A Novel Concept for a Prosthetic Hand with a Bidirectional Interface: A Feasibility Study

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A Novel Concept for a Prosthetic Hand with a Bidirectional Interface: A Feasibility Study

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Abstract—**A conceptually novel prosthesis consisting of a mechatronic hand, an electromyographic classifier and a tactile display, has been developed and evaluated by addressing problems related to controllability in prosthetics: intention extraction, perception and feeling of ownership. Experiments have been performed and encouraging results for a young transradial amputee are reported.**

Index Terms— **Prosthetics, EMG classification, mechatronic hand, tactile display, rubber-hand effect**

I. INTRODUCTION

A complete prosthetic hand system that allows voluntary action and provides sensory perception to the user, ideally consists of two components: (i) the dexterous and sensorized mechatronic hand, and (ii) the user-prosthesis interface (UPI), i.e. a system able to decode the user's intention into hand motions, and a sensory feedback system providing the user with enriched perception of the environment and the device.

Efferent UPIs have been investigated but traditional prosthetic hand control is still based on electromyographic (EMG) signal processing [1], and ideas for sensory substitution systems have been mainly based on electrotactile or vibrotactile feedback principles [2]. Commercial active prostheses are difficult to control mainly because of the limited bandwidth of the UPI communication link in both afferent and efferent pathways. The main sensory feedback available is the user's direct vision; no tactile or proprioceptive feedback is intentionally delivered to the amputee. Because of the effort required to control many EMG inputs simultaneously, only simple single-DoF (degree of freedom) hands seem to be accepted [3] and commercially available (e.g. OttoBock hands). These employ two recording channels that cover the (up to) 19 muscles activity from the residual limb; gathering more detailed information from the muscles is evident. Bad controllability often determines that prostheses are perceived by amputees as external devices and therefore abandoned [4]. Since a bidirectional interfaced prosthesis is not yet commercially available, many attempts have been made employing UPIs with different levels of invasiveness. Vibrotactile or electrotactile interfaces have been tested with the Ultralight hand [7], the MANUS [8], the Southampton hand, [9], the CyberHand [10], [11], and the Yokoi hand [12]. In [5] and [6] direct neural feedback and control of an artificial arm in amputees have been achieved using surgical implanted peripheral neural interfaces. Latest trends propose reinnervation procedures [13] to obtain a bidirectional link for control and perception. From an analysis of the state of the art and of amputees wishes [4] it is clear that the needs for easily controllable, and perceived (sensory and cognitively) prostheses able to restore grasping capabilities are huge.

The objective of this work was to develop an innovative, intuitively controllable prosthesis employing: (i) a multi-DoF, sensorized hand and (ii) an non-invasive UPI composed of a self-learning EMG classifier and an innovative tactile display. To measure its performance, acceptability and efficacy with an amputee, three main problems associated with the controllability and aspects of self-consciousness related to the feeling of ownership [14] of a prosthetic hand have been addressed. This paper presents the bidirectional hand platform developed, the experiments combined in a one-day intensive session, and the promising results of such experiments with a young transradial amputee.

II. MATERIALS, METHODS AND EXPERIMENTS

A. Prosthetic Hand Platform

A stand-alone version of the Cyberhand [10] was used (see Fig. 1). It has five underactuated fingers driven by six motors: five are employed for the independent flexion/extension of the fingers, plus one for the opposition of the thumb (detailed description in [10]). Integrated in the hand are position sensors (encoders) and tendon tension sensors (able to measure the grasp force for each finger [11]). Control loops

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(position/force) are embedded in a 8-bit microcontroller-based architecture and triggered by external commands from a standard RS232 bus.

