Proximodistal gradient in the perception of delayed stiffness

Ilana Nisky and Amir Karniel
Department of Biomedical Engineering
Ben-Gurion University of the Negev
Beer-Sheva, Israel
{nisky, akarniel}@bgu.ac.il

Abstract— **introduction of successful telerehabilitation into the variety of techniques that are available to the therapist will forever change the field of rehabilitation. Accurate perception of the remote environment's mechanical properties and of stiffness in particular is extremely important for successful telerehabilitation. In the current study we present the framework for exploring perception of delayed stiffness when probing is executed using movement with different joints, and provide experimental results supporting the existence of proximodistal gradient in the perception of delayed stiffness. We found that delayed stiffness was underestimated to a larger extent after probing with wrist than with elbow. We suggest that the observed gradient in perception reveals a proximodistal gradient in control: proximal joints are dominated by force control, whereas distal joints are dominated by position control.**

Keywords- ***telerehabilitation; perception; stiffness; delay; proximodistal gradient; haptics; human motor control; force control; position control; impedance control***

I. INTRODUCTION

Introduction of successful telerehabilitation into the variety of techniques that are available to the therapist will allow transferring rehabilitation from hospitals to community health system, and therefore will improve patient's compliance, accessibility, and frequent therapy sessions. Moreover, robotic rehabilitation is expected to provide new possible treatment by extending the therapist capabilities, and facilitating the simultaneous treatment of a few patients. In order to provide the therapist with force feedback about the interaction with the patient, the treatment has to be performed through a bilateral teleoperation system. Ideally, in bilateral teleoperation, the operator holds a master robot which determines the motion of a remote slave robot and continuously receives instantaneous force feedback. Accurate feedback with negligible delay can considerably improve the performance [1, 2]. However, due to the distance between the master and slave, and limits in information rate and propagation velocity, the force feedback incurs some unavoidable and often significant delays. The delay may cause instability and distorts perception of mechanical properties of the manipulated object [3-5]. In many applications, such as telesurgery and telerehabilitation, accurate perception as well as accurate action is extremely important. Telerehabilitaiton, with the proper robotics and software support is expected to provide the therapist with the flexibility to use different joints and select which joint pivots his/her movement in interaction with the patient. In order to design optimal interface, one should understand the perception of delayed objects and the effects of the specific joints used for the probing.

Intuitively we feel that our fingers are more dexterous than our shoulder, and the shoulder muscles must be stronger than the finger muscles. Indeed, there is evidence for discrepancy in the control of proximal versus distal joints. There are different control loops for distal and proximal muscles in the cerebellum and in reflex pathways; the cortical route for long loop reflexes may be of primary importance in regulating contractions of distal muscles, while subcortical reflex pathways may be largely responsible for the afferent regulation of proximal muscles [6]. The cortico-spinal system is known to exert greater excitatory influence over distal than over proximal muscles [7-10]. In monkeys, corticomotoneural cells make more frequent and more potent terminations in the motorneuron pools of distal muscles compared with proximal muscles[11]. In healthy subjects a proximodistal gradient in accuracy of endpoint position, and opposite gradient in maximum controllable force and resolution of force control were reported [12, 13]. Lu et al. [14] showed that selective hemispheric anesthesia caused decrement in distal but not proximal proprioception of position. In addition, proximodistal gradient was reported in residual motor function after hemispherectomy [15] and stroke [7]. In the current study we explored whether a proximodistal gradient exists in the perception of delayed stiffness.

In recent studies [3, 4] the effect of delay on the perception of delayed stiffness was explored when a subject interacts with virtual elastic force fields, emulated by a robotic manipulandum. In these studies, it was found that subjects overestimate delayed stiffness and that overestimation increases monotonically with increasing delay [3]. Furthermore, subjects interacting with delayed elastic force fields tend to underestimate the stiffness if they do not move across the field's boundary, and overestimate it when they do move across the boundary [4]. A model based on a convex linear combination between regression of force-over-position, which predicts underestimation of delayed stiffness, and position-over-force, which predicts overestimation of delayed stiffness, according to the relative fraction of probing movements completed outside the elastic field best predicted

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the behavioral results. However, the possible influence of the specific joints that were used for probing was not explored.

