INVENTEURS DU MONDE NUMÉRIQUE

Montpellier le 14 février 2018

CAMIN
Inria, Université de Montpellier
860 Rue Saint Priest
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Objet : Lettre de recommandation

Nous, soussignés, Christine Azevedo Coste et David Guiraud, directeurs de thèse de Mme Wafa Tigra souhaitons lui apporter tout notre soutien concernant sa candidature au prix de thèse IFRATH. En effet, Wafa a montré durant ces trois années, une implication tout à fait impressionnante dans son travail de recherche mais aussi dans son activité d'enseignement. Nous avons pu apprécier ses compétences pédagogiques au travers de nombreux exposés scientifiques au sein de l'équipe ou à l'extérieur, en français, en anglais, très pointus scientifiquement ou au contraire très vulgarisés (fête de la science notamment). Elle a d'ailleurs obtenu la qualification en 61ième section CNU.

Coté scientifique, son travail de thèse démontre une pluridisciplinarité réelle. Les rapports de thèse ainsi que les publications dont une en journal sélectif (IEEE TNSRE), attestent par l'évaluation des pairs, un travail reconnu et d'excellent niveau en tout juste 3 ans de thèse. D'un point de vue humain, Wafa a su gérer la complexité de mise en œuvre de protocoles cliniques avec tout ce que cela implique, demande CPP-ANSM puis mise en œuvre concrète en clinique (un au bloc opératoire, un en clinique spécialisée). Son travail sur la restauration de la préhension chez les tétraplégiques par stimulation neurale sélective implantée, reste un sujet central de l'équipe car son travail pionnier en a démontré la faisabilité. D'ailleurs deux autres journaux sont en préparation dont un, on l'espère dans une revue de prestige puisque nous sommes les seuls à proposer une stimulation neurale sélective implantée pour restaurer cette fonction. Ces recherches s'inscrivent directement dans la thématique handicap et en particulier pour les déficiences sensori-motrices sévères, ici la tétraplégie complète, sans alternative thérapeutique.

Elle est actuellement accueillie dans l'équipe de recherche clinique de la société Integrum sous la responsabilité du Pr. Max Ortiz Catalan. Il travaille sur la commande de prothèses robotisées pour amputés avec retours sensoriels par stimulation des voies afférentes. Ce groupe (Integrum et l'université de Chalmers) est mondialement connue et elle a été sélectionnée pour un poste important lié aux essais cliniques.

La thèse était financé par un industriel (thèse CIFRE) qui a demandé deux ans d'embargo sur la publication du manuscrit (mais ne nous a pas restreint sur les publications scientifiques non techniques), temps qu'il a jugé nécessaire pour prendre une décision sur un éventuel développement d'un produit industriel dans un domaine il est vrai, très concurrentiel. Cet embargo prend fin en décembre de cette année. Cela montre la qualité des résultats obtenus y compris dans une perspective applicative dans un avenir à moyen terme.

Pour toutes ces raisons, nous soutenons sans réserve la candidature de Mme Wafa Tigra.

Pour valoir ce que de droit

Dr David GUIRAUD

DR. Christine AZEVEDO COSTE

Résumé de la thèse

Wafa Tigra

15 février 2018

La stimulation électrique fonctionnelle implantée (SEF) est utilisée avec succès dans un nombre croissant d'applications, incluant les pacemakers, la stimulation cerveau profond, le contrôle de la douleur et la restauration de l'audition. De plus, seuls les dispositifs utilisant la SEF permettent de restaurer des mouvements dans un contexte d'usage quotidien. Des tentatives d'utilisation de cette technologie ont été faites pour la rééducation fonctionnelle ou la récupération de fonctions (préhension, déambulation) chez des personnes paraplégiques et tétraplégiques [1, 2, 3, 4, 5]. Cependant, pour les fonctions motrices complexes, cette technologie a rarement atteint le stade de la production industrielle et de la commercialisation, exception faite, pour le système Freehand® (NeuroControl Corporation, USA), pendant une courte période. Ce dispositif implanté sur plus de 300 personnes tétraplégiques, a prouvé que les bénéfices pour les patients pouvaient être très importants puisqu'il permet d'effectuer des mouvements de préhension palmaire et latérale pour les patients tétraplégiques via un stimulateur implanté à 8 canaux contrôlé par l'épaule opposée [6, 7]. Les patients semblent être satisfaits de cette solution palliative qui améliore la qualité de la vie quotidienne. Toutefois ce système unique n'est plus commercialisé depuis 2001. Bien que ses bénéfices fonctionnels fussent importants, ce dispositifs présentait des carences au niveau de la commande et des fonctionnalités offertes. De plus, certaines limitations pourraient être corrigées au regard des progrès technologiques récents.
Afin de développer des neuroprothèses implantées viables comme solutions palliatives pour les personnes atteintes d'handicaps moteurs, trois grands défis doivent être abordés, parmi lesquels :

— l'intégration des paramètres de commande de la neuroprothèse dans un modèle numérique [8]
— une stimulation sélective neurale, et
— la construction de dispositifs de mesure (pour le contrôle de la stimulation) de petite taille, fiables, sûrs et faciles à implanter.

L'implantation du capteur permettra une utilisation autonome du système par les patients ce qui ne fut pas le cas pour le système Freehand® puisque celui-ci nécessitait l'intervention quotidienne d'une aide humaine pour son positionnement sur l'épaule.

Ce travail de thèse, basé sur le succès du système Freehand® a proposé une approche originale basée sur (i) une stimulation sélective nerveuse (à l'aide d'une électrode gouttière multi contact) pour rétablir des mouvements de préhension chez des sujets tétraplégiques et (ii) l'utilisation de signaux émanant de muscles supra lésionnels pour le contrôle ergonomique de cette stimulation. La première

partie de la thèse a été dédiée à la rédaction des deux protocoles expérimentaux (étude de la stimulation implantée et étude des possibilités de contrôle du patient). Ceux ci ont été soumis à un comité de protection des personnes ainsi qu'à l'autorité compétente. Une fois l'aval du comité de protection des personnes Sud Méditerranée IV et de l'Agence Nationale de Sécurité du Médicament et des produits de santé reçu, des expérimentations humaine en per-opératoire et en ambulatoire ont été mises en place de façon à valider certains points clefs (stimulation neurale, mesure implantée, contrôle. . .). Des experimentations animales ont précédé celles ci. La seconde étape a consisté à mettre au point les algorithmes de traitement temps réel du signal enregistré par des capteurs EMG et inertiels. L'objectif étant d'évaluer les capacités des patients à contrôler leurs mouvements et contraction de façon dirigée, fine et graduée. La validation a été faite au travers d'une main robotique (Shadow hand®) avec laquelle le patient a interagi via ses mouvements et contractions musculaires résiduels. Une validation expérimentale basée sur une stimulation électrique de surface a conclu cette étape.

1 Résultats obtenus

Les expérimentations humaines et animales réalisées en conditions aiguës ont démontré la faisabilité de notre approche. Ainsi, la stimulation du nerf sciatique par notre électrode gouttière a permis d'activer sélectivement plusieurs muscles antagonistes chez les 5 animaux inclus dans l'étude. Une sélectivité intra fasciculaire est retrouvée chez 3 des 5 animaux. La stimulation des nerfs médian et radial chez six sujets tétraplégiques a permis d'activer **sélectivement** les muscles permettant une :

- chez le patient I : flexion du poignet
- chez le patient II : extension du pouce, extension des doigts, une extension simultanée du poignet était également possible
- chez le patient III : flexion du coude, supination, extension du poignet
- chez le patient IV : extension du poignet, extension du pouce, extension des doigts
- chez le patient V : supination, flexion du coude, extension du poignet, une extension simultanée du poignet, des doigts et du coude était également possible
- chez le patient VI : prehension latérale ou "key grip", flexion des doigts, opposition du pouce

Concernant le contrôle de la neuroprothèse, nous avons mis en évidence chez les 13 sujets tétraplégiques ayant participé aux expérimentations, une combinaison de muscles pouvant être utilisée pour piloter facilement une main robotique ou sa propre main. Des contractions continues ou gradées de ces muscles peuvent être maintenues et ce, sans aucun apprentissage ou entrainement préalable. Les modalités de contrôle et les muscles préférentiels sont "sujet-dépendant".

Ainsi, sur la base des spécifications fonctionnelles révélées à la fin de la thèse, il a été démontré qu'un système totalement implantable permettant de rétablir des mouvements de prehension et comprenant un nombre limité de composants pouvait être élaboré.

Ce travail a été développé en co-direction avec Charles Fattal (MD, PhD, Médecin Chef de Service Centre de Rééducation Fonctionnelle DIVIO Dijon), Anthony Gelis (MD, Centre Neurologique Propara, Montpellier, spécialisé dans les patients atteints de blessures de la moelle épinière), Jacques Teissier (Chirurgien orthopédique ayant implanté 6 des 7 systèmes FreeHand® en France, Clinique Beau Soleil, Montpellier), Bertrand Coulet (Chirurgien Orthopédique, CHU Lapeyronie, Montpellier) et le groupe MXM (conception de l'implant et commercialisation, Sophia Antipolis).

Références

[1] N. J. Rijkhoff, "Neuroprostheses to treat neurogenic bladder dysfunction : current status and future perspectives," *Child's nervous system*, vol. 20, no. 2, pp. 75–86, 2004.

[2] P. Taylor, J. Esnouf, and J. Hobby, "The functional impact of the freehand system on tetraplegic hand function. clinical results," *Spinal Cord*, vol. 40, no. 11, pp. 560–566, 2002.

[3] R. Kobetic, R. J. Triolo, J. P. Uhlir, C. Bieri, M. Wibowo, G. Polando, E. B. Marsolais, J. Davis, K. A. Ferguson, and M. Sharma, "Implanted functional electrical stimulation system for mobility in paraplegia : a follow-up case report," *Rehabilitation Engineering, IEEE Transactions on*, vol. 7, no. 4, pp. 390–398, 1999.

[4] K. Von Wild, P. Rabischong, G. Brunelli, M. Benichou, and K. Krishnan, *Computer added locomotion by implanted electrical stimulation in paraplegic patients (SUAW)*. Springer, 2002.

