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Artificial Proprioception for Myoelectric Control

Tobias Pistohl*, Andrew Jackson, Ganesh Gowrishankar, Deepak Joshi,
and Kianoush Nazarpour, *Member, IEEE*

Abstract—**The typical control of myoelectric interfaces, be it in real-life prosthetic applications or laboratory settings, largely relies on visual feedback, while proprioceptive feedback from controlling muscles is not very informative about the task carried out. If proprioceptive feedback were artificially provided to a non-controlling limb, could it be effectively integrated into myoelectric control? In a two-dimensional myoelectric-controlled centre-out task, we aimed to restore proprioception by guiding subjects' right hands along the trajectory of a visual cursor they were controlling with isometric muscle contractions in their left hand. Overall task success was equally high with vision alone as it was with the additional proprioceptive signal, indicating that visual feedback was already sufficient. Still, presence of artificial proprioception did enhance control when visual feedback was not available. Interestingly, sensory integration of the proprioceptive information was established while it appeared to be redundant to existing visual feedback. However, utilization of the artificial proprioceptive signal was severely impaired when it was vertically mirrored with respect to visual feedback, outlining the importance of congruence of sensory modalities for implicit multi-sensory integration.**

I. INTRODUCTION

Myoelectric interfaces use the electromyogram (EMG) – electric activity recorded from a muscle – to control computers or electrically actuated devices, such as prosthetic arms or hands. During the operation of myoelectric interfaces users typically rely on visual feedback alone. Proprioceptive information is available from controlling muscles to some extent, but offers little information about the state of the controlled device: When Radhakrishnan et al. [1] used vibration to perturb proprioception of controlling arm muscles during myoelectric control of a computerized task, they found that, while accuracy was diminished, subjects still learned to control the task at the same rate. A possible way to remedy the loss of proprioceptive information is to artificially provide positional cues to intact limbs. Similar concepts have been explored with control executed via brain-machine interfaces [2] or finger force [3]. However, those provided the feedback signal to the same limb that would have been affected by the control signal in a natural setting, which is not practical for myoelectric prostheses. We supplied an artificial proprioceptive sense by moving the right arm of subjects controlling a task with myoelectric activity from their left hand. We tested whether the novel feedback signal could enhance myoelectric control and whether it added a benefit to existing visual feedback. For the information supplied by artificial proprioceptive feedback, a map linking visual task and proprioceptive signal will have to be established. We tested under which conditions this map will be built, and whether it requires visual and proprioceptive positions to be congruent.

II. METHODS

A. Subjects

40 healthy right-handed subjects took part in the experiments; 21 participated in experiment 1 and 19 in both experiments 2 and 3, which were run in close succession with only a few moments interruption. All subjects gave their informed written consent before participation. The study was approved by the local ethics committee at Newcastle University.

B. Electromyographic recordings

We recorded electric activity of muscles in the immobilized left hand and forearm. For experiment 1 EMGs were recorded from *abductor policis brevis* (APB) and *abductor digiti minimi* (ADM). For experiments 2 and 3, we recorded additional signals from the *first dorsal interosseus* (1DI) and *extensor carpi radialis* (ECR). APB, ADM and 1DI are intrinsic hand muscles, abducting thumb, little finger and index finger, respectively; ECR is located in the forearm and extends the hand at the wrist joint. Adhesive gel electrodes (Bio-logic, Natus Medical Inc., Mundelein, IL, USA) were positioned over the belly of the muscle and an adjacent knuckle in the case of the intrinsic hand muscles, or on two positions along the muscle in the case of ECR. Myoelectric signals were amplified (NL844/NL820A, Digitimer, Hertfordshire, UK) with the gain adjusted between 0.1K and 5K, low-pass filtered at 1 kHz and subsequently digitized at 2.5 kHz sampling frequency (NI USB-6229, BNC, National Instruments, Austin, TX, USA).

Before the start of an experiment, the signal amplitudes during rest and comfortable contraction were recorded for every single EMG signal. To determine comfortable contraction levels, subjects were asked to contract the respective muscle at a moderate level that would not cause fatigue. Signal offsets were routinely subtracted from each channel be-

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*T. Pistohl is with the Institute of Neuroscience, Newcastle University, Newcastle upon Tyne, NE2 4HH, UK. (e-mail: tobias.pistohl@ncl.ac.uk).