B. *EMG Classification System*

Myoelectric signals are picked up from the forearm muscles on the residual limb by means of 8 pairs of surface electrodes (Ag/AgCl); signals are filtered (2nd order band-pass filter, bandwidth 3-1000 Hz), amplified (Gain 5000), sampled (at 10 kHz), and digitized (12-bits A/D-converter) by a data acquisition board (DAS16/330, Measurement Computing). A data-glove (Cyberglove, Virtual Technologies) with finger joint angle sensors, is fitted on the healthy hand and used for mapping EMG signals to hand movements (the wearer is instructed to perform synchronous movements with both healthy and phantom hands). A custom made application implementing (in Visual C++) local approximation using lazy learning [15] is responsible for such mapping (for details see [16]). After the training phase, where the system associates muscle activity to hand movements, the algorithm is used to predict (searching the nearest neighbor using the Euclidean distance) in real time hand movements, i.e. to control the prosthesis based on EMG signals (see Fig. 1E).

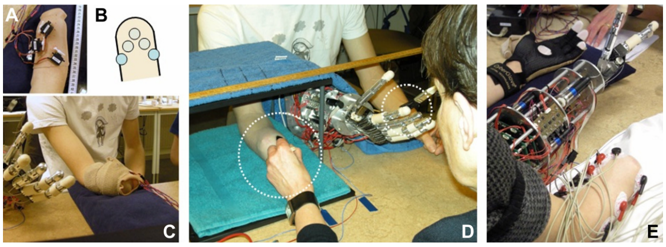

Fig. 1 Platform integration and experiments. A) The servos applied on the subject's residual limb. B) Scheme of the tactile display on the volar aspect of the residual limb. C)Tactile feedback experimental set-up. D) Rubber hand experimental set-up. E) Myoelectric control experimental set-up.

C. *Tactile Display*

The Tactile display consists of five servo motors (DS281, Graupner) controlled by a electronic system equipped with an RS232 interface making it possible to control it from a standard PC (see [17] for details). Buttons (12mm in diameter) at the end of the servo shafts exert a sustained pressure on the skin, activating mechanoreceptors, hence giving rise to a tactile sensation. Servos are placed on the volar aspect of the amputee's residual limb (Fig. 1A-B) in a pattern corresponding to the fingertips of the hand that is sensorically replaced [18], and are connected to the tendon force sensors of the robot hand in such a way that a stimulation of one of the robot fingers gives rise to a similar, but displaced, stimulation on the skin of the amputee.

D. *Participant & Order of Experiments*

The participant was a 23-year-old man who had a traumatic right-hand transradial amputation 16 cm below the elbow two years before; he was fitted with a 2 DoF EMG prosthesis (motorised hook and wrist). After giving informed consent he participated in three experiments as in the following order: (i) tactile feedback experiments, TFE, (perception); (ii) rubber-hand experiment, RHE, (feeling of ownership); (iii) myoelectric control experiment, MCE, (action). This order was chosen for practical reasons. The most tiring experiment, MCE, was performed last; it required 2-3 hours to be completed (correct placement of the electrodes, calibration of the systems, experimental session, electrodes removal) and was done after a one hour break (lunch time) from the others. Both the TFE (35-45 min) and the RHE (20-30 min) were done in the morning before the break.

E. *Tactile Feedback Experiments*

Sensory feedback delivery was investigated by stimulating the subject's residual limb (cf. Fig. 1C) with an indenting force proportional to the grasping force of the hand (based on tendon tension sensors). The idea was to evaluate how such feedback can be discriminated by the user and this study has focused on one participant evaluating following components:

Authors should consider the following points:

1) discrimination between stimulations applied on five different sites with a fixed level of pressure, FD;
2) discrimination between three pressure levels, PD (stimulations corresponding to a light touch, to holding, and to squeezing an object applied to a single site on the residual limb);
3) discrimination between five different combinations of sites and pressures, as for grasp discrimination: GD (these combinations where chosen to reflect sensation of five commonly used grasps in activities of daily life, ADL: lateral, tridigital, light/medium/strong cylindrical grasps implying the capability to discriminate different pressure level on different sites simultaneously).