[5] R. Davis, T. Houdayer, B. Andrews, S. Emmons, and J. Patrick, "Paraplegia : prolonged closed-loop standing with implanted nucleus fes-22 stimulator and andrews' foot-ankle orthosis," *Stereotactic and functional neurosurgery*, vol. 69, no. 1-4, pp. 281–287, 1997.

[6] B. Smith, P. H. Peckham, M. W. Keith, and D. D. Roscoe, "An externally powered, multichannel, implantable stimulator for versatile control of paralyzed muscle," *Biomedical Engineering, IEEE Transactions on*, no. 7, pp. 499–508, 1987.

[7] B. Smith, Z. Tang, M. W. Johnson, S. Pourmehdi, M. M. Gazdik, J. R. Buckett, and P. H. Peckham, "An externally powered, multichannel, implantable stimulator-telemeter for control of paralyzed muscle," *Biomedical Engineering, IEEE Transactions on*, vol. 45, no. 4, pp. 463–475, 1998.

[8] R. Robert, "Model–based development of neuroprostheses for paraplegic patients," *Philosophical Transactions of the Royal Society B : Biological Sciences*, vol. 354, no. 1385, pp. 877–894, 1999.

Wafa TIGRA – Docteure en Systèmes Automatiques et Microélectroniques (Génie biomédical)

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Thèmes de recherche

Recherche clinique - Stimulation électrique fonctionnelle nerveuse - Neuroprothèse - Préhension – Interface Homme-Machine - Tétraplégie - Amputation - Retour sensitif

Diplômes

Doctorat en Systèmes Automatiques et Microélectroniques — *Novembre 2013-Décembre 2016, Montpellier (34)*
"Assistance à la préhension par stimulation électrique fonctionnelle chez le sujet tétraplégique"

Master Physique Biomédicale — *Septembre 2011-Juillet 2013, Montpellier (34)*

Licence de Biologie, Physiologie et Neuroscience — *Septembre 2008-Juin 2011, Montpellier (34)*

Baccalauréat Scientifique — *Juin 2007, Nîmes (30)*

Compétences complémentaires

Physique expérimentale/Méthodes d'imagerie biomédicale : microscopie optique (transmission, fluorescence,…), IRM, TEP, SPECT
Biologie : électrophysiologie (EMG, ENG, EEG), techniques d'analyse biochimique : southern blot et ses dérivés, chromatographie, spectrophotométrie, immunofluorescence
Formation expérimentation animale (niveau 1)
Informatique : Matlab, R, Python, HTML, CSS, LaTeX, Pack Office, ImageJ, NEURON, SPATCH
Langues : Anglais (courant : lu, écrit, parlé), Espagnol (scolaire)

Activités de recherche et développement

PostDoc (Suède-2018) : projet Osseointegration Human Machine Gateway porté par le Pr Max Ortiz

PhD/PostDoc (France-2013-2017) : Après un questionnaire portant sur les attentes et les besoins de la population tétraplégique que j'ai construit et administré auprès de la population tétraplégique du centre Propara pour blessé médullaire à Montpellier, j'ai effectué une étude de la littérature portant sur les neuroprothèses du membre supérieur disponibles pour le sujet tétraplégique. Mon sujet de thèse s'est construit sur les résultats émanant de ces deux études. Ainsi, le but de ma thèse a été de proposer une approche originale pour le rétablissement de mouvements de préhension. Cette approche est basée sur une stimulation électrique nerveuse et l'utilisation de signaux EMG émanant de muscle supra lésionnels pour le contrôle de cette stimulation. Cette approche permet d'une part de limiter le nombre de composants implantés et les risques liés à la présence de ces composants et d'autre part de proposer un mode de pilotage ergonomique permettant d'augmenter l'acceptabilité de ces dispositifs et donc l'observance des sujets. Ces deux parties distinctes mais indispensables à la fourniture d'un dispositif complet m'ont amenées à monter aux cours de ces années de thèse, deux protocoles expérimentaux qui ont nécessité l'accord d'un comité de protection des personnes (CPP) et de l'agence nationale de sécurité des médicaments et des produits de santé (ANSM). Cette thèse pluridisciplinaire a été effectuée au sein de l'équipe CAMIN de l'INRIA et de l'entreprise MXM (thèse CIFRE). Deux articles journaux et deux articles « conférence » ont émanés de ces travaux de thèse:

Tigra, W et al. **A novel EMG interface for individuals with tetraplegia to pilot robot hand grasping. IEEE on Trans Neural Syst Rehabil Eng. 2016** DOI: 10.1109/TNSRE.2016.2609478

Tigra, W et al**. Exploring Selective Neural Electrical Stimulation for Upper Limb Function restoration on European J Transl Myology 2016 26(2)** DOI: 10.4081/ejtm.2016.6035

Tigra, W et al. **Exploring selective neural electrical stimulation for upper limb functions restoration** (Présentation orale, Juin 2016). In *IFESS: International Functional Electrical Stimulation Society*.

Tigra, W et al. **Ergonomics of the control by a quadriplegic of hand functions (Poster).** Neural Engineering (NER), 2015 7th International IEEE/EMBS Conference on **DOI:** 10.1109/NER.2015.7146734

Mon stage de M1 a consisté à étudier, via IRM et SRM, les effets de l'hypertrophie musculaire induite pharmacologiquement sur la fonction et le métabolisme énergétique du muscle squelettique chez des souris atteintes de myopathies. Il a eu lieu au *Centre de Résonance Magnétique Biologique et Médical* (CRMBM), Marseille.

Activités d'enseignement

A l'Université de Montpellier (UM), j'ai effectué un service de 123 heures d'enseignement, devant des publics différents et à des niveaux variés : en Licence Biologie, en Master STIC pour la Santé et en École d'Ingénieurs PEIP-STI (Polytech' Montpellier). A l'Université de Nîmes (UNIMES), j'ai effectué un service de 205 heures d'enseignement, devant les étudiants inscrits en Licence 1 Sciences et Vie et L1 Mathématiques Informatique, Mathématiques Physique et Mathématiques Physique Préparation Concours (CUPGE).
Je liste ici l'ensemble des enseignements que j'ai dispensés, classés par Unité d'Enseignement (U.E.).
-Electromagnétisme-Optique (TD, 25h)
-Electromagnétisme-Transports-Optique (TP, 180h)
-Outils Informatiques (TP, 117h)
-Neuroprothèse et Robotique Médicale (CM, 6h)
-Electromagnétisme-Optique-Mécanique (TD, 25h)
L'ensemble des TP a été accompagné de corrections des rapports. J'ai également effectué des surveillances d'examens pour l'UE Outils Informatiques.
Enfin, j'ai eu l'occasion d'encadrer un étudiant ingénieur provenant de l'ENSEIRB-MATMECA (Bordeaux) pour son projet de fin d'étude et deux étudiantes de Licence 3 Biologie pour leur projet de fin de licence.

Investissement dans la vie du laboratoire

Représentante des doctorants (membre du conseil de l'école doctorale I2S, 2016)
Organisation et participation à la fête de la science, Antibes (octobre 2015).
Co - organisation de la conférence des doctorants (DOCTISS 2015), UM, juin 2015
Participation à l'organisation de la conférence « 7^{th} Neural Engineering » (2015, Montpellier. Accueil des participants et encadrement d'événement social).

A novel EMG interface for individuals with tetraplegia to pilot robot hand grasping

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***Abstract*—This article introduces a new human-machine interface for individuals with tetraplegia. We investigated the feasibility of piloting an assistive device by processing supra-lesional muscle responses online. The ability to voluntarily contract a set of selected muscles was assessed in five spinal cord-injured subjects through electromyographic (EMG) analysis. Two subjects were also asked to use the EMG interface to control palmar and lateral grasping of a robot hand. The use of different muscles and control modalities was also assessed. These preliminary results open the way to new interface solutions for high-level spinal cord-injured patients.**

***Index terms*—** Control, electromyographic (EMG), grip function, robot hand, tetraplegia.

I. INTRODUCTION

Consequences of complete spinal cord injury (SCI) are often devastating for patients. This observation is particularly true for trauma at cervical levels (tetraplegia), since this impedes the use of the four limbs. Indeed, a complete SCI prevents any communication between the central nervous system and the sub-lesional peripheral nervous system, which receives no cervical commands. However, moving paralyzed limbs after such trauma is still possible, as for example when sufficient electric current is applied. Cells (neurons or myocytes), are then excited and generate the action potentials responsible for muscle contraction [1],[2],[3],[4]. Nevertheless, the interaction of the tetraplegic person with his/her electrical stimulation device, to control the artificial contractions and achieve a given task at the desired instant, is still problematic. The reason is that both the range of possible voluntary movements, and the media available to detect intention, are limited. Various interface types have therefore been tested in recent years. For lower limbs, these interfaces include push buttons on walker handles in assisted-gait [5], accelerometers for movement detection in assisted-sit-to-stand [6], electromyography (EMG) [7] and evoked-electromyography (eEMG) [8] and, most recently, brain computer interfaces (BCI) [9]. For upper limbs (restoring hand movement), researchers have proposed the use of breath control, joysticks, electromyography (EMG) [10], shoulder movements [11], and voluntary wrist extension [12]. In this last work, a wrist osseointegrated Hall effect sensor implant provided the functional electrical stimulation (FES) of a hand neuroprosthesis. Keller et al. proposed using surface EMG from the deltoid muscle of the contralateral arm to stimulate the hand muscles [13]. In [14], the EMG signal from the ipsilateral wrist extensor muscles was used to pilot a hand neuroprosthesis. An implanted device [15] took advantage of the shoulder and neck muscles to control the FES applied to the arm and hand muscles. EMG signals were also used to control an upper limb exoskeleton in [16].

Orthotics and FES can be effective in restoring hand movements, but the piloting modalities are often unrelated to the patient's level of injury and remaining motor functions, making the use of these devices somewhat limited. We believe that poor ergonomics and comfort issues related to the piloting modes also explain this low usage. In this paper, we therefore present a control modality closely linked to the patients remaining capacities in the context of tetraplegia.