While in robotics we find a clear distinction between force, position, and hybrid control [16], it is still unclear whether such a distinction exists in the human motor control system. Combining independent force and position control was explored by Chib et al. [17] where the errors in combined motion and force task were predicted by sum of the errors in separate force task and motion task. More recently it was suggested that the nervous system switches between motion and force control to control transition from downward tapping to vertical force production [18]. The combined model suggested in [4] is based on the perception of stiffness as an active process that combines the concurrent operations of force and of a position control systems, depending on the relative amount of interaction with the boundary of the force field. It is suggested that the estimation process is directly related to the control policy that guides the hand. Namely, force control implies estimation of stiffness according to regression of position over force, yielding overestimation of delayed stiffness, whereas position control implies estimation of stiffness according to regression of force over position, yielding underestimation of delayed stiffness. In the current study we suggest that the weighting between the force and position controllers is not similar across different joints, and that there is a proximodistal gradient in the transition between force and position control.

We hypothesize that when subjects probe virtual elastic force fields without crossing the boundary of the field there is a proximodistal gradient in underestimation of delayed stiffness, and that it is related to gradient in combination of force and position control modes. Namely, proximal joints, such as shoulder and elbow, are dominated by force control, whereas distal joints, such as wrist, are dominated by position control. In this study we present the framework for exploring these hypotheses and provide experimental results supporting the proposed proximodistal gradient.

II. METHODS

A. Subjects, Apparatus and Protocol

Thirteen subjects participated in the experiments after signing the informed consent form as stipulated by the local Helsinki Committee. A seated subject held, with his/her dominant hand, the handle of PHANTOM® Desktop™ haptic device. The subject looked at a projection glass of a Reachin®/Sensegraphics® virtual reality system, placed horizontally above the hand (Fig. 1a), on which was displayed, in full-screen width, a virtual spring-like field as blue or red square. An opaque screen was fixed under the glass to prevent visual information about hand position. Hand position was sampled through digital encoders in the haptic device at 77 Hz, and this information was used online to calculate the force feedback, which was interpolated and rendered at 1 KHz.

To investigate subjective stiffness perception, a forced-choice paradigm was used: in each trial, subjects were presented with two virtual spring-like fields and were asked to choose which one of them was stiffer by probing both fields without time limits. One of the fields - the "D field" - had always a stiffness of 85 N/m, and its force feedback was delayed by 50 ms in half of the trials. The other – the "K field" – had stiffness varying in the different trials between 10 different equally spaced stiffness levels in the range of 40-130 N/m. The force feedback of the K field was never delayed. We chose 50ms delay because it represents "median" delay [19], i.e., large enough to be significant at typical probing velocities, and therefore to allow clearly observable distortion effects, but small enough to maintain the perception of the spring effect. Each pair of K and D fields was considered as a "single trial". The subjects performed 20 training trials and 200 test trials. Only the test trials were analyzed. Subjects were never provided with feedback about their answers. Subjects received only partial visual feedback of the probing hand location, only in directions perpendicular to the probing direction. Subjects were free to switch between the force fields as often as they wished and to probe each force field for as long as they wished. To switch between the two fields, subjects had to press a virtual button located below the working area, at $x = x_i$. Once they felt ready, they were asked to state which field was stiffer by pressing an appropriate button with the free nonprobing hand.

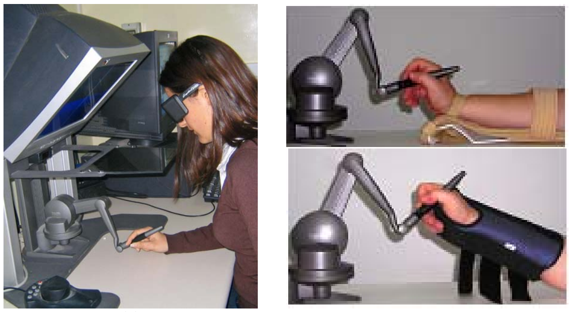

(a) (b)

Figure 1. Experimental setup: (a) The subject and the virtual reality system (b) Two movement types in perception of delayed stiffness experiment: wrist movement (up), and elbow movement (down)

Subjects were instructed to make rapid probing movements and to keep the hand in motion. To avoid force saturation, subjects were asked to generate only short movements into the field, and an auditory cue was sounded at the maximum allowed level of penetration (4.5 cm). After a short practice (during training trials), subjects learned to make short movements and to avoid this (intentionally annoying) auditory cue in most of the trials.