The evaluation protocol for these was divided into a *training phase*, a *reinforced learning phase* and an *evaluating phase*. Training consisted of a sequence of random stimulations (50 in FD, 27 in PD, 15 in GD) of the residual limb while the subject was looking at a graphical displaying the properties (site and pressure) of the stimulations. This was done to make the subject familiar with the system. During reinforced learning sequences of random stimulations (50 in FD, 27 in PD, 15 in GD) were delivered while the subject was wearing a blindfold and earmuffs excluding the use of auditory and visual feedback. After each stimulation, the subject answered what he thought was the correct answer after which the operator revealed the correct one, reinforcing the learning process. The evaluation phase consisted of sequences of random stimulations (25 in FD, 21 in PD, 15 in GD) delivered while wearing a blindfold and earmuffs. Answers from the reinforced learning and evaluating phase were logged for later analysis.

F. *Rubber-Hand Experiment*

Aspects of body awareness for a complete functional substitution of the natural hand were explored: to this aim, attempts to induce the rubber-hand illusion employing the robotic hand were done. In the rubber-hand illusion [14], synchronous brushstrokes, applied to a rubber hand in full view and to the participant's real hand, which is hidden under a table or behind a screen, produce the experience that the touch is located on the rubber hand and that the rubber hand is one's own hand. The protocol used was adapted from [14]: the CyberHand and the skin of the subject's stump were simultaneously stimulated with a small brush (see Fig. 1D). For periods of 60 seconds, we exposed the participant to the illusion condition (synchronous brushstrokes) and a control condition (asynchronous touches), presented three times each. Before and after the stimulation trials, the participant was required to close his eyes and point to where he had felt the touches on a ruler mounted on the table. The pointing drift was calculated as the distance between the indicating index finger and the residual limb after the stimulation period minus the distance between the indicating index finger and the residual limb before the stimulation period. We then compared the "tactile drift" between the synchronous and asynchronous conditions. At the end the participant completed a questionnaire [14] with nine questions: three of them relate to the extent of feeling of "body ownership"; the other six questions serve as control for task compliance and "placebo effect". The participant had to rate these statements using a seven point scale where -3 meant "strongly disagree" and +3 meant "strongly agree" (0 meant uncertainty).

G. *Myoelectric Control Experiment*

Real-time control of a multi-DoF prosthesis through the use of an EMG classifier based on machine learning was investigated. The goal was to allow the subject to voluntarily perform seven hand movements and prehensile patterns useful in ADLs: thumb flexion; index finger flexion; thumb opposition; middle, ring, little finger flexion; long fingers flexion; tridigital grasp; lateral grip/key grip. Such movements were performed with the CyberHand in a natural position in front of the subject, and with the residual limb in a resting position (cf. Fig. 1E). The protocol was divided into two phases: the *training phase* (where the predictor is trained) and the *evaluation phase* (where the artificial hand is controlled by the predictor). In the *training phase*, the data-glove was used to record the movements of the contralateral hand as the subject was instructed to perform synchronously one of the movements with both his "hands" (the participant had to imagine that he was moving his phantom hand synchronously with the existing contralateral hand); meanwhile the EMG of the residual limb was recorded together with the hand positions for training the predictor. During the *evaluation phase* the subject was asked to perform one particular movement with his residual limb, and the EMG pattern was classified into one of the seven grasp types, which were executed by the CyberHand. Training data was cleared between each session since the subject got better at using his muscles with time; the procedure was repeated four times. Each movement consisted of a recording lasting for two seconds: if a movement had an Euclidean distance closest to a reference movement for more than 50% during the recording, then the movement is considered correctly classified (as in [16]).

