Testing the ability to represent and control a contact force

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Abstract—**While the concept of force is solidly grounded in Newtonian mechanics, it is not known if it is also represented in a consistent way by our brains as they control interactions of the hand with external objects. For example, a force of 10 Newton applied against different springs will cause different amounts of displacement. Are we able to represent 10 Newton in a way that is independent of the effects of applying such force to different objects? Here, we developed a simple method to address this question by engaging subjects in a task whose success depends critically upon the ability to exert a fixed force against different simulated springs. Our preliminary findings indicate that while this task is difficult, subjects learn after some training to exert the same force against different springs and in different directions.**

I. Introduction

AMONG all proprioceptive functions, the sensation of muscular effort/force is arguably one with the greatest impact on daily activities. The removal of sensory feedback to the central nervous system (CNS) has long been known to impair, though not abolish, motor function, particularly in tasks requiring dexterity and context-dependent control [1]. In particular, motor control for goal-directed behavior requires accurate sensory information concerning both the external and internal environmental condition of the body, and proprioception has a critical role in this [2]. In fact, developments and improvements in task performance depend on multiple sensory feedback sources, including vision and the various proprioceptive sensors that signal the physical state of the limb as muscle spindle receptors, Golgi tendon organs and mechanoreceptors in the skin [3]. Recent studies adopted force control tasks with pure haptic feedback for promoting short-term focused attention in people with mental disorders such as Attention Deficit Disorders (ADD). In particular, Wang and coworkers found that engaging in accurate force control while visual and auditory information are blocked has a reinforcing effect on short-term focused attention [4]. Exploiting the haptic channel could be an appropriate and optimal method for the learning of force control tasks. In this pilot study, we investigated if it is possible to learn a specific amount of force after training that exploits the haptic channel. In particular, we explored the possible learning strategies adopted if position sense and force sense are dissociated i.e. if different hand positions correspond to the same level of force.

II. Material and Methods

A. Experimental Set-Up

Six healthy human subjects (24.50±0.39 years, 3 females) provided written consent to participate in a single-session experiment that was approved by a local ethics committee in accord with the Declaration of Helsinki. Subjects sat 1m from a 40" monitor mounted vertically at eye level. They grasped the instrumented handle of a planar manipulandum [5] with their right hand. The arm and hand were hidden by an opaque screen. The handle included a forearm support that partly compensated for gravity. Hand position, and contact forces were sampled at a rate of 100 samples per second.

B. Task

Subjects performed a force control task designed to test their ability to produce a steady hand force of 10N when the relationship between hand force and displacement (i.e., environmental stiffness) could change from one trial to the next. The experimental session included a *training phase* (10 blocks of 30 trials each), and a *generalization phase* (30 trials; see Fig. 1, panel a). During the *training* phase, subjects were to produce and hold for 2 seconds a hand force in the forward direction as close as possible – but not exceeding – a specified desired value (F_r = 10 N). The robot generated an elastic environment that opposed the subject's hand forces:

$$F = -K_i(x - x_0) \quad (1)$$

where x_i is the hand's displacement from a comfortable resting position x_0, F is the hand force produced by the subject, and K_i is the stiffness of the robotic on trial i. On any given trial, K_i could take one of 6 different stiffness values. If the subject applied more than the required force, the robot simulated the "breaking of the virtual spring" in that the force opposing displacement suddenly turned off (i.e. $K_i$was set to 0). The display monitor provided three visual cues that helped subjects perform their task. The first cue was a "starting position" target located on the central-lowest part of the screen; this cue corresponded to the hand position when subjects generated no force against the robot

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handle. The second cue was a cursor representing hand position and was visible only within a 1.5 cm radius of the starting position; this cue assisted subjects in minimizing the interface force at the onset of each trial. The third cue was a score (knowledge of results, KR), which at the end of each trial provided performance feedback related to hand force production. The score was a nonlinear function of the steady-state hand force within the last 2 s of the trial (i.e., during the hold period). If the subject was able to maintain the hand force below the required force (applied force F: $0 < F \leq F_r$), they received a trial score that was a quadratic function of force ranging from 0 to 100. If instead the subject "broke the spring," they received a score of 0 on that trial, Fig.1, panel b. The quadratic function was set to encourage subjects to take risks by increasing the reward more rapidly than a linear function of the distance of the applied force from the desired value. During the *generalization* phase*,* subjects were required to produce and hold for 2 seconds 10 N hand force in the rightward direction. The load conditions were identical to those in the training phase. The cues also were similar, except that subjects received no score during the generalization phase.