We calculated the force feedback exerted by the haptic device with the aim to emulate a spring-like field according to $F(t) = -K(x(t-\Delta t) - x_{0n})$, where K is the stiffness level, Δt is the delay, and x_{0n} is the field's boundary, always unreachable, i.e., $x(t) > x_{0n}\ \forall t$. This ensured that the subject's hand remained inside the elastic force field and away from the boundary during the entire probing session in both delayed and nondelayed force fields. Accordingly, subjects always felt some nonzero force. This experimental setup is equivalent to probing stiffness while always maintaining contact with the probed object, similarly to abdominal palpation performed by a doctor during physical examination. To prevent discontinuity in the exerted force at the point of switching, the locations of the boundaries, x_{0n}, were calculated such that $-K(x_i - x_{0n}) = F_i = -1.06N$. Subjects switched between the fields by pressing a virtual button located at x_i; therefore, they remained at the point of switching for more than 50 ms and felt a force of 1.06 N, regardless of the stiffness level or the delay of the current force field.

Each subject repeated each experiment twice, using different joints – wrist and elbow – to execute probing movements. We forced movement about specific joint using splints, as depicted in Fig. 1b.

B. Data Analysis

1) Psychometric curve

The psychometric curve is a common method of quantifying a subject's performance in a psychophysical task. It relates an observer's performance to an independent variable, usually quantifying some physical property of a stimulus [20]. The general form of the psychometric function is:

$$\psi(x,\alpha,\beta,\gamma,\lambda) = \gamma + (1-\gamma-\lambda)F(x,\alpha,\beta) \qquad (1)$$

where x is the physical property of the stimulus. The shape of the curve is determined by the parameters [α, β, γ, λ] and the choice of a two-parameter function F, typically a sigmoid function. We used the psignifit toolbox version 2.5.6 for Matlab [20] to fit the psychometric curves, and found confidence intervals by the bias-corrected and accelerated ($\mathrm{BC_a}$) bootstrap method described in [21].

We derived the psychometric function by estimating the subject's probability to answer "D is stiffer" as a function of the actual difference $\Delta K = K_D - K_K$, where K_D is the stiffness of the D field and K_K is the stiffness of the K field. This probability was calculated from the subject's answers according to:

$$P(\Delta K) = \frac{\sum_{n=1}^{N(\Delta K)} A[n]}{N(\Delta K)}; \qquad A[n] = \begin{cases} 1 & D \;\; stiffer \\ 0 & K \;\; stiffer \end{cases} \qquad (2)$$

where $A[n]$ is a binary representation of the subject's answer, and $N(\Delta K)$ is the total number of trials with stiffness difference ΔK.

2) Point of Subjective Equality (PSE)

After fitting the psychometric curve, we used the 0.5 threshold value to find the point of subjective equality (PSE), indicating the stiffness difference that was perceived to be zero. When the subject could not discriminate between the fields, the probability to answer that the D field has higher level of stiffness is 0.5. Following [20] and assuming that F describes the psychological mechanism of decision, and λ, γ are stimulus-independent error rates, we used $F^{-1}(0.5)$ to estimate the PSE. Our expectation was to observe zero PSE values for the curves derived from nondelayed trials. For delayed trials, the whole curve was expected to shift. A positive PSE value implies underestimation of delayed stiffness, since the delayed and nondelayed fields were perceived equal when the actual difference between their stiffness levels was positive. Similarly, negative PSE value implies overestimation of delayed stiffness.

3) Movement analysis

The data collected comprise the trajectories in the force-position plane, i.e., each subject's hand position and force exerted by the haptic device. For each trial we estimated the following parameters:

- **Mean probing movement period** - we automatically identified each probing movement according to local maxima and minima of the position trajectory (reversal points – blue and green circles in Fig. 2). Then we calculated number of probing movements in each trial, n_p, according to the number of local maxima, and calculated mean probing movement period $T_p = t_{trial}/n_p$, where t_{trial} is total probing time for the trial.
- **Mean penetration** – we calculated the difference between mean local maxima and minima of the position trajectory.
- **Mean absolute velocity** – we calculated the average of absolute value of velocity during the whole trial, i.e. $M_V = \frac{1}{N-1}\sum_{k=2}^{N}\left|(x_k - x_{k-1})/(t_k - t_{k-1})\right|$ where N is the number of sampled points during the trial, and x_k, t_k are the sampled position and time respectively.