We propose here to evaluate the capacity and comfort of contracting supra-lesional muscles [17], and assess the feasibility of using EMG signals as an intuitive mode of controlling of functional assistive devices for upper limbs. In this preliminary study, we focus on the comfort and capacity for contracting four upper limb muscles (trapezius, deltoid, platysma and biceps) in individuals with tetraplegia. We then investigate the feasibility of using these contractions to control the motions of a robot hand.

A robot hand was preferred to conventional grippers since it allows manipulators or humanoids to handle complex shaped parts or objects that were originally designed for humans, at the cost of more sophisticated mechanical designs and control strategies [18],[19]. Recently, robot hand usage has been extended to the design of prostheses for amputees, under the control of brain-computer interfaces [20], or EMG signals [21],[22],[23],[24]. However, to our knowledge, surface EMG signals (in contrast to neural signals [25],[26]) have never been used by tetraplegic individuals to pilot robot hands. CWRU [7], for example, used EMG signals to pilot the patient's own hand through FES, whereas Dalley et al. [27] used EMG within a finite state machine to control a robot hand, but with healthy subjects. Furthermore, in most of the cited works, a single motor was used to open or close a finger, a design constraint that impedes precise hand postures and grasps. Using a fully dexterous robot hand allowed us to further investigate the possibilities of an EMG interface to control different grasping modalities owing to the visual feedback provided by the robot hand. Furthermore, the dimensions and degrees of freedom are very close to those of the human hand, therefore providing the user an intuitive representation of the final movement that he/she can control with, for example, FES-based hand movement restoration. The goal of the study was two-fold: (i) to assess the ability of tetraplegic patients to pilot a robot hand device via muscle contractions even though the contractions are not functional. The EMG signals came from

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supra-lesional muscles that can be very weak and unable to produce any movement; and (ii) to compare different control modalities.

In the following section, we present the protocol and experimental setup. We then present the results on the efficacy and comfort of the continuous or graded contraction of different muscles, along with details on the participants capacity to pilot the robot hand using these contractions.

II. Material and Methods

A. Subjects and selected muscles

The study was conducted during scheduled clinical assessments at the Propara Neurological Rehabilitation Center in Montpellier, France. Thus, the experiments had to be of limited duration. The subjects were informed verbally and in writing about the procedure and gave their signed informed consent according to the internal rules of the medical board of the Centre Mutualiste Neurologique Propara. The experiments were performed with five tetraplegic male subjects with lesional levels between C5 and C7 (see Table I). Subject 2 had undergone muscle-tendon transfer surgery at the time of inclusion.

Surface BIOTRACE Electrodes (Controle graphique S.A, France) were used for EMG recordings. Pairs of surface-recording electrodes (1cm distance) were positioned above the four muscles on each body side. Subjects did not receive any pre-training before these experiments. They were only instructed on the movements for contracting the various muscles.

TABLE I
Subject characteristics

Subject ID	Age	Level of the lesion	AIS[1] score	Interval time since SCI (years)
1	33	C6	A	4
2	35	C7	A	13
3	21	C7	A	0,5
4	48	C5	A	32
5	45	C6	C	4

As the muscles selected to control hand grasp devices are likely to be used in a daily context by tetraplegic subjects, these muscles should be under voluntary control. The targeted tetraplegic patients had no muscle under voluntary control under the elbow. The use of facial muscles to pilot a hand grasp device has never been studied because social acceptability would probably be problematic. In addition, muscle synergies were sought (e.g., hand closing could be linked to elbow flexion, as performed via the biceps or deltoid muscle). For these reasons, we chose to study the EMG activity of four upper arm muscles (right and left): the middle deltoid, the superior trapezius, the biceps and the platysma. Nevertheless, there were slight differences in these eight muscles based on each subjects remaining ability. EMG signals are initially recorded on the ipsilateral and contralateral sides of the dominant upper limb.Yet, patients 1 and 3 showed signs of fatigue and they did not use the contralateral (left) limb. The superior trapezius, middle deltoid, biceps and platysma muscles of the ipsilateral side of the dominant (right) upper limb were thus studied for these subjects. For subjects 2 and 4, both (left and right) superior trapezii, middle deltoids, bicepses, and platysmas were considered. For patient 5, the deltoid was remplaced by the middle trapezius, which has a similar motor schema, since strong electrocardiogram signals were observed on the deltoid EMG signal. To guarantee that the selected EMG would not impede available functionality, the patients' forearms were placed in an arm brace and EMGs signals were recorded with quasi-isometric movements.

[1]The ASIA (American Spinal Injury Association) Impairment Scale (AIS) classifies the severity (i.e. completeness) of a spinal cord injury. The AIS is a multi-dimensional approach to categorize motor and sensory impairment in individuals with SCI. It identifies sensory and motor levels indicative of the most rostral spinal levels, from A (complete SCI) to E (normal sensory and motor function) [28].

B. EMG processing

Surface EMG signals were recorded with an insulated National Instrument acquisition card NI USB 6218, 32 inputs, 16-bit (National Instruments Corp., Austin, TX, USA). BIOVISION EMG amplifiers (Wherheim, Germany) were used, with gain set to 1000. The acquisition card was connected to a battery-run laptop computer. The acquisition was made at 2.5kHz.

For the first three subjects, the data processing was offline: EMG data were filtered with a high-pass filter (20Hz, fourth-order Butterworth filter, 0 phase). Then, a low-pass filter was applied to the absolute value of the EMG to obtain its envelope (2Hz, fourth-order Butterworth filter). The data processing was online for the other two subjects in order to control the robot hand motion. We applied the same filtering except for the first filter, which had a non-zero phase. In all cases, the filtered EMG signal is denoted with $s(t)$.

A calibration phase was performed for each muscle's EMG. Subjects were asked to first relax the muscle and then to strongly contract it. The corresponding EMG signals were stored and post-processed to obtain the maximum envelope. The thresholds were then set as a proportion of the normalized value of the EMG signal (value for a maximal contraction = 1). The high and low thresholds were experimentally determined to $s_L = 0.3 \pm 0.1$ and $s_H = 0.44 \pm 0.14$ through the calibration process, in order to avoid false detection against noise, while maintaining them as low as possible, to require only a small effort from the patient. These thresholds, s_L and s_H ($s_H > s_L > 0$), were used to trigger the states of the robot hand finite state machine (FSM), as explained below.

FSMs have been used in some myoelectric control studies, mostly on healthy or amputees subjects, but never with tetraplegic subjects [27]. In our study, the goal was to determine whether the muscles in the immediate supra-lesional region could be used by tetraplegic patients to control a robot hand. We relied on myoelectric signals, even from very weak muscles that were unable to generate torque sufficient to pilot the hand. As we controlled only three hand states through event-triggered commands, an FSM was appropriate. On the contrary, EMG pattern recognition is mostly used to progressively pilot several hand movements from many sensors.

TABLE II
DESCRIPTION OF THE FIVE HAND CONTROL MODES

Mode n^o	Description
1	Continuous muscle contraction provokes grasping. When the muscle is relaxed, the hand opens.
2	A first contraction of 2 s triggers grasping. The hand remains closed even when the muscle is relaxed. The next 2 s contraction triggers hand opening.
3	Grasping is related to EMG amplitude (stronger EMG signal leads to tighter closure). When the muscle is relaxed, the hand opens.
4	Contracting (for 2 s) first muscle 1 causes palmar pinch (palmar grasping); then, the hand can be opened by contracting (for 2 s) muscle 2. Instead, contracting first (for 2 s) muscle 2 causes key-grip (lateral grasping), followed by hand opening if muscle 1 is contracted (for 2 s).
5	Contraction of muscle 1 causes a palmar pinch, whereas contraction of muscle 2 causes key-grip. In both cases, to stop the closure, subjects must stop muscle contraction (cf. Fig. 1).

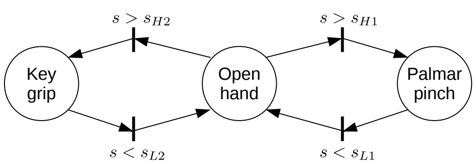


Fig. 1. Finite state machine used to control the hand in Mode 5.

C. Robot hand control

We chose to use the robot hand since it gives patients much more realistic feedback on task achievement (via grasp of real objects) compared to a virtual equivalent (e.g., a simulator). With a real (yet robot) hand, patients can perform the task as if FES had been used on their hand. The Shadow Dexterous Hand (Shadow Robot Company, London, UK) closely reproduces the kinematics and dexterity of the human hand. The model used here is a right hand with 19 cable-driven joints (denoted by angle $\mathbf{q}_i$ for each finger $i = 1, \ldots, 5$): two in the wrist, four in the thumb and little finger, and three in the index, middle and ring fingers. Each fingertip is equipped with a BioTac tactile sensor (SynTouch, Los Angeles, CA, USA). These sensors mimic human fingertips by measuring pressure, vibrations and temperature. The hand is controlled through ROS[1], with the control loop running at 200Hz.