K. Nazarpour is with the Institute of Neuroscience, Newcastle University, Newcastle upon Tyne, NE2 4HH, UK. (e-mail: k.nazarpour@ncl.ac.uk).

G. Gowrishankar is with the Advanced Telecommunications Research Institute International, 2-2-2 Hikaridai, Seika-cho, Soraku-gun, Kyoto, Japan (e-mail: gganesh@atr.jp).

D. Joshi is with the Department of Electrical and Electronics Engineering, Graphic Era University, Dehradun, Uttarakhand – 248002, India (e-mail: joshideepak2004@yahoo.co.in)

A. Jackson is with the Institute of Neuroscience, Newcastle University, Newcastle upon Tyne, NE2 4HH, UK. (e-mail: andrew.jackson@ncl.ac.uk).

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fore any further processing. The instantaneous activation level of each recorded muscle was estimated by averaging the rectified EMG of the last 750 ms. In an analogous way, resting levels and comfortable contraction levels were calculated from the calibration data. Normalized muscle activation levels y_n were computed online by dividing instantaneous levels y by levels of comfortable contraction y_c, after subtracting resting levels y_r: $y_n = (y - y_r) / (y_c - y_r)$.

C. *Artificial proprioception*

We used an active manipulandum to provide artificial proprioceptive feedback about movement and position to subjects' right arms, by guiding their hands along a trajectory controlled by myoelectric activity in their left hand and arm. A schematic view of the setup is shown in Fig. 1a. Participants of the study held on to a rotating handle mounted onto the end of a parallelogram arm. A button built into the handle had to be held during the experiment to enable the motors driving the manipulandum. Left hand and arm of a subject was immobilized on an armrest with a modified glove and a Velcro strap across the arm, high enough to allow free movement of the manipulandum. Subjects observed the contents of a monitor, mounted on top, through a mirror so that they perceived a virtual horizontal display at the height of the manipulandum's handle.

In some experimental conditions, the manipulandum was made to closely follow a visual cursor moving in the virtual plane, through a PID controller implemented into the experimental software. Cursor position determined the position of the manipulandum's handle; movement of the handle on the other hand did not change cursor position, so that the experimental task could not be affected by right arm movements of the subject. Subjects were, however, strongly discouraged from moving or resisting the manipulandum actively. Since high-frequency noise could induce vibrations into the handle that deteriorate proprioceptive accuracy, the PID controller was set up to mainly follow low-frequency movements that were relevant to the task.

D. *Experiments*

Recording, online-processing, experimental control and user interface were handled by Python-based software, developed for this purpose.

1) *Task layout*

The experiment consisted of a myoelectric-controlled centre-out task with four circular targets (⌀ 2.4 cm) at 45°, 75°, 105° and 135° on a quarter circle of 8.6 cm radius around the circular starting zone (⌀ 3.6 cm) in the lower part of the workspace (Fig. 1a). The position of a yellow cursor (⌀ 1.8 cm) was determined by the activation levels of two muscles. Contraction of a muscle caused the cursor to move along the muscle's direction of action (DoA) in an amount proportional to the online-estimated muscle activation level, whereas relaxation brought the cursor to the starting position. The two DoA vectors were pointing out from the starting point in 45° and 135° direction, as shown in Fig. 1a. This arrangement was designed to be unintuitive, that is, DoAs were not reflected in movements the respective muscles would cause in the unobstructed hand.