Subjects were excluded from the analysis if their mean probing movement period across trials was found to be more than 0.5s in one of the conditions, since long probing movement essentially eliminates the effect of the delay. In such cases the influence of noise is larger than the influence of delay. Three subjects were excluded from the analysis due to this criterion, and therefore we present the results of ten subjects in the results section.

4) Optimal proximity index

We constructed a model that uses subjects' trajectories in

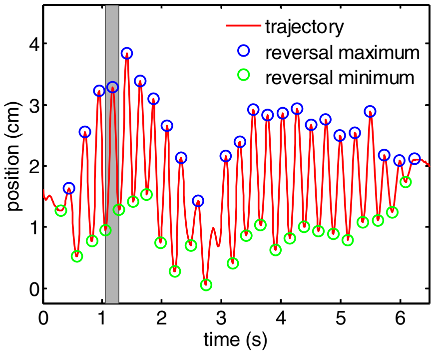
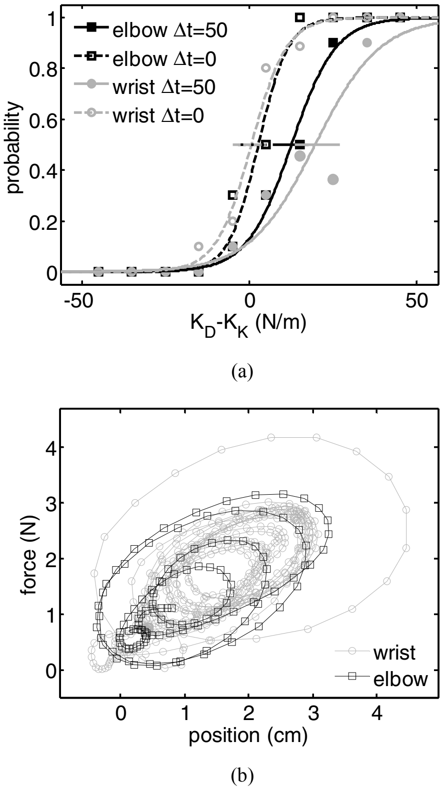


Figure 2: An example of a position trajectory from a single trial of a single subject as a function of probing time. Blue and green circles indicate local maxima and minima respectively. Shaded area highlights a single probing movement. All the movement depicted here is inside the spring-like force field.

force position plane to estimate the stiffness of spring-like fields, and assessed its ability to predict subjects' answer to the question: "Which field is stiffer?" The model's prediction of the subject's answer was calculated according to the sign of the difference between estimations of D and K stiffness levels, $\hat{K}_D$ and $\hat{K}_K$ respectively, and calculated the total score according to:

$$\begin{gathered} S=\frac{\sum_{n=1}^{N_{delayed}} S[n]}{N_{delayed}}; \\ S[n]=\begin{cases}1 & \hat{A}[n]=A[n]\\ 0 & \hat{A}[n]\neq A[n]\end{cases} \\ \hat{A}[n]=\begin{cases}1 & \hat{K}_D[n]-\hat{K}_K[n]>0\\ 0 & \hat{K}_D[n]-\hat{K}_K[n]<0\end{cases} \end{gathered} \tag{3}$$



(a)

(b)

Figure 3: Example of subject's results in wrist (gray) and elbow (black) conditions. (a) Psychometric curves fitted according to answers in delayed (solid) and nondelayed (dashed) trials. Horisontal error bars are 95% confidence intervals for the estimation of PSE. In non-delayed trials the probability to answer "D stiffer" changes from zero to one around zero difference between D and K force fields, whereas the curves fitted to answers in delayed trials are shifted to the right, indicating underestimation. The curve describing answers in the "wrist" condition is shifted further to the right than in the "elbow" condition. (b) Force-position trajectories from two similar trials in both conditions. Trajectories are ellipsoid due to the effect of delay

where $N_{delayed}$ is the total number of delayed trials, $A[n]$ is the subject's answer in trial n (see (2)). This score represents the model's probability to agree with the subject's answers.

The estimation of stiffness according to the model is based on convex combination of slopes of regression of force over position, $\hat{K}_{FP}$, and position over force, $\hat{K}_{PF}$, namely

$$.\qquad \hat{K}=\beta\hat{K}_{FP}+(1-\beta)\hat{K}_{PF} \tag{4}$$

One should note that the outcome of estimation of stiffness according to the slope of a regression line strongly depends on the choice of dependent and independent variables. In the case of force-position trajectories in delayed elastic force field, the regression of force over position yield underestimation, whereas regression of position over force yields overestimation (see [4] for a detailed discussion about the difference between these two ways of fitting the regression line).