In this work, the hand could be controlled in five alternative modes, shown in Table II. Each mode corresponds to a different FSM, and the transitions between states are triggered by muscle contractions and relaxations. Three hand states were used: open hand, palmar pinch, and key-grip (see Fig.2). Unlike the other modes, mode 3. is not an "all–or–nothing" closing, but allows progressive closing, according to the amplitude of the EMG signal. To begin grasping, contraction has to

[1]http://www.ros.org

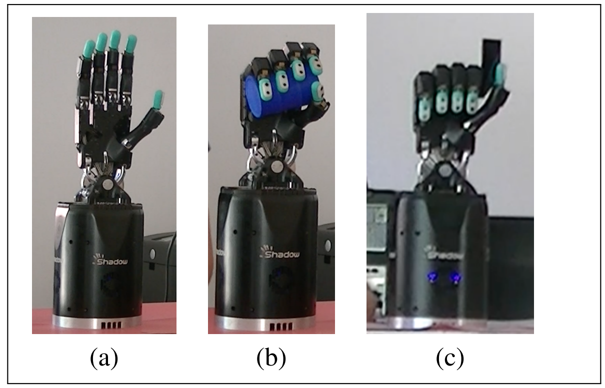


Fig. 2. Different states of the robot hand: (a) open hand, (b) palmar pinch (palmar grasping), (c) Key-grip (lateral grasping).

be above the first chosen threshold, and then the finger position is proportional to the EMG envelope amplitude. One muscle is monitored in modes 1 to 3, and two muscles in modes 4 and 5 (see Table II). Hysteresis was used: we considered a muscle contracted if $s(t) > s_H$ and relaxed if $s(t) < s_L$. For $s(t) \in [s_L, s_H]$, the muscle (hence, hand) state is not changed. In modes 1-3, only one – predetermined – grasp (palmar) was used, whereas in modes 4 and 5, the user was able to change the grasp (palmar/lateral) type online via the EMG signal. Each state was characterized by the five finger target joint values, $\mathbf{q}_i^*$. In all modes, except for mode 3, these were pre-tuned offline to constant values (corresponding to open and closed configurations).In mode 3, however, the desired finger position $\mathbf{q}_i^*$ was obtained by interpolating between open and closed positions ($\mathbf{q}_i^o$ and $\mathbf{q}_i^c$):

$$\mathbf{q}_i^* = \mathbf{q}_i^o (1 + e(\mathbf{q}_i^c - \mathbf{q}_i^o)), \tag{1}$$

with e the contraction level, normalized between 0 (no contraction) and 1 (full contraction):

$$e = \begin{cases} 1 & \text{if } s > s_H, \\ 0 & \text{if } s < s_L, \\ \frac{s - s_L}{s_H - s_L} & \text{otherwise.} \end{cases} \tag{2}$$

We now outline how the target values $\mathbf{q}_i^*$ were attained.

For the two grasping states, finger motion should stop as soon as contact with the grasped object occurs. To detect contact on each fingertip i, we use the pressure measurement P_i on the corresponding BioTac. At time t, the contact state (defined by the binary value $C_i(t)$) is detected by a hysteresis comparator over P_i:

$$C_i(t) = \begin{cases} 1 & \text{if } P_i > P_H, \\ 0 & \text{if } P_i < P_L \text{ or } t = 0, \\ C_i(t - T) & \text{otherwise.} \end{cases} \tag{3}$$

Here, P_H and P_L ($P_H > P_L > 0$) are the pre-tuned high and low thresholds at which C_i changes, and T is the sampling period. For the open hand state, we do not account for fingertip contact, and keep $C_i(t) = 0$.

For all three states, an online trajectory generator (OTG) is used to generate the joint commands $\mathbf{q}_i$, ensuring smooth motion of each finger to its target value $\mathbf{q}_i^*$. The commands depend on the contact state:

$$\mathbf{q}_i(t) = \begin{cases} OTG(\mathbf{q}_i(t-T), \mathbf{q}_i^*, \dot{\mathbf{q}}_i^M), & \text{if } C_i(t) = 0, \\ \mathbf{q}_i(t-T) & \text{otherwise,} \end{cases} \quad (4)$$

with $\dot{\mathbf{q}}_i^M$ the vector of – known – maximum motor velocities allowed for the joints of finger i. Each finger is controlled by a separate OTG, in order to stop only the ones in contact. As OTG, we used the Reflexxes Motion Library[2].

D. Experimental protocols

The experiments were performed through two successive protocols at two different times and with two different sets of patients to limit the duration of the session within their clinical assessment. The first time (protocol A, subjects 1,2 and 3, Fig. 3), we checked whether the patients could contract each muscle (assumed to be supra-lesional but not far from the lesion) with a sufficient level of EMG. The second time (protocol B, subjects 4 and 5, Fig. 3) we tested their ability to control the robot hand without previous practice so visual feedback (from observing the hand) was added to the proprioceptive feedback (subjects 4 and 5). Both protocols are described below.

1) Protocol A - EMG alone:
This protocol evaluated the subjects' capacity to voluntarily control the different muscles and the comfort and ease of contraction (Fig. 3). Each task was performed only once since the objective was achieved at the first attempt, thereby confirming the easiness of command. Moreover, warm-up was not necessary, since the muscles were not used to output torque but only to generate usable EMG. For each muscle, the subjects performed two tasks:

1) maintain maximum contraction for 15 seconds,
2) successively maintain three levels of contraction (low, medium, high), each for 5 seconds.

2) Protocol B - EMG driving robot hand motion:
For this second protocol, muscle contractions controlled the robot hand motion (see Fig. 4). Protocol B was thus composed of two consecutive parts: individual, and preferred muscle assessment.

a) Individual muscle assessment:
In the first part of protocol B, individual muscle contractions were assessed through three tasks.
T1) calibrate: s_L and s_H are set,
T2) maintain maximum contraction for 5 seconds,
T3) maintain contraction as long as possible (after the minimum of 15 seconds.
In tasks 2 and 3, the contraction level had the empirically defined threshold s_H. After each muscle assessment, the subject was asked to assess the comfort, fatigue and ease of contraction efforts through a questionnaire. The questionnaire was inspired by the ISO 9241-9 standard on "Ergonomics of non-keyboard input devices." Once all eight muscles were

[2]http://www.reflexxes.ws

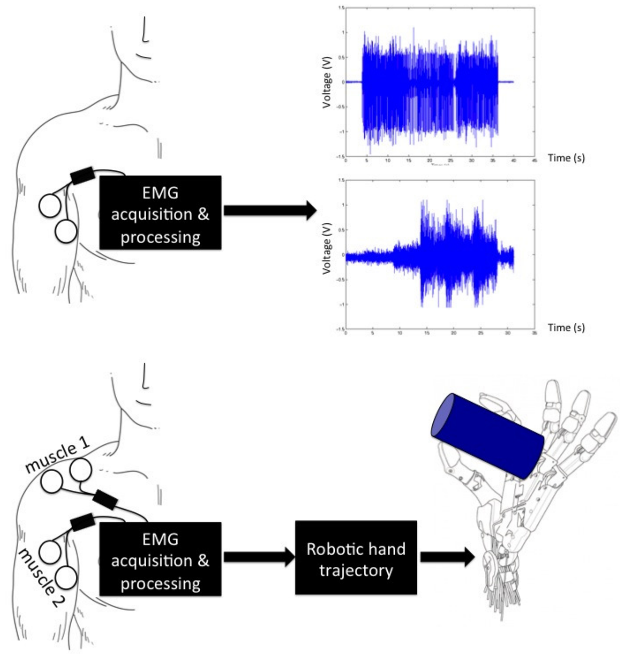


Fig. 3. **Top:** Principle of EMG recording and analysis (protocol A). **Bottom:** Principle of robot hand control through EMG signals. (protocol B).

tested, the subjects were asked to select the two preferred muscles. These two muscles were then taken into account to evaluate the different robot hand control modes in the second part of the protocol.

Fig. 4. Protocol B: setup description and upper arm positioning during EMG recordings.

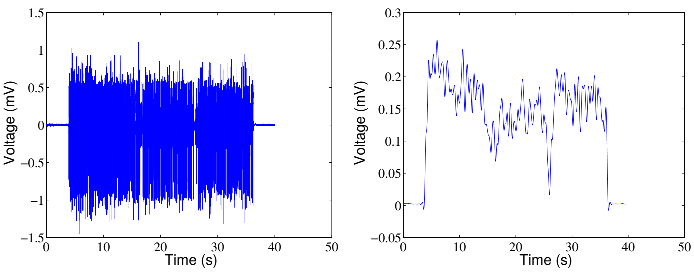
b) Preferred muscle assessment:
Two muscles were selected among the eight, based on subjective patients assessments. The choice of preferential muscles was up to the patient, with the constraint that these two muscles must be on the same side. All five modes of robot hand control (shown in Table II) were tested and evaluated.
For mode 5, the subject was instructed to select contraction muscle 1 or 2 (i.e., either palmar or lateral grasping), depending on the object randomly presented by the experimenter. Two objects were presented to the subject, one with a cylindrical or spherical shape requiring palmar

grasping, the other with a triangular prism shape requiring lateral grasping. The subject had to trigger the correct closure of the robot hand through the contraction of the appropriate muscle to grasp the presented object. Each type of prehension was tested at least five times during the 11 randomized trials.

III. Results

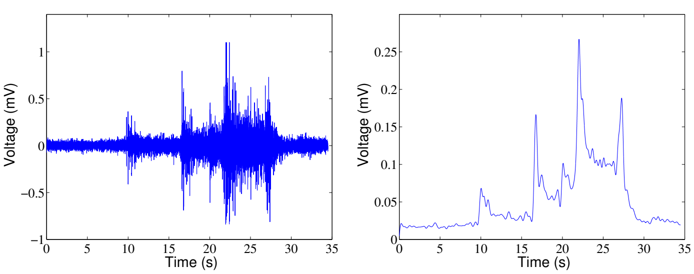
A. EMG Results

We analyzed EMG data from continuous (Fig. 5 (a) and Fig. 5 (b)) and graded (Fig. 5 (c) and Fig. 5 (d)) muscle contractions. Data on each subject's ability to contract the different muscles is presented in Table III. All subjects were able to individually contract the eight muscles on demand for at least 7 seconds, except subject 1 for biceps (no voluntary contraction was visible in the EMG signal).



(a) (b)

3 successive biceps muscle contractions (Subj. 4).



(c) (d)

Graded contraction of sup. trapezius muscle (Subj. 3).

Fig. 5. Example of muscle contractions observed in SCI subjects. Raw signal (a and c), filtered signal (b and d).

Interestingly, a contraction could be extracted from the EMG signals even for very weak muscles. This is illustrated in Fig. 5 (a) and Fig. 5 (b), where a voluntary sustained contraction of the subject's left biceps can be seen. He was able to maintain his contraction for more than 30 seconds. Although this subject presented a C5 lesion with non-functional biceps activity (no elbow flexion), this very weak EMG activity of the biceps could still be turned into a functional command to pilot a device.

Among our five patients, there was only one case where a very weak muscle produced a functional EMG signal. This muscle had an MRC[1] score of 1. For all other muscles with EMG activity, the MRC score was ≥ 3. For protocol A (subjects 1-3), we present in Table IV the ability to grade muscle contraction. The three subjects were able to achieve the three levels of contraction (low, medium and high). The biceps of subject 1 was not tested here, as continuous voluntary contraction was not visible in the EMG signal. In Fig. 5 (c) and Fig. 5 (d), we present an example of a trial from subject 3. He was able to perform an isometric graded contraction of his superior trapezius muscle, but had difficulties holding the contraction for more than 5 seconds. The amplitude of contraction was increased by a factor of seven from 17.3 $\pm$1.9 (rest level), 34.3$\pm$14.9 (low contraction), 43.7 $\pm$36.1 (middle contraction) to 78.7$\pm$38.5 (high contraction). In protocol B, the subjects were able to maintain the contraction of each of the tested muscles.