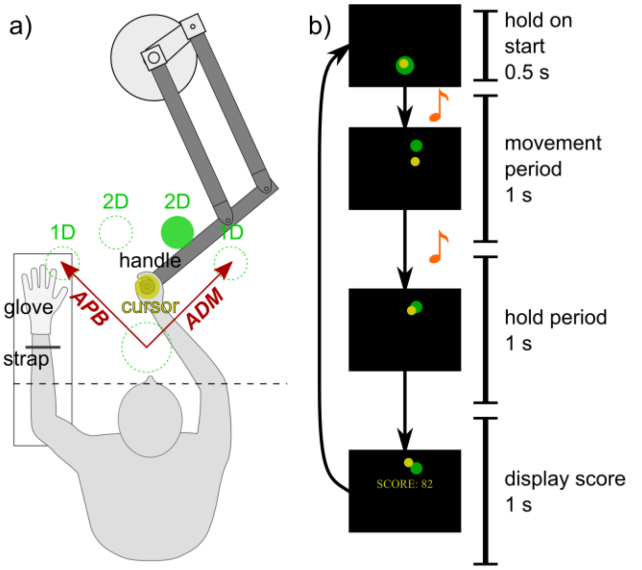

Figure 1: Experimental procedure. (a) Schematic top view on experimental setup. Subjects controlled the task through isometric contractions in their immobilized left hand, while positional feedback was supplied to the right hand through movement of a manipulandum. Cursor (yellow) and target (green) were projected from above to appear in a virtual plane at the height of the manipulandum's handle. (b) Trial structure: after the cursor was held in the starting zone for 0.5 s, a new target appeared (auditory cue). A second auditory cue marked the end of the movement period and the start of the hold period. A score, based on cursor-target match during the hold period, was presented at the end of the trial.

The four target positions were divided into two groups: 1D targets, represented by the lateral positions (45° and 135°), and 2D targets which included the two central targets (75° and 105°). For 2D targets, two-dimensional cursor position was determined by the vector sum of both DoA vectors, scaled by the normalized activation level y_n of their respective muscle: $x = \sum_{i=1}^{2} y_{n,i} \, DoA_i$.

For movements to 1D targets, activation of the muscle with a DoA perpendicular to target direction was ignored, resulting in a simpler, one-dimensional control scheme.

2) *Trial structure*

Each trial consisted of four distinct phases, outlined in Fig. 1b: At the beginning a green circle in the lower workspace indicated the starting zone. The experiment continued after the cursor overlapped with the starting zone for 0.5 s. An auditory signal marked the beginning of a movement period during which one of the four targets was shown. During this period of 1 s length subjects were supposed to move the cursor to the newly presented target and try to hold it there during the ensuing hold period, marked by another auditory cue, for one more second. A performance related score was calculated, reflecting the percentage of time the cursor was in contact to the target circle during the hold period. This value was presented to the subject for one second, with target and last cursor position still visible on the screen.

3) *Experiment 1*

Experiment 1 consisted of 480 trials, divided in two parts: a familiarization phase of 120 trials during which subjects got visual and artificial proprioceptive feedback (VF+PF condition) and a test phase of 360 trials with only half of the trials running in VF+PF condition. In the remaining trials, subjects, with equal frequency, either received only artificial proprioceptive feedback with no visible cursor (PF condition), only visual feedback (VF condition) or neither of both (noFB condition). During the test phase conditions occurred in a pseudorandom order so that in each set of 24 consecutive trials, each of the feedback conditions PF, VF and noFB came up in combination with each of four targets exactly once, while in the same set of trials, condition VF+PF was combined with each target three times. Cursor position was controlled by muscles APB (DoA: 135°, up left) and ADM (DoA: 45°, up right), as illustrated in Fig. 1a. Subjects for this experiment were naïve to the concepts of myoelectric control as well as artificial proprioception.

4) Experiment 2

In experiment 2, subjects received only visual feedback (VF condition) during the 120 trials of the familiarization phase. The test phase was equivalent to that of experiment 1; however the overall number of trials was reduced to 240, so that the test phase consisted of only 120 trials. DoAs and controlling muscles were the same as in experiment 1. This experiment was carried out with a new group of volunteers, who had not experienced artificial proprioception before, that is, who did not participate in experiment 1.

5) Experiment 3

Experiment 3 followed after experiment 2 with the same participants. To minimize the effect of prior training in the new experiment, muscles 1DI and ECR were used for cursor control instead of APB and ADM. The experiment consisted of 240 trials. Otherwise experimental conditions reflected those of experiment 1 with the critical difference that in PF condition the artificial proprioceptive feedback was not congruent to the cursor movement, but mirrored on the vertical midline so that the manipulandum was guiding the participant's right hand to the left when the cursor moved the right and vice versa.