For each subject and for each hand configuration condition we optimized the weight in this combination to obtain the best possible score for the model and extracted the optimal proximity indexes $\beta_{elbow}, \beta_{wrist}$.

III. RESULTS

A. *Evidence for proximodistal gradient*

The psychometric curves fitted to eight out of ten subjects' answers from delayed trials in the wrist probing condition were shifted further to the right than in the elbow probing condition. See Fig. 3a for an example of such curves of one subject in elbow (solid black) and wrist (solid gray) conditions.

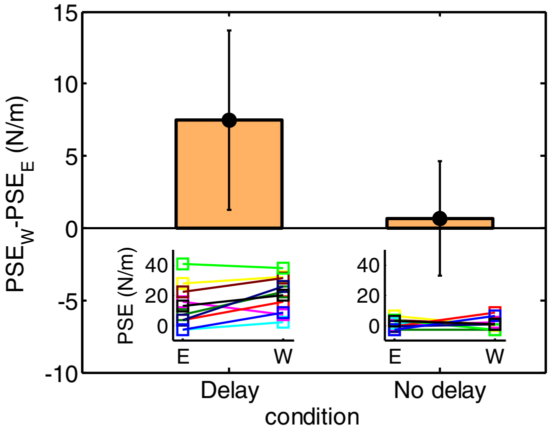
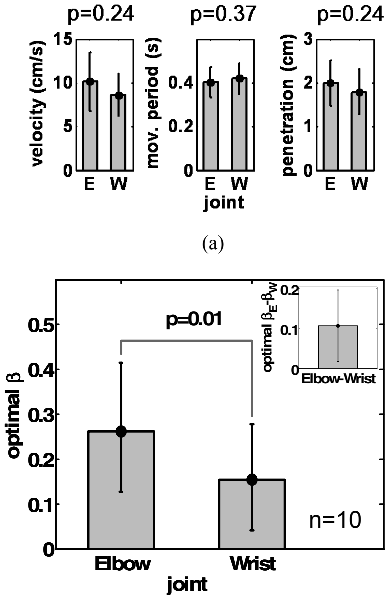


Figure 4: Stronger underestimation of delayed stiffness when subjects probe the force field with their wrist than with their elbow is depicted by a statistically significant (see text) negative difference PSE_{wrist}-PSE_{elbow} in delayed but not nondelayed conditions. Bars are mean PSE difference and error bars are 95% confidence intervals. Left and right insets depict individual PSE values fitted to subjects answers in delayed and nondelayed conditions respectively. In the delayed condition eight out of ten subjects underestimated delayed stiffness stronger when probing with their wrist (W) that with their elbow (E). In the nondelayed (control) condition all PSE values are around zero, indicating no change in estimation of stiffness between K and D

Consequently, the point of subjective equality (PSE) in the wrist condition was higher than in the elbow condition for these subjects (Fig. 4 left inset). As expected, no such effect, or any shift in psychometric curves, was observed in nondelayed trials: in Fig. 3a (dashed curves) the probability to answer "D stiffer" changes from zero to one around zero difference between D and K force fields, and in Fig. 4 right inset all PSE values are around zero. Overall, we observed a statistically significant difference between $\mathrm{PSE}_{\mathrm{wrist}}$ and $\mathrm{PSE}_{\mathrm{elbow}}$, estimated from subjects' answers in the delayed stiffness condition (one-sided paired t-test, p=0.0115, one-sided Wilcoxon sign-rank test, p=0.0137), but not in the nondelayed condition (one-sided paired t-test, p=0.35, one-sided Wilcoxon sign-rank test, p=0.42), as depicted in Fig. 4. These results indicate stronger underestimation of delayed stiffness when subjects used their wrist than when they used their shoulder to probe the force field, supporting our proximodistal gradient hypothesis.