[1]The MRC (Medical Research Council) Scale assesses muscle power in patients with peripheral nerve lesions from 0 (no contraction) to 5 (normal power).

B. Hand results

The tasks (e.g., holding the object in the robot hand for 5 s) were successfully achieved with each of the tested muscles. Among the tested modes, mode 2 was the favorite mode for subject 4. Mode 1 was the favorite mode for subject 5. Regarding the preferential muscle: Subject 4 chose the left biceps as muscle 1 and the left superior trapezius as muscle 2, whereas subject 5 chose the left superior and left middle trapezius, respectively, as 1 and 2. Muscle 1 contraction resulted in palmar grasping, whereas a contraction of muscle 2 resulted in lateral grasping (mode 5).

We randomly presented two distinct objects to subjects 4 and 5. They performed 11 hand grasping tests with the robot hand (Fig. 6). To grasp the objects, the subjects had to make either a palmar prehension via muscle 1 contraction, or a lateral prehension through muscle 2 contraction. Among the 11 trials, subject 4 had 100% success, while patient 5 managed to seize eight objects out of 11. The three failures occurred with the palmar grasp because of co-contraction. Indeed, co-contraction was still present to some degree but this was the first muscle to reach the threshold that is considered to trigger the hand movement. Patient 5 tended to push the shoulder back (this activated the middle trapeze) just before raising it (this activated the superior trapezius).

C. Comfort survey

For protocol B (subjects 4-5), we present in Table V the responses of the subjects to the questionnaire on comfort and fatigue, related to the contraction of the different muscles. Each subject declared some muscles to be easier and more comfortable to contract (in terms of effort, fatigue, and concentration) than others.

IV. Discussion

The control of a neuroprosthesis by the user - that is, the patient - is a key issue, especially when the objective is to restore movement. Control should be intuitive and thus easily linked to task finality [4], [3], [12]. Furthermore, interfaces are based on the observation (i.e., sensing) of

TABLE III
MUSCLE CONTRACTION ABILITIES. **D**: MAXIMUM CONTRACTION DURATION. ** FAVORITE MUSCLE, *WITH HELP OF ARM SUPPORT

Subject ID	superior trapezius		middle deltoid / middle trapezius		biceps		platysma	
	Right (I)	Left (C)	Right (I)	Left (C)	Right (I)	Left (C)	Right (I)	Left (C)
1	10s**	NA	>15s	NA	0	NA	>15s	NA
2	>15s**	>15s	>15s	>15s	>15s	>15s	>15s	>15s
3	>15s	NA	>15s	NA	>15s	NA	>15s	>15s
4	>15s*	>15s*	>15s	>15s*	7s	>15s**	>15s	>15s
5	>15s	15s	>15s	>15s**	>15s	>15s**	14s	>15s

TABLE IV
ABILITY TO GRADE THE CONTRACTION FOR THE 3 FIRST SUBJECTS, TIME FOR EACH CONTRACTION: 5 S (PROTOCOL A)

	Level of contraction	**upper Trapezius**			**middle Deltoid**			**Biceps**			**Platysma**		
		Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)
Subject 1	1	75.33	18.87	0.32	72.93	9.51	0.6	NA	NA	NA	53.7	16.88	0.39
	2	104	12.9	0.44	84.53	10.53	0.69	NA	NA	NA	59.83	14.3	0.44
	3	237	59.9	1	122.13	12.87	1	NA	NA	NA	135.83	19.4	1
Subject 2	1	50.94	7.81	0.22	273.3	59.9	0.52	110.9	8.07	0.39	73.7	2	0.35
	2	96.36	3.87	0.42	370	73.2	0.71	164.8	30.8	0.58	157.5	14.5	0.74
	3	226.97	211.51	1	522	61.1	1	285.8	50.5	1	213	51.6	1
Subject 3	1	53.93	19.32	0.29	85.42	5	0.25	21.38	6.39	0.37	42.5	11.19	0.30
	2	116.32	38.11	0.63	185	33.75	0.54	41.5	8.74	0.72	100	15.11	0.70
	3	185	56.05	1	345	72.25	1	57.38	10.21	1	143.61	32.58	1

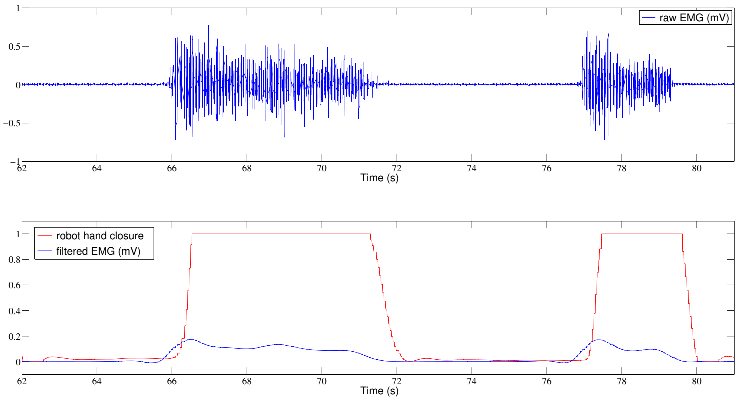
TABLE V
EVALUATION OF INDIVIDUAL MUSCLE CONTRACTION FOR SUBJECTS 4 AND 5 (PROTOCOL B), * 1=VERY HIGH EFFORTS AND FATIGUE, 7=VERY LOW EFFORTS AND FATIGUE

	Superior trapezius				**Middle deltoid / Middle trapezius**				**Biceps**				**Platysma**			
	Right		Left		Right		Left		Right		Left		Right		Left	
	Comfort	Fatigue	Comfort	Fatigue	Comfort	Fatigue	Comfort	Fatigue	Comfort	Fatigue	Comfort	Fatigue	Comfort	Fatigue	Comfort	Fatigue
Subject 4	3.8	2	3	2	4.5	2.5	3.3	5.3	4.3	3.7	5	5.7	2.25	2.5	3	2
Subject 5	7	4.3	2.5	1	6.8	6.3	4	3	2.5	5	3.5	6.3	2	1	3.5	3

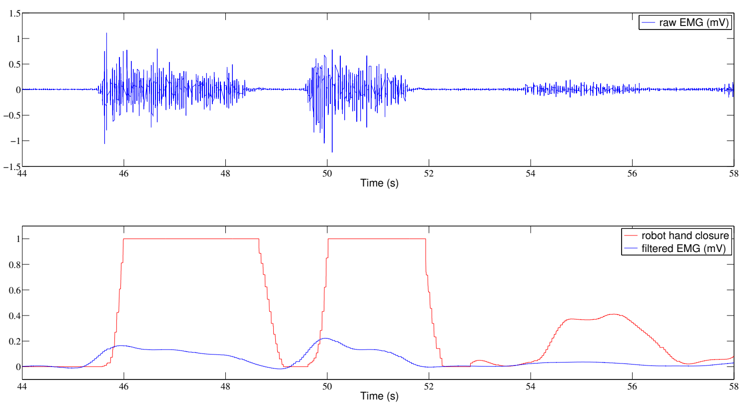
voluntary actions (even mentally imagined, as with BCI interfaces [9]). EMG is widely used to achieve this goal for amputees, but for patients with tetraplegia, the use of supra-lesional muscles to control infra-lesional muscles was a neat option. The second generation of the Freehand system was successfully developed and is the only implanted EMG-controlled neuroprosthesis to date. As far as we know, robot hands for tetraplegics have not yet been controlled using EMG.

The feasibility of using supra-lesional muscle EMG was not straightforward. Indeed, the available muscles are few and most of them cannot be considered valid as they are underused and their motor schema is in some cases deeply impaired, with no functional output. This leads to highly fatigable and weak muscles, but also to the loss of synergy between the paralyzed muscles that are normally involved in upper limb movements. In some cases, even if the muscle is contractable, the produced contraction is not functional (does not induce any joint motion).

Here, the goal was to understand whether the immediately supra-lesional muscles of tetraplegic patients could be used to control a robot hand. The targeted population - that is, tetraplegics with potentially weak supra-lesional muscles - should have a very simple interface for two reasons: (i) simple contraction schemes to control the hand limit cognitive fatigue, and (ii) short contractions limit physiological fatigue. These two constraints mean that the hand should be controlled with predefined postures and not in a proportional way. Thus, the output of our control framework was a limited set of hand states, while its input, except for one mode (mode 3), was a limited set of EMG levels. In this context, the FSM scheme should be preferred. In our study, we found in all five subjects a combination of muscles such that each was able to easily perform the tasks (protocol A) that is, to maintain a



(a) Mode 1



(b) Mode 3

Fig. 6. Example of robot hand trajectories generated from EMG recording in subject 5 for modes 1 and 3. **Top:** raw EMG, **Bottom:** filtered EMG (blue) and hand trajectory (red).0: hand is open, 1: hand is closed.

continuous contraction or a grade contraction, so that it could be quantified by an EMG signal. We were able to calibrate quite low thresholds, so that patients did not have to contract much and experience fatigue. Moreover, these experiments were conducted during the scheduled clinical assessment, so no training was offered, even during the session. The patients were merely asked to contract muscles and to try to hold objects with the robot hand. All were able to control it immediately. The calibration procedure is linked only to EMG signal scaling so that, as a whole, the system is very easy to use in a clinical context, compared with approaches like BCI, for instance. Interestingly, the lesion age had no influence on performance.

Two subjects participated in the second session (protocol B), in which the EMG signals were used to control a robot hand. This was achieved without any prior learning or training. We show that both the used muscle, and the way the contraction controls the hand (control mode), have a drastic effect on performance. This robot hand approach may thus be a very good paradigm for rehabilitation or training, for future FES-based control of the patients' own hand.