III. RESULTS

A. *Tactile Feedback Experiments*

The results of the FD and the GD experiments are presented in Fig.2: the upper row presents the reinforced learning data (i.e. during training), while the lower row is related to the evaluation phases (i.e. after training). The X-axes denotes the stimulation applied by the tactile display, the Y-axes denotes the answer given by the subject; the area of circles represent the frequency of the answer related to that stimulation (based on 10 trials in the FD and 15 trials in the GD during reinforced learning phase, and based on 5 trials in the FD and 3 trials in the GD during the evaluation phase). The results of the PD experiment are 100% correct in both the experimental phases. The graphs show the subject's ability to discriminate stimulations related to different fingers (1-5 in the FD graphs) and to different grasps (a-e in GD graphs). The FD evaluation (after training) reported an overall success percentage of 68%, while the GD 87%. In the FD evaluation adjacent stimulation sites were occasionally confused between each other. The same happen in the GD evaluation. By comparing the results during and after training learning effects can be seen. In the FD experiment each different stimulation apart from stimulation no.5 (little finger), gets better recognized; nevertheless, since the little finger results gets worse, the overall success percentage doesn't really change: from 66% in reinforced learning to 68% in evaluation. In the GD experiment instead, improvements can be seen for each singular stimulation and also globally (from 67% to 87%). No learning is seen during the PD experiment.

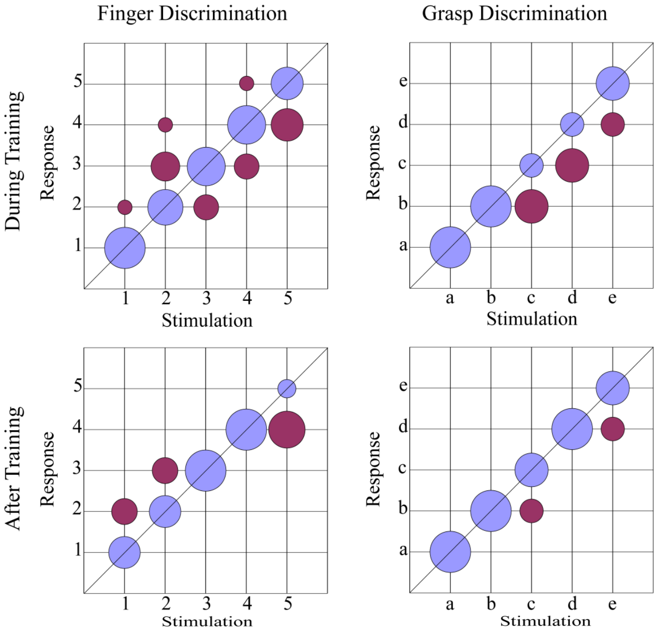

Fig. 2 Tactile feedback experiments results. In the FD graphs numbers refer to fingers, in the GD letters (a..e) refer to the five grips: lateral, tridigital, light /medium/strong cylindrical grasps. The X axes denote the stimulation, the Y axes the subject's answer. Correct answers lie on the traced straight line. FD

during learning graph is based on 10 trials for each finger stimulation. FD after training graph is based on 5 trials for each finger stimulation. GD graphs are based on 3 trials for each grasp stimulation.

B. *Rubber-Hand Experiments*

The subject had a strong illusion of sensory transfer: in the questionnaire, he rated the illusion with +2 on the three statements related to illusion and a score of -1, -3, -3, 0, -3, 0 on the six control statements. He indicated a pointing drift toward the prosthesis of 4.8 cm with synchronous stimulations and no drift (0 cm) with asynchronous stimulations. This difference reveals behavioral evidence for the illusion that could not be biased by task compliance or suggestibility (cf. [19] for details).

C. *Myoelectric Control Experiments*

Table 1 shows correct classification percentage for each movement in four consecutive evaluation phases; percentages are based on three trials for each movement in each evaluation step. The table points out two issues. Firstly, performances get better with training; this is true in general (the “Mean” value increases from 67% in the first evaluation phase to 95% in the last one) and for each singular movement (apart from movement A, thumb flexion). Secondly, after three trainings i.e. Evaluation 3 in the table, controllability becomes very high with success percentage above 90%. Such excellent results are confirmed by the positive opinion on the system conveyed by the subject.

TABLE I
MYOELECTRIC CONTROL EXPERIMENT

Movement	ID	Eval. 1 [%]	Eval. 2 [%]	Eval. 3 [%]	Eval. 4 [%]
Thumb flexion	A	100	100	100	67
Index flexion	B	67	33	67	100
Thumb opposition	C	67	67	100	100
MRL fiuger flexion	D	100	100	100	100
Long finger flexion	E	0	0	100	100
Tridigital grasp	F	100	100	67	100
Lateral grip	G	33	67	100	100
Mean		67	67	90	95

Success percentage in the four evaluation phases for the 7 movements. MRL is middle, ring, little. Percentages are based on 3 trials for each movement in each evaluation step. Mean is the average percentage of all movements in each evaluation phase (based on 21 movements).