B. Proximity index gradient indicates proximodistal gradient in force position control

Examples of force-position trajectories in wrist (gray circles) and elbow (black squares) conditions from similar trial are depicted in Fig. 3b. The trajectories are qualitatively similar, and it is clear that delay had substantial effect on both trajectories, which would otherwise be similar to straight lines. There was no statistically significant difference between the elbow and wrist conditions in mean velocity, mean probing movement period, and mean penetration (one-sided paired t-test, p=0.24, p=0.37, and p=0.24 respectively), as depicted in Fig. 5a. This analysis provides a control for the possibility that the observed difference reflects a simple mechanical difference between the movements. The optimal values of β_{elbow} were statistically significantly higher than of β_{wrist} (one-sided bootstrap test p=0.01, one-sided paired t-test, p=0.029, one-sided Wilcoxon sign-rank test, p=0.045), as depicted in Fig. 5b.



(a)

(b)

Figure 5: (a) No significant difference in mean absolute velocity (left), mean movement period (middle), and mean penetration into force field (right) between elbow and wrist probing conditions. (b) Optimal proximity index is statistically significantly higher in elbow than in wrist probing condition. Inset describes the difference between optimal proximity indices for elbow and wrist probing conditions. Bars are the mean, and error bars are 95% confidence intervals for the estimation of the mean in each plot. All tests are one sided paired tests.

IV. DISCUSSION

In this study we reproduced the previously reported results as to the influence of delay on the perception of stiffness, as well as found evidence for the existence of proximodistal gradient in the perception of delayed stiffness. The expected underestimation of the delayed stiffness was statistically significantly larger when subjects used their wrist for probing compared to the condition in which subjects used their elbow.

In previous studies we explored the effect of delay on the perception of stiffness [3, 4], and found that subjects interacting with delayed elastic force fields tend to underestimate the stiffness if they do not move across the field's boundary, and overestimate it when they do move across the boundary. A model based on a convex linear combination between regression of force-over-position and position-over-force according to the relative fraction of probing movements completed outside and inside the field best predicted the behavioral results. The observed perceptual effect is explained by the operation of a control system that combines force and position control policies according to the demands of the contact with the environment – homogeneous space versus interaction with a boundary. Inside an elastic field, the appropriate control causality is implemented by a state controller that attempts to enforce a trajectory of the hand, and the stiffness is estimated by regressing sensed force over imposed position. Conversely, if the hand encounters a boundary, the appropriate control causality is implemented by a force controller that attempts to regulate the interface force, and the corresponding stiffness estimation strategy is a local regression of position over force. This approach is particularly safe in the presence of rigid objects.

Here we extended that model to include the influence of a proximity index on the weighting between force and position control. In the current study all subjects did not have access to the elastic force field's boundary. However, the optimal weighting parameter, β from (4), was not zero. Moreover, the optimal β was higher when subjects probed the elastic force fields with their elbow than with their wrist, and therefore we refer to the weighting parameter β as proximity index. We suggest that there is a proximodistal gradient in control modes; namely, proximal joints, such as shoulder and elbow, are dominated by force control, whereas distal joints, such as wrist, are dominated by position control. For the purpose of illustrating the logic behind such a gradient in control we wish to consider an everyday scenario of inserting a key into a keyhole while holding a heavy grocery bag. To succeed in such a task one needs to precisely control the position (angles) of the digits and wrist in order to aim the key at the keyhole, and precisely compensate for interaction forces at the shoulder in order to maintain stable posture.

Understanding the effect of delay on perception is expected to contribute to building better teleoperation systems, in general, and to promote telesurgery and telerehabilitation, in particular. Accurate perception of mechanical stiffness is important for diagnosis, such as in the case of evaluation of spasticity [22] or judgment of posteroanterior spinal stiffness [23], as well as for treatment. Mechanical stiffness is not completely equivalent to the clinical concept of stiffness [23]; nevertheless, its correct perception is a necessary condition for intact perception of more complicated concepts involved in clinical evaluations. Therefore, the fact that the joint that is used in the process of probing can completely alter the perception of delayed stiffness must be considered in building the successful telerehabilitation systems and procedures of the future.

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REFERENCES

[1] G. Niemeyer and J. J. E. Slotine, "Telemanipulation with time delays," International Journal of Robotics Research, vol. 23, pp. 873-890, Sep 2004.

[2] T. B. Sheridan, Telerobotics, Automation, and Human Supervisory Control: MIT Press, 1992.

[3] A. Pressman, L. H. Welty, A. Karniel, and F. A. Mussa-Ivaldi, "Perception of delayed stiffness," International Journal of Robotics Research, vol. 26, pp. 1191-1203, 2007.

[4] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "A Regression and Boundary-Crossing-Based Model for the Perception of Delayed Stiffness," Haptics, IEEE Transactions on, vol. 1, pp. 73-82, 2008.