These two subjects did not have the same preferred mode of control, but clearly preferred one over the others. Mode 1 (continuous contraction to maintain robot hand closure) seems to be more intuitive, as the contraction is directly linked to the posture of the hand, but mode 2 (an impulsive contraction provokes robot hand closure/opening) induces less fatigue as it needs only short muscle contractions to toggle from open to closed hand. Depending on their remaining motor functions, patients feel more or less comfortable with a given mode. Also, the choice of the preferred control mode would probably be different after a training period. In our opinion, patients should select their preferred mode themselves. However, a larger study would give indications on how to classify patients preferred modes, based on the assessment of their muscle state. In any case, control cannot be defined through a single mode and should be adapted to each patient and probably to each task and fatigue state.

For practical reasons, we decided that the two EMGs would be located on the same side without any knowledge beforehand as to which side to equip. The subject selected one preferred muscle and based on this choice, the second muscle was selected on the same side. A major issue with this decision is that the two muscles sometimes co-contract and in mode 5 (muscle 1 contraction causes palmar pinch and muscle 2 contraction causes key-grip) the robot hand grasping task selected by the system was not always the one the user intended to execute.

In the future, patients will control their own hand by means of electrical stimulation instead of a distant robot hand, and the choice of which body side to equip with EMG will need to be made with respect to the task that the stimulated hand must achieve. For example, if muscle contraction is associated with arm motion, this might well disturb the grasping to be achieved. Furthermore, an analysis is needed to determine the effect of the dominant side on performance.

For our patients, grasping would not be disturbed since shoulder movements do not induce forearm movements. The questionnaire at the end of each test allowed us to evaluate the ease of using EMG as a control method. Preferential muscles were chosen so as not to disturb the functionalities available to the subjects. Yet, one can also imagine a system that deactivates electrostimulation when the patient wishes to use his/her remaining functionality for other purposes. In this case, the subject would be able to contract his/her muscles without causing hand movements. Furthermore, one can imagine using forearm/arm muscle synergies or relevant motor schemas to facilitate the learning (e.g. hand closing when the elbow bends, hand opening during elbow extension, and so on).

The interesting property of the proposed interface is that even a weak muscle can produce a proper EMG signal. As an example, subject 4 was able to control the robot hand with a weak muscle to produce functional movement. In other words, a non-functional muscle in the context of natural movements can be turned into a functional muscle in the context of assistive technology and one can even expect that motor performances will improve with training.

V. Conclusion

We have demonstrated the feasibility of extracting contraction recordings from supra-lesional muscles in individuals with tetraplegia that are sufficiently rich in information to pilot a robot hand. The choice of muscles and modes of control are patient-dependent. Any available contractable muscle - and not just functional muscles - can be candidates and should be evaluated. The control principle could also be used for FES applied to the patient arm, or to control an external device such as a robot arm or electric wheelchair, or as a template of rehabilitation movements. The robot hand might help to select (via their residual control capacity), and possibly train, patients as potential candidates for an implanted neuroprosthetic device. A greater number of patients using the robot hand would provide a better picture of the range of performance. Therefore, the next step will be to extend the study to a wider group of patients, to provide a better picture of the range of performance. We also plan to use the robot hand as a part of a training protocol for future FES devices.

Acknowledgments

The authors wish to thank the subjects who invested time into this research, as well as MXM-Axonic/ANRT for support with the PhD grant, CIFRE # 2013/0867. The work was also supported in part by the ANR (French National Research Agency) SISCob project ANR-14-CE27-0016. Last, the authors also warmly thank Violaine Leynaert, occupational therapist at Propara Center, for her precious help.

References

[1] M. W. Keith, P. H. Peckham, G. B. Thrope, K. C. Stroh, B. Smith, J. R. Buckett, K. L. Kilgore, and J. W. Jatich, “Implantable functional neuromuscular stimulation in the tetraplegic hand,” The Journal of hand surgery, vol. 14, no. 3, pp. 524–530, 1989.

[2] C. Billian and P. H. Gorman, “Upper extremity applications of functional neuromuscular stimulation,” Assistive Technology, vol. 4, no. 1, pp. 31–39, 1992.

[3] M. W. Keith, “Neuroprostheses for the upper extremity,” Microsurgery, vol. 21, no. 6, pp. 256–263, 2001.

[4] N. Hoshimiya, a. Naito, M. Yajima, and Y. Handa, “A multichannel FES system for the restoration of motor functions in high spinal cord injury patients: a respiration-controlled system for multijoint upper extremity.” IEEE transactions on bio-medical engineering, vol. 36, no. 7, pp. 754–60, Jul. 1989. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/2787283

[5] D. Guiraud, T. Stieglitz, K. Koch, J. Divoux, and P. Rabischong, “An implantable neuroprosthesis for standing and walking in paraplegia: 5-year patient follow-up.” J Neural Eng., vol. 3, no. 4, pp. 268–75, 2006.

[6] J. Jovic, C. Azevedo Coste, P. Fraisse, S. Henkous, and C. Fattal, “Coordinating Upper and Lower Body During FES-Assisted Transfers in Persons With Spinal Cord Injury in Order to Reduce Arm Support,” Neuromodulation: Technology at the Neural Interface, vol. 18, p. 7, May 2015. [Online]. Available: http://hal-lirmm.ccsd.cnrs.fr/lirmm-01146757

[7] C. W. Moss, K. L. Kilgore, and P. H. Peckham, “A novel command signal for motor neuroprosthetic control,” Neurorehabilitation and neural repair, vol. 25, no. 9, pp. 847–854, 2011.

[8] Q. Zhang, M. Hayashibe, and C. Azevedo Coste, “Evoked electromyography-based closed-loop torque control in functional electrical stimulation,” IEEE Trans Biomed Eng., vol. 60, no. 8, pp. 2299–307, 2013.

[9] C. King, P. Wang, C. McCrimmon, C. Chou, A. Do, and Z. Nenadic, “The feasibility of a brain-computer interface functional electrical stimulation system for the restoration of overground walking after paraplegia.” Journal of NeuroEngineering and Rehabilitation, vol. 3, no. 4, pp. 268–75, 2015.

[10] J. S. Knutson, H. A. Hoyen, K. L. Kilgore, and P. H. Peckham, “Simulated neuroprosthesis state activation and hand-position control using myoelectric signals from wrist muscles.” J Rehabil Res Dev, vol. 41, no. 3B, pp. 461–72, 2004.

[11] R. L. Hart, K. L. Kilgore, and P. H. Peckham, “A comparison between control methods for implanted fes hand-grasp systems,” Rehabilitation Engineering, IEEE Transactions on, vol. 6, no. 2, pp. 208–218, 1998.

[12] N. Bhadra, P. H. Peckham, M. W. Keith, K. L. Kilgore, F. Montague, M. Gazdik, and T. Stage, “Implementation of an implantable joint-angle transducer,” Journal of rehabilitation research and development, vol. 39, no. 3, pp. 411–422, 2002.

[13] T. Keller, A. Curt, M. R. Popovic, A. Signer, and V. Dietz, “Grasping in high lesioned tetraplegic subjects using the EMG controlled neuroprosthesis,” NeuroRehabilitation-An Interdisciplinary Journal, vol. 10, no. 3, pp. 251–256, 1998.

[14] R. Thorsen, D. Dalla Costa, S. Chiaramonte, L. Binda, E. Beghi, T. Redaelli, E. Occhi, and M. Ferrarin, “A noninvasive neuroprosthesis augments hand grasp force in individuals with cervical spinal cord injury: The functional and therapeutic effects,” The Scientific World Journal, vol. 2013, 2013.

[15] W. D. Memberg, K. H. Polasek, R. L. Hart, A. M. Bryden, K. L. Kilgore, G. A. Nemunaitis, H. A. Hoyen, M. W. Keith, and R. F. Kirsch, “Implanted neuroprosthesis for restoring arm and hand function in people with high level tetraplegia,” Archives of physical medicine and rehabilitation, vol. 95, no. 6, pp. 1201–1211, 2014.

[16] M. DiCicco, L. Lucas, and Y. Matsuoka, “Comparison of control strategies for an EMG controlled orthotic exoskeleton for the hand,” in IEEE Int. Conf. on Robotics and Automation, ICRA, vol. 2, 2004, pp. 1622–1627.

[17] W. Tigra, C. Azevedo Coste, C. Fattal, and D. Guiraud, “Ergonomics of the control by a quadriplegic of hand functions,” in Neural Engineering (NER), 7th Int. IEEE/EMBS Conf. on, 2015, pp. 759–762.

[18] M. Cutkosky, “On grasp choice, grasp models, and the design of hands for manufacturing tasks,” Robotics and Automation, IEEE Trans. on, vol. 5, no. 3, pp. 269–279, Jun 1989.

[19] A. Bicchi, “Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity,” Robotics and Automation, IEEE Trans. on, vol. 16, no. 6, pp. 652–662, Dec 2000.

[20] J. Weisz, C. Elvezio, and P. K. Allen, “A user interface for assistive grasping,” in IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, IROS, 2013.

[21] K. Farry, I. Walker, and R. Baraniuk, “Myoelectric teleoperation of a complex robotic hand,” Robotics and Automation, IEEE Trans. on, vol. 12, no. 5, pp. 775–788, Oct 1996.

[22] L. Zollo, S. Roccella, E. Guglielmelli, M. Carrozza, and P. Dario, “Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications,” Mechatronics, IEEE/ASME Trans. on, vol. 12, no. 4, pp. 418–429, Aug 2007.

[23] C. Cipriani, F. Zaccone, S. Micera, and M. Carrozza, “On the shared control of an EMG-controlled prosthetic hand: Analysis of user,” Robotics, IEEE Trans. on, vol. 24, no. 1, pp. 170–184, Feb 2008.

[24] B. A. Kent, N. Karnati, and E. D. Engeberg, “Electromyogram synergy control of a dexterous artificial hand to unscrew and screw objects,” Journal of NeuroEngineering and Rehabilitation, vol. 11, no. 41, 2014.

[25] L. R. Hochberg, D. Bacher, B. Jarosiewicz, N. Y. Masse, J. D. Simeral, J. Vogel, S. Haddadin, J. Liu, S. S. Cash, P. Van der Smagt, and J. P. Donoghue, “Reach and grasp by people with tetraplegia using a neurally controlled robotic arm,” Nature, vol. 485, no. 7398, pp. 372–375, 2012.

