) / (x_t - x_0 + \Delta p); \quad G_f = 1 / G_x \quad (2)$$

where x_t is target position and x_0 is as defined in Eq. 1.

We used a procedure that is described in detail in [4, 7] in order to fit psychometric functions to the probability of answering that training block field was stiffer as a function of the difference in k_t between catch field and trained field [14] and extract the point of

subjective equality (PSE). The motormetric curve relates a subject's motor, not verbal, responses to the stimulus. We used a procedure that is described in [7] to fit motormetric functions to the probability to overshoot at catch trial relatively to the median of penetration in last three trials in training block as a function of the difference in k_t between catch field and trained field, and extracted the point of motor response equality (PMRE) from them. Positive values of these PSE or PMRE indicate underestimation of the stiffness of the trained field, and negative values indicate overestimation.

3 Results and Conclusions

In this study we present, for the first time, psychometric and motormetric evaluation of the stiffness of nonlinear needle-insertion-like force field.

The psychometric component of the task in *Experiment 1* was difficult, and therefore two of the subjects failed to discriminate between the fields. The stiffness of the N field was overestimated relative to the stiffness of L field according to both motormetric (paired t-test $t_6=-3.02$, $p=0.023$, significant) and psychometric (paired t-test $t_4=-1.32$, $p=0.26$, nonsignificant) measures, as depicted in Fig. 3a.

The motormetric and psychometric effects of delay on perception of stiffness of nonlinear elastic force field were different. *Experiment 2* revealed that delay caused motormetric underestimation that was consistent across subjects (paired t-test $t_6=6.86$, $p=0.0004$) and no change in psychometric perception (paired t-test $t_5=-1.66$, $p=0.16$) of D field, as depicted in Fig. 3b. This gap is consistent with our findings about linear elastic force fields [7]. Here we report motormetric underestimation, which is consistent with absolute penetration in [7] which is relevant for telesurgery; however, it is interesting to explore in a future study why the delay did not affect the psychometric estimation unlike in the case of linear force fields [3–5]. The gap between perception and action that is demonstrated by different effects of delay supports our suggestion [13] that transparency of teleoperation systems in general, and telesurgery systems in particular, should be assessed using multidimensional transparency measures that include perceptual as well as motor components. Moreover, a focus on these two components is critical for additional aspects in surgery, such as training of surgeons and skills evaluation.

We show here for the first time that it is possible to eliminate the motormetric effect of delay using the transparentizing procedure that we suggested in [13]. In *Experiment 3* we cancelled the motormetric effect of delay, namely reduced the PMRE [N/mm] from 0.028 to -2×10^{-4} and from 0.043 to 0.007, without changing psychometric perception of the stiffness of nonlinear force field for both subjects. However, this finding needs to be validated with additional subjects in various conditions.

The results presented here provide an additional step towards achieving efficient and transparent teleoperation and telesurgery.

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Fig. 1. Teleoperation system: (a) General case (b) Simplified ideal channel with delay and gain.

Fig. 2.

Experimental setup: (a) Seated subject in setup. Dots on screen are start and end point.

White line is partial position feedback. (b) Trajectory of nonlinear tissue force field in force position space. (c) Trajectory of nonlinear tissue force field with delay.

Fig. 3.

Motormetric and psychometric differences in perception. Vertical axis is difference in PMRE (motormetric) and PSE (psychometric) values between task and base conditions. Negative difference is overestimation and positive difference is underestimation of the stiffness of task force field relative to base field. (a) Experiment 1 – overestimation of the stiffness of nonlinear force field. (b) Experiment 2 – delay causes underestimation in motormetric but not psychometric perception of nonlinear stiffness. Bars are differences in means and error bars are 95% confidence intervals for the difference means. Color insets show individual subjects' PSE (right) or PMRE (left).

Table 1

The parameters of Eq. 1 in the different experimental setups. All stiffness levels are in [N/mm]. All delays are in [ms]. Icons are force-position trajectories similar to Fig. 2b–c.

Exp.	Task	Base	Catch
1		$k_{\theta 1} = k_t = 0.06$ $k_{\theta 2} = 0.02$ $t_1 = t_2 = 0$ $G_x = G_f = 1$	$k_{\theta 1} = k_{ti}$ $k_{\theta 2} = 0$
2		$k_{\theta 1} = k_t = 0.06$ $k_{\theta 2} = 0.02$ $t_1 = t_2 = 25$ $G_x = G_f = 1$	$k_{\theta 1} = k_{ti}$ $k_{\theta 2} = 0.02$ $t_1 = t_2 = 0$
3	Similar to Experiment 2, but $G_x < 1$ $G_f = 1/G_x$		