E. Performance metrics

In order to evaluate subject performance and track learning, we calculated the Euclidean distance between the centres of cursor and target, and averaged this measure over the time of the hold period in each trial. The error measure 'distance-to-target' was normalized so that a value of 1.0 reflects the radius between starting point and the quarter-circle of the targets, whereas values close to zero indicate accurate matching of the target with little error.

III. RESULTS

A. Non-learning subjects

Our analysis focused on differential learning effects. To avoid a bias by non-learning subjects, we excluded those from analysis, who couldn't gain viable control over the task.

As a common criterion for the exclusion of subjects, we based this decision on trials 121 to 240, which had comparable conditions in all three experiments. Subjects were considered to be non-learners, if the average distance-to-target measure of all trials with visual feedback (conditions VF+PF and VF) was greater than 0.8. Thus, two subjects were excluded in experiment 1, three in experiment 2 and one in experiment 3.

B. Experiment 1

We evaluated average subject performance over the course of the experiment to produce learning curves as displayed in Fig 2. Trials from all learning subjects were pooled and averaged over stretches of 24 trials per subject, separating trials from different conditions within that period. Whereas the temporal evolution of distance-to-target in conditions PF, VF and noFB, only encountered in the test phase after the initial 120 trials, could be well approximated by an exponential fit, the more rapid initial learning phase in VF+PF condition was accounted for by the use of a double exponential function.

A comparison between different conditions reveals that performance was highest (i.e., errors were lowest) whenever visual feedback was present, independent of whether additional proprioceptive feedback was supplied (VF+PF) or not (VF). Lowest performance was encountered in the noFB condition, serving as a baseline of pure feed-forward type control, independent of sensory feedback. Task performance with artificial proprioception as the only kind of sensory feedback (PF condition) was consistently weaker than with visual feedback, but, at the same time, better than in the noFB condition. A significantly lower average of distance-to-target in PF vs. noFB condition (Fig. 2, black asterisks) and significantly higher average than in VF condition (red asterisks) was confirmed by applying a paired *t*-test over stretches of 24 trials, containing one trial to each target for each of the three conditions (PF, VF and noFB) for each subject. We paired trials of the same subject and to the same target but in different conditions and used a Bonferroni correction for multiple comparisons to test for a family-wise error rate < 0.05.

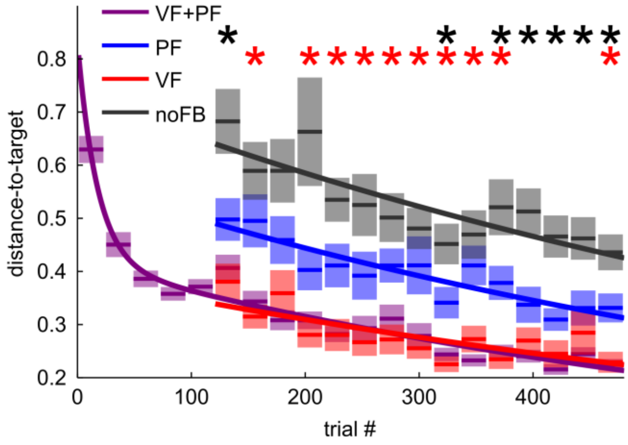

Figure 2: Learning of myoelectric-control in experiment 1. Distance-to-target values of the hold period averaged over trials of the same condition within each set of 24 consecutive trials; data pooled over all subjects. Semi-transparent boxes show ± standard error around the mean (solid lines). Exponential fits overlaid for conditions PF (blue), VF (red) and noFB (black) and a double exponential fit for condition VF+PF (purple). Paired *t*-tests were run between PF trials and VF or noFB trials within a set. Red and black asterisks indicate significantly different distance-to-target values in PF vs. VF and noFB, respectively (family-wise error rate < 0.05; Bonferroni correction).

Control errors in movements to the peripheral 1D targets (not shown) were lower than for the substantially more difficult movement to 2D targets. However, the relations between different conditions with respect to subject performance were the same for both kinds of targets.

C. *Experiment 2*

We conducted experiment 2 with new subjects to test whether integration of the novel proprioceptive feedback into sensorimotor control depended on its experience during the familiarization phase. Therefore condition VF+PF in the familiarization phase was replaced with condition VF, withholding artificial proprioception until the onset of the test phase in trials 121-240.