[26] G. Pfurtscheller, G. R. Müller, J. Pfurtscheller, H. J. Gernerd, and R. Rupp, “Thought control of functional electrical stimulation to restore hand grasp in a patient with tetraplegia,” Neuroscience Letters, vol. 351, no. 1, pp. 33–36, 2003.

[27] S. A. Dalley, H. A. Varol, and M. Goldfarb, “A method for the control of multigrasp myoelectric prosthetic hands,” Neural Systems and Rehabilitation Engineering, IEEE Transactions on, vol. 20, no. 1, pp. 58–67, 2012.

[28] S. C. Kirshblum, S. P. Burns, F. Biering-Sorensen, W. Donovan, D. E. Graves, A. Jha, M. Johansen, L. Jones, A. Krassioukov, M. Mulcahey et al., “International standards for neurological classification of spinal cord injury (revised 2011),” The journal of spinal cord medicine, vol. 34, no. 6, pp. 535–546, 2011.

Exploring selective neural electrical stimulation for upper limb function restoration

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Abstract

This article introduces a new approach of selective neural electrical stimulation of the upper limb nerves. Median and radial nerves of individuals with tetraplegia are stimulated via a multipolar cuff electrode to elicit movements of wrist and hand in acute conditions during a surgical intervention. Various configurations corresponding to various combinations of a 12-poles cuff electrode contacts are tested. Video recording and electromyographic (EMG) signals recorded via sterile surface electrodes are used to evaluate the selectivity of each stimulation configuration in terms of activated muscles. In this abstract we introduce the protocol and preliminary results will be presented during the conference.

Key Words: electrical stimulation, neural selectivity, grasping function restoration

Eur J Transl Myol 2016 26 (2) 161-164

Prevalence of complete spinal cord injury (SCI), is estimated at 2 million people worldwide. SCI consequences are often devastating for patients. For trauma at cervical levels (tetraplegia), among many dysfunctions, one of the most impressive is the loss of use of four limbs.

In complete SCI, sub-lesional peripheral nervous system (PNS), does not receive anymore commands from the central nervous system (CNS) because communication is impeded. Although some assistive devices allow them to palliate basic functions, recovery of grasp movements is still seen as a priority for these patients to regain autonomy[1,2,3,4]. To restore hand movements, electrical stimulation remains almost the only solution. Indeed, applying an electrical current sufficient to excite cells (neurons or myocytes) allows the initiation of action potentials responsible for muscle contraction. Moving paralyzed limbs after such trauma becomes possible[5,6,7,8,9]. Implanted systems, such as the Freehand System (Neurocontrol, USA) or the FESMate (Japan) use epimysial or intramuscular electrodes to activate directly muscles to restore movements of the upper limb, while in the non-implanted systems, such as the Bionic Glove (Canada) or the Handmaster (Israel), the stimulation is delivered through surface electrodes. In implanted systems, activation of each muscle requires the use of at least one electrode, complexity of the device and number of foreign bodies may be high, up to 12 channels for the Freehand for instance. Risks of failure, externalization of foreign bodies and infections spreading along wires are further increased. Moreover, the needed surgery involves multiple procedures and takes considerable time and care to be successfully achieved. In one study[10], it has been necessary to re-operate on four subjects over nine to make adjustments of the system while three other surgeries have been required to replace or remove broken electrodes or exchange an implant/receiver. However, patients become more independent of daily living activities, thus limiting the needs of a human aid. Although these devices have emerged as one of the most promising techniques for the restoration of hand function for SCI or stroke subjects, their use is still very limited in terms of acceptability, efficacy and trade-off between benefit / risk. Indeed, the higher the patient's lesional level is, the larger the number of muscles to be stimulated to achieve gripping movements is. A method which allows to activate more than one muscle by electrode becomes relevant. Another approach has been used for decades; functional surgery, which is mainly based on muscle-tendon transfers and opened a wide field of improvement of the functional potential of

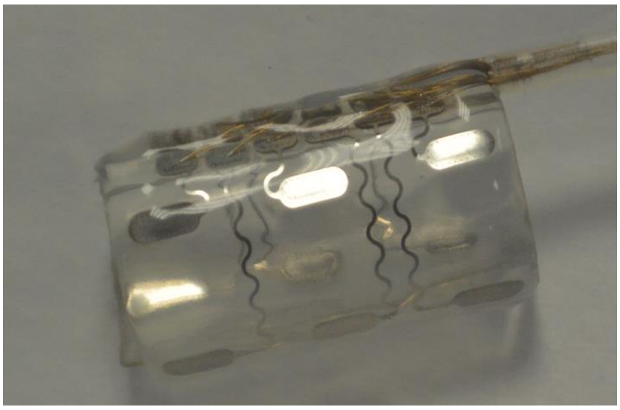

Fig 1. *12-poles multipolar cuff electrode*

tetraplegics[11,12]. In these procedures, the distal portion of a functional tendon-muscle is detached from its natural insertion point and then fixed on a non-functional adjacent tendon in order to give back original function of the non functional tendon. For example, transfer of the biceps brachii muscle on triceps brachii muscle may allow restoring an active elbow extension, residual elbow flexion being provided by the other flexors (brachialis and brachioradialis). However, this type of approach requires the presence of a sufficient number of muscles under voluntary control, which is not always possible. Moreover, the post surgical rehabilitation does not systematically allow the recovery of the desired movement[13]. Keith et al.[7] combined epimysial FES and muscle-tendon transfert in the Freehand implantation but their procedure was based on epimysial electrodes that needs to spread the system over all the used muscles. Therefore, if we combine muscle-tendon transfer and selective neural FES, patients with no forearm voluntary movements but with biceps and deltoid muscles still under voluntary control, could recover an active elbow extension via tendon transfer and hand movements via neural FES. Thus, the combination of a tendon transfer surgery and a multipolar electric neural stimulation (number of poles ≥ 4) would optimize muscle residual activity while making the electrostimulation device less cumbersome to implement. Indeed, placed above nerve junctions, multipolar electrodes would allow selective activation of several fascicles of the same nerve. This selective activation could potentially activate different hand functions and / or muscles. Control of multiple functions via a single electrode could reduce the number of foreign bodies and electrodes. Besides, the needed energy to activate muscle decreases compared to epimysial or intramuscular stimulation. Indeed, a neural stimulation requires 10 times less energy. In the following, we present our ongoing research protocol. In acute conditions during a surgical intervention, we stimulate upper limb nerves of tetraplegic patients using multipolar cuff electrodes, to selectively activate movements of wrist and hand.

Materials and Methods

Subjects

Subjects are spinal cord injured with lesional level up to C7, AIS A or B with positive electrical mapping with a minimum score of 4/5 on the Medical Research Council (MRC) Scale for at least one extensor among Extensor Carpi Radialis Longus (ECRL), Extensor Carpi Radialis Brevis (ECRB), Extensor Digitorum Communis (EDC), Extensor Pollicis (EPL) Longus or one flexor among Flexor Pollicis Longus (FPL), Flexor Digitorum Superficialis (FDS), Flexor Digitorum Profundus (FDP). Age is between 18 and 65 years and patients are in a stable neurological state for at least 6 months.
An information note explaining the aim of the study is delivered to the participants who sign an informed consent. The study is conducted, during musculo-tendinous transfers of arm or forearm muscles, at the Private Hospital Beau Soleil and the University Hospital Center Lapeyronie, Montpellier, France. Ethical agreement was obtained (CPP Sud Mediterrannée IV, Montpellier, France, February 10th, 2015).

Multipolar electrical stimulation

Cuff electrodes

Multipolar cuff electrodes (length 20mm, 12 oblong contacts of 2,2mm^2, designed by CorTec GmbH, Freiburg, Germany (Fig.1)) are placed around the median and/or radial nerves next to the elbow joint. The 12 contacts are positioned to have 3 rings of 4 contacts positioned at 90° from each other. The 12 contacts can be independently activated via a dedicated software and stimulator. Electrodes were designed to be positioned optimally on the median and radial human nerves.

Electrical stimulator

The neurostimulator, *R&STIM 12*, (designed jointly by MXM-AXONIC company and INRIA-DEMAR lab) allows the control of the 12 individual poles and 1 reference. All poles are addressed simultaneously to generate 3D current spreading over the 12 contacts. A synchronization output allows interfacing with signal recorders. Each active pole (i.e. implied in the electrode configuration) can be defined as a cathode or an anode. *R&STIM 12* is operated from a dedicated PC software (Lunatum developed by MXM-AXONIC company) which allows to program various configurations of stimulation. The main characteristics of *R&STIM 12* are the following:

- Maximum output current: Imax = 5mA,
- Current resolution: $\Delta I = 1.3\mu A$
- Temporal resolution: $\Delta t = 1\mu s$
- Maximum pulse width: Tmax = 2 ms,

Table 1. *- Examples of stimulation configurations*

Name of the configuration - Number of Pole	1	2	3	4	5	6	7	8	9	10	11	12
Ring Longitudinal	2	1	2	1	-3	-3	-3	-3	2	1	2	1
Tripolaire TransverseA	0	0	0	0	6	-12	6	0	0	0	0	0
Tripolaire TransverseB	6	-12	6	0	0	0	0	0	0	0	0	0
Tripolaire TransverseC	0	0	0	0	0	0	0	0	6	-12	6	0
1 Cathode Ring Anode	1	2	1	2	-12	0	0	0	6	0	0	0
Tripolaire Longitudinal	6	0	0	0	-12	0	0	0	6	0	0	0
Steering	1	0	1	1	0	-12	0	6	1	0	1	1

Selective configuration design

After a simulation study, the more interesting combinations of poles from a selectivity performance point of view, were determined leading to up to 40 configurations to be tested on each nerve. When relevant, the same configurations of stimulation are reproduced on the 3 rings to investigate possible fascicular re-organization within the few millimeters which separate each ring (see Table 1).