[5] A. Pressman, I. Nisky, A. Karniel, and F. A. Mussa-Ivaldi, "Probing Virtual Boundaries and the Perception of Delayed Stiffness," Advanced Robotics, vol. 22, pp. 119-140, 2008.

[6] E. Kandel, J. Schwartz, and T. Jessel, Principles of neural science 4ed.: McGraw-Hill, 2000.

[7] A. Turton and R. N. Lemon, "The contribution of fast corticospinal input to the voluntary activation of proximal muscles in normal subjects and in stroke patients," Experimental Brain Research, vol. 129, pp. 559-572, 1999.

[8] B. Brouwer and P. Ashby, "Corticospinal projections to upper and lower limb spinal motoneurons in man," Electroencephalogr Clin Neurophysiol, vol. 76, pp. 509-19, 1990.

[9] E. Palmer and P. Ashby, "Corticospinal projections to upper limb motoneurones in humans," Journal of Physiology, vol. 448, pp. 397-412, March 1992.

[10] R. N. Lemon and J. Griffiths, "Comparing the function of the corticospinal system in different species: Organizational differences for motor specialization?," Muscle & Nerve, vol. 32, pp. 261-279, 2005.

[11] B. J. McKiernan, J. K. Marcario, J. H. Karrer, and P. D. Cheney, "Corticomotoneuronal Postspike Effects in Shoulder, Elbow, Wrist, Digit, and Intrinsic Hand Muscles During a Reach and Prehension Task," J Neurophysiol, vol. 80, pp. 1961-1980, October 1998.

[12] H. Z. Tan, M. A. Srinivassan, B. Eberman, and B. Cheng, "Human factors for the design of force reflecting haptic interfaces " in DSC Dynamic Systems and Control (The American Society of Mechanical Engineers). vol. 55-1, C. J. Radcliffe, Ed., 1994.

[13] J. Biggs and M. A. Srinivasan, "Haptic Interfaces," in Handbook of Virtual Environments, K. Stanney, Ed. London: Lawrence Earlbaum, Inc, pp. 93-115, 2002.

[14] L. H. Lu, A. M. Barrett, J. E. Cibula, R. L. Gilmore, and K. M. Heilman, "Proprioception more impaired distally than proximally in subjects with hemispheric dysfunction," Neurology, vol. 55, pp. 596-597, August 2000.

[15] H. C. Dijkerman, F. Vargha-Khadem, C. E. Polkey, and L. Weiskrantz, "Ipsilesional and contralesional sensorimotor function after hemispherectomy: Differences between distal and proximal function," Neuropsychologia, vol. 46, pp. 886-901, 2008.

[16] M. H. Raibert and J. J. Craig, "Hybrid position/force control of manipulators," ASME Journal of Dynamic Systems, Measurement, and Control, vol. 102, pp. 126-133, 1981.

[17] V. S. Chib, M. A. Krutky, K. M. Lynch, and F. A. Mussa-Ivaldi, "The nervous system independently controls motion and force," in Advances in computational motor control, symposium at the Society for Neuroscience Conference Atlanta, Ga. , 2006.

[18] M. Venkadesan and F. J. Valero-Cuevas, "Neural Control of Motion-to-Force Transitions with the Fingertip," Journal of Neurosciense, vol. 28, pp. 1366-1373, February 2008.

[19] D. A. Lawrence, "Stability and Transparency in Bilateral Teleoperation," Robotics and Automation, IEEE Transactions on, vol. 9, pp. 624-627, 1993.

[20] F. A. Wichmann and N. J. Hill, "The psychometric function: II. Bootstrap-based confidence intervals and sampling," Perception & Psychophysics, vol. 63, pp. 1314-1329, Nov 2001.

[21] F. A. Wichmann and N. J. Hill, "The psychometric function: I. Fitting, sampling, and goodness of fit," Perception & Psychophysics, vol. 63, pp. 1293-1313, Nov 2001.

[22] D. Barus and S. H. Kozin, "The Evaluation and Treatment of Elbow Dysfunction Secondary to Spasticity and Paralysis," Journal of Hand Therapy, vol. 19, pp. 192-205, 2006.

[23] C. Maher and R. Adams, "Is the clinical concept of spinal stiffness multidimensional?," Physical Therapy, vol. 75, pp. 854-860, October 1995.