IV. DISCUSSION

The proposed prosthesis presents several innovations with respect to the state of the art. The force information is transferred without altering its physical principle (as in previous systems [2]): i.e. a force stimulation on the hand is delivered as a force stimulation on the residual limb. This approach seems to be correctly perceived, but its potential impact is higher considering if the actuators were directly placed on perceived phantom fingers [20]. All the algorithms implemented are embeddable in a low power portable device. The hand may also be reduced in size and the inherent modularity permits to easily replace components or algorithms. The potentials of this concept are preliminary shown by the results achieved in the experiments.

The results of the TFE are not statistically significant but very encouraging: the evaluating phases report success percentages of 68%, 100% and 87% in FD, PD and GD respectively. Such results have been achieved after a short training procedure (less than 20 minutes). Misclassified responses can be explained considering the short distance (about 2 cm), which is on the limit of classical two-point discrimination of the forearm [21], between consecutive buttons on the residual limb (relating to consecutive sites): when misclassified, in the FD, sites have been confused with adjacent ones both during the reinforced learning (95% of cases) and the evaluation phases (100%). For similar reasons the GD misclassified trials have been confused with neighboring tactile patterns; interestingly GD misclassification is polarized; i.e. stronger cylindrical grips are (wrongly) recognized as lighter ones, and light cylindrical grasps as tridigitals; never vice-versa. In other words the subject has never “felt” more information than what was delivered. The TFE globally reported interesting results (85% correct answers), i.e. a promising start-point towards the achievement of a practical feedback system. The case study suggests that the rubber hand illusion can be induced in amputees using a robotic hand prosthesis. This referral of somatosensory sensations using multisensory illusions may play an important role in the training process necessary to establish useful sensory functions in hand prostheses. Outcomes from MCE are preliminary but significant: after three trainings misclassification has occurred only in 5% of trials; in particular, only thumb flexion has been confused (once) with thumb opposition. Results should be contextualized within experimental conditions far from real life: all movements were performed with the stump in a resting position (due to dimensions of the prototypes). Since the subject achieved great control, after the MCE, we tried to combine the experiments: we wanted to see if the rubber hand illusion could be produced as the subject controlled the CyberHand. He was instructed to observe the movements of the robotic hand he voluntarily and freely generated. We tested this while he simply “moved” the artificial hand and looked at it and while adding simultaneous brushings (simulating the tactile feedback). This combined experience supports a transfer of somatic sensations and ownership onto the prosthesis, higher when the controlled movements were supplemented by the synchronous brushings, but interestingly, even when no brushing was employed ([19] for details). This experience suggests that a strong sense of ownership (key element for an accepted prosthesis) may occur with the combination of three components: (i) a dexterous, sensorized and anthropomorphic prosthesis (traditional 1-2 DoF prosthesis are felt as external devices and abandoned [4]), (ii) good –and multi-DoF- controllability, (iii) a feedback system that delivers synchronous stimulation with the tactile events on the artificial hand. This actually confirms the bioengineering definition of the ideal prosthesis given in the introduction. The subject was really satisfied with the higher degree of functionality offered to him by the platform, and of his performances during experiments. He was hopeful for future developments of this research and the outcomes of this experience have traced guidelines for future work. Hardware must be reengineered: i.e. a lightweight anthropomorphic transradial hand connected to a socket with embedded EMG and tactile systems must be developed. Such a system, by inducing sensory transfer could be felt as part of amputees body. Moreover it will allow testing ADLs in a real life scenarios (e.g. cooking in a kitchen) with a large group of users, and will act as test bench for the investigation of practical EMG control algorithms, i.e. the bottle-neck of the whole system.

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