Protocol and methodology

Cuff electrodes are placed around the median and/or radial nerves. Nerves are stimulated with increasing intensity. The protocol consists of the activation of one or more poles of the electrode. The stimulation pulse is biphasic, balanced but asymmetric, followed by a passive discharge to guaranty charge balance. Pulse width is fixed and intensity is modulated (up to 2.4 mA). For each configuration and intensity, a tetanic stimulus is induced for 2 seconds. For the first patient pulse width was 500 µs and stimulation frequency 25 Hz. Cuff electrode did not fit perfectly, shorter pulse widths did not produced any movements. Surface EMG electrodes are placed upon the ERCL or ERCB, EDP, EDS, FDS, FDS and FPL muscles to record EMG signals. This allows us to evaluate the selectivity capacity of our configurations. Nevertheless, because the radial and median nerves activate more muscles than the recorded ones, in particular deep muscles contraction may not be detected, a synchronized video recording with the stimulator is performed. The video analysis is used to assess the functional selectivity capacity of our different stimulation configurations based on hand and wrist movements analysis

Judgment criteria

The primary judgment criterion is based on the quantification of the strength and the selectivity of muscle recruitment induced by the electrical stimulation of the median and/or radial nerves. The strength of recruitment and the selectivity are quantified for ECRL or ECRB, EDC, EPL, FPL, FDS and FDP muscles using electromyography.

For a given configuration *C* and intensity *I*, a signal which reflects muscle activation is obtained for each muscle. Amplitudes of compound muscle action potentials (CMAP) are measured from the reference to the highest magnitude of the M-wave negative voltage. Then, for each configuration, those signals are normalized to the maximal amplitude of the CMAPs. We note the normalized signal $CMAP\text{-}EMG_{CI}$. $CMAP\text{-}EMG_{CI}$ below 0.05 are considered equal to 0. Intensities of stimulation corresponding to 20, 50 and 100% of EMGcmax are determined for each configuration and for each of the 6 muscles. For each configuration, up to 18 series (6 muscles and 3 levels of activation) can be determined. For each series, an ***index of selectivity*** $SI_m(I)\%$ is determined. $SI_m(I)\%$ is defined as the ratiobetween the normalized signal $CMAP\text{-}EMG_{CI}$ of the m muscle whose nerve was stimulated with the optimal intensity *I* causing an activation of $n_{\%}(\mu_i)$ and the sum of normalized signal $CMAP\text{-}EMG_{CI}$ (μ_j) of the 6 muscles:

$$SI_m(I)_{\%} = \frac{\mu_i}{\sum_{j=1}^{6} \mu_j}$$

$SI_m(I)\%$ corresponds to the selectivity index. $SI_m(I)\%$ is between 0 et 1, where 0 indicates no selectivity and 1 indicates that only the muscle *m* is activated. A selectivity index curve is plotted, from $SI_m(I)\%$. The surgeon also evaluates muscle strength produced by the electrical stimulation (MRC scale). Finally, we have developed a software to track hand movements in the recorded video in order to qualify the motion range and type.

Results

We included 2 patients. Selective activation of the flexor carpi radialis and palmaris longus muscles was possible for the patient 1 from 600 µA with grade 3 on the MRC scale. Preliminary quantitative results will be presented at the 2016 IFESS Conference to be held June 7 – 9, 2016 at La Grande Motte, Montpellier, France.

Discussion

Currently, there is no more commercial implanted stimulation neuroprosthesis allowing to restore hand movements. If the results of this study will be positive, it could lead us to design a new neuroprosthesis based on nerve stimulation for grasp movements in high tetraplegic subjects recovery. Even if the results can not be conclusive to how well a cuff electrode will work in chronic condition to selectively activate a high number of muscle groups because in chronic condition the electrode-nerve interface will have different properties due to impedance changes for example, we expect that our number of contact and modification of stimulation parameters will selectively activate the same muscle groups. Thus, a device using such technology would, in combination with tendon transfer surgery, be materially lighter than those which existed, would require less time for its implementation, and less power for its operation. An interface for piloting the stimulation is studied in parallel.[15]

Contributions

WT: protocol design, experimental setup implement-tation, data acquisition; DG: coordination of the technical and theoretical aspects of the study. Data acquisition and processing expertise; DA: technical expertise in stimulator design and programming; BC: neurosurgery and patient follow up; AG: patient recruitment, muscle mapping and patient follow up; CF: study design, expertise in FES applied to SCI rehabilitation; PM: stimulator design and stimu-lation pattern software programming; CP: experimental setup and data analysis support; OR: stimulation patterns definition and data processing; JT: neurosurgery and patient follow up; CA: coordination of the experimental aspects of the study. Protocol and setup design expertise.

Acknowledgements

The authors wish to thanks the subjects who participated in this study, S. Henkous, for her help in the writing of the protocol, as well as V. Leynaert, JL Divoux, MXM-Axonic and ANRT support the PhD grant, CIFRE #2013/0867.

Conflict of Interest

The authors declare no potential conflict of interests.

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References

1. Snoek GJ, IJzerman MJ, Hermens HJ, Maxwell D, Biering-Sorensen F. Survey of the needs of patients with spinal cord injury: impact and priority for improvement in hand function in tetraplegics," Spinal cord 2004;42:526–32.
2. Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. J Neurotrauma 2004;21:1371–83.
3. Hanson R, Franklin M. Sexual loss in relation to other functional losses for spinal cord injured males. Arch Phys Med Rehabil 1976;57: 291.
4. Estores IM, The consumer's perspective and the professional literature: what do persons with spinal cord injury want? J Rehabil Res Dev 2003;40:93-8.
5. Keith MW, Peckham PH, Thrope GB, et al. Implantable functional neuromuscular stimulation in the tetraplegic hand. J Hand Surg Am 1989;14:524-30.
6. Billian C, Gorman PH. Upper extremity applications of functional neuromuscular stimulation. Assist Technol 1992;4:31-9.
7. Keith MW. Neuroprostheses for the upper extremity. Microsurgery 2001;21:256–63.
8. Hoshimiya N, Naito A, Yajima M, Handa Y. A multichannel FES system for the restoration of motor functions in high spinal cord injury patients: a respiration-controlled system for multijoint upper extremity. IEEE transactions on bio-medical engineering. 1989;36:754–60.
9. Peckham PH, Keith MW, Kilgore KL, et al. Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study Arch Phys Med Rehabil 2001;82:1380-8.
10. Hobby J, Taylor P, Esnouf J. Restoration of tetraplegic hand function by use of the neurocontrol freehand system. J Hand Surg Br 2001;26:459-64.
11. Lamb DW, Chan K. Surgical reconstruction of the upper limb in traumatic tetraplegia. J Bone Joint Surg 1983;65:291–8.
12. Mohammed KD, Rothwell AG, Sinclair SW, Willems S, Bean AR. Upper-limb surgery for tetraplegia. J Bone Joint Surg Br 1992;74:873-9.
13. Hovius S. Musculo-tendinous transfers of the hand and forearm. Clin Neurol Neurosurg 1993;95:S92-4. Review.
14. Tigra W, Azevedo Coste C, Fattal C, Guiraud D. Ergonomics of the control by a quadriplegic of hand functions, in Neural Engineering (NER), 7th Int. IEEE/EMBS Conf, 2015, 759–62.

Ergonomics of the control by a quadriplegic of hand functions

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***Abstract*— In subjects with complete Spinal Cord Injury (SCI) above C7, the four limbs are paralyzed (quadriplegia). Recovery of grasping movements is then reported as a priority. Indeed, most activities of daily living are achieved through upper limbs. Thus, restoration of hand and forearm active mobility could significantly increase independence and quality of life of these people and decrease their need of human aid. Although most of the subjects plebiscite pharmacological or biological solutions, only orthotics and Functional Electrical Stimulation (FES) allow, so far, to restore hand movements but they are rarely used. Ergonomics and comfort of piloting mode could partly explain the low usage of these systems. In this context, our aim is to explore possible solutions for subjects to interact with such devices. In this article we propose to evaluate the capacity of active upper limb muscles contraction to be used to intuitively control FES in tetraplegic subjects. In this study, we assessed the ability to gradually contract different muscles: trapezius, deltoid, platysma and biceps. Three subjects with C6 to C7 neurological level of lesion were included. We show that over the active upper limb muscles tested, contraction of the trapezius muscle was considered by the subjects as the most comfortable and could be employed as an intuitive mode of control of functional assistive devices.**

I. INTRODUCTION

Prevalence of spinal cord injuries (SCI) continues to increase and although technical aids (passive braces, wheelchairs,...) allow to give back some independence, inability of quadriplegic subjects to perform grip movements strongly limits their quality of life. Recovery of grasping movements is reported as a priority [1]. In recent decades, surgical procedures such as muscle-tendon transfers or, more recently, nerve transfers have been proposed to regain mobility of the arm and hand after several weeks of rehabilitation. However, these two methods require the presence of enough muscles or nerves under voluntary control to restore the required movement. At present, in the absence of enough voluntary active muscle and nerves, only active orthotics or devices using FES allow to restore hand movements. They have been used for over 25 years in rehabilitation centers. Spasticity and muscular atrophy are decreased, and limb mobilization is improved when using such assistive devices [2]. One main challenge in this context is to provide the subject with an interface to allow him/her to interact with the system. Indeed, the subject has to control the action of the assistive device with his own motions. Controlling the system has to be as natural as possible and to allow the user to obtain a quality hand opening and closing as well as an increase in strength during grasping. User should also be able to hold his hand into a desired position and select different gripping modes. Various interfaces have been tested in the past: joysticks, joint movement detection, switches, breath control, electromyography (EMG) signals among others. In [3] voluntary wrist extension is used as mode control. A wrist osseointegrated Hall effect sensor implant serve for FES hand neuroprosthesis. Nevertheless, wrist extension is limited to subjects who have a below C6 injury. Obviously, control interfaces are highly dependent on the subject's level of injury and remaining voluntary activity. The use of EMG signals from muscles under voluntary control proves to be an alternative because whatever their level of injury, each subject should be able to contract some muscles. Dietz et al. proposed to use surface EMG from deltoid muscle of contralateral arm to pilot a device which stimulates hand muscles [4]. In [5] the EMG signal from ipsilateral wrist extensor muscles is used to pilot a hand neuroprosthesis. An implanted device [6] uses shoulder and neck muscles to control the FES applied to arm and hand muscles. EMG signals are also used to control an upper limb exosqueleton in [7