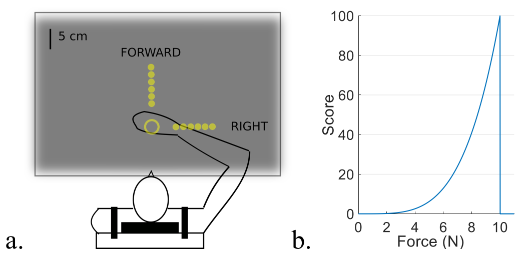

Fig. 1. *Panel a*. *Task description*. Subject is represented with the hand located in the starting position (big empty target). *Training phase* consists in the random "reaching" of the 6 yellow targets located in the forward direction. *Generalization phase* consists in the random "reaching" of the other 6 targets located in the right direction *Panel b*. Score function.

C. *Data analysis*

To evaluate the ability of subjects to learn a specific amount of force, we computed, both for the training and generalization phase, the following metrics:

- *Score* (0-100)
- *Final force level* (N): steady-state hand force during the hold period (average value)
- *Rate of Failure (%)*: proportion of trials where subjects "broke" the virtual spring.

We tested for learning by comparing the performance in block 1 (T1) and block 10 (T10) of the training phase. We tested for generalization by comparing the performance between the generalization block (G1) and the last block of training (T10). We used a non-parametric test (Wilcoxon signed rank test) since the number of participants was small and the performance variables were not normally distributed.

III. Results

Preliminary results are reported about the *training* phase and the *generalization phase* for every subject with respect the mean trend computed for all subjects. In particular, we report results relative to Score (and relative force) and Rate of Failure (%), in Fig. 2, first row. We observed a significant improvement between T1 and T10 (score: p=0.0277, z=-2.2014; rate of failure: p=0.0273, z=2.2075) and a consistent performance during G1, compared to T10 (score: p=0.3454, z=0.9435; rate of failure: p=0.1402, z=-1.4751). The second row of Fig.2 reports the mean value of score for K_i at T1 (blue) and at T10 (red). We observed a difference between pre- and post-training for every K_i, already supported by previous statistics. In the last plot we report the rate of failure for every K_i: we have great failures at T1 especially for high K_i. After training these differences are minimal between K_i.

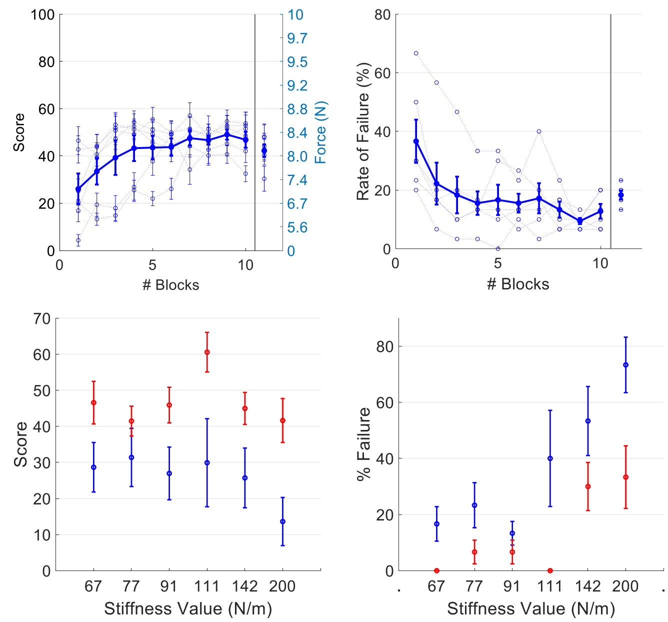

Fig. 2. *First row.* Mean (thick line) and single subject (dotted lines) score value and relative value of force on the right axis. On the right Rate of failure (%). Both parameters are for training phase (#blocks: 1,10) and *generalization phase* (block 11). *Second row*. Mean value of score for each value of stiffness at first block (blue) and at last block (red). On the right Rate of failure (%).

IV. Conclusion

Our preliminary results suggest that learning to produce a steady value of hand force in the presence of environmental uncertainty is possible in just a few sessions of training. Furthermore, this work provides a preliminary proof of concept that this skill generalizes across directions i.e. subjects are able to exert the learned force in a different arm configuration requiring different muscle activations. It is important to further investigate how these factors can impact the learning process.

References

[1] A. Prochazka, "Proprioceptive feedback and movement regulation," *Compr. Physiol.*, 2010.

[2] B. L. Riemann et al., "The sensorimotor system, part I: the physiologic basis of functional joint stability," *J. Athl. Train.*, 2002.

[3] T. Judkins et al., "Visuo-proprioceptive interactions during adaptation of the human reach," *J. Neurophysiol.*, 2013.

[4] D. Wang et al. , "Force control tasks with pure haptic feedback promote short-term focused attention," *IEEE Trans. Haptics*, 2014.

[5] M. Casadio et al., "Braccio di Ferro: a new haptic workstation for neuromotor rehabilitation.," *Technol. Health Care*, 2006.