While average distance-to-target in VF+PF condition was still not significantly different from VF condition at the same stage of learning, performance in PF condition equaled that of the noFB condition in the beginning of the test phase and only got significantly better in later trials (Fig. 3a).

The learning curve for VF condition shows a considerable step towards higher control errors after the first introduction of artificial proprioceptive feedback. The second part of the curve in Fig. 3a was therefore fitted with a separate exponential function to accommodate this sudden change.

D. *Experiment 3*

With experiment 3 we tested whether the integration of artificial proprioception into sensorimotor control was enabled by the fact that vision and artificial proprioception provided congruent feedback, or whether more arbitrary relations – with proprioception as a mirror image of vision – would be learned equally.

During the familiarization phase very rapid initial learning with VF+PF could be observed (Fig. 3b) – which could be expected, since subjects were not naïve to myoelectric control any more, after participating in experiment 2.

Control in PF condition was significantly more accurate than in condition noFB in later trials (black asterisk). However, control errors were equally high for both conditions in the early trials of the test phase.

IV. DISCUSSION

In our experiments artificial proprioception, supplied to a non-controlling arm, did not increase overall task success of myoelectric control. However, without visual feedback artificial proprioception improved performance significantly over the case of no feedback, when subjects had to rely on an internalized forward model of myoelectric control to estimate cursor position. Our experiments suggest that the ability to use the novel proprioceptive signal for control was formed during an initial phase in which it was consistently supplied together with congruent visual information (VF+PF). This is remarkable, since equal performance levels in VF+PF and VF conditions indicate that artificial proprioception does not offer a significant benefit as long as visual feedback is available. Nevertheless, proprioceptive information about cursor position, supplied to the right arm, was successfully used for feedback control during the first trials of PF condition. This was not the case when, in experiment 2, artificial proprioception was only introduced when subjects already had to rely on it (PF condition). The sudden step in task-related performance in VF condition of experiment 2, after introducing artificial proprioception, might reflect a globally increased computational load caused by the integration of an additional feedback signal into myoelectric control. Implicit integration of artificial proprioception into sensorimotor control may have been helped by the fact that visual and proprioceptive information were supplied in a congruent manner, reflecting day-to-day experience and suggesting a pre-existing spatial map. Incongruent proprioceptive feedback in experiment 3 on the other hand could be used through training, but this learning process was only started when proprioceptive feedback had to be relied upon. This agrees with Pipereit et al. [4], who state that proprioception is not used in sensorimotor adaptation, when it conflicts with vision. Therefore we hypothesize that proprioceptive information in experiment 3, which was informative, but conflicted with a standard visuospatial map, was given little weight until visual feedback was removed (PF condition).

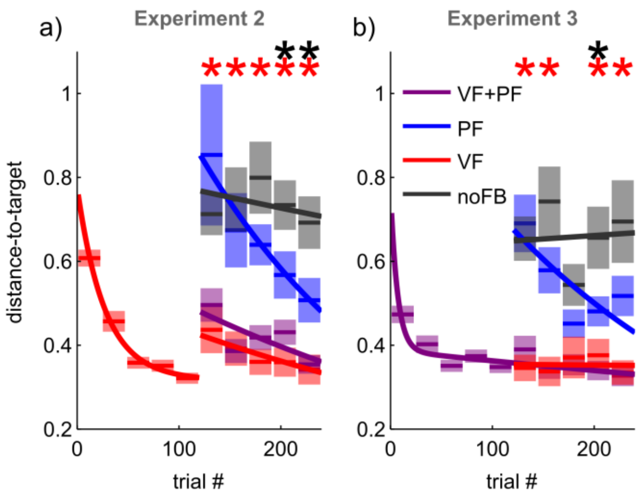

Figure 3: Learning in experiments 2 and 3 (cf. Fig. 2). (a) Experiment 2: familiarization phase with VF condition (instead of VF+PF). Fit for VF condition divided into a double exponential part for the familiarization phase and a separate exponential part for the test phase. (b) Experiment 3: artificial proprioceptive feedback mirrored at vertical midline. Control was switched to muscles 1DI and ECR to invalidate previously trained muscle mappings with APB and ADM in experiment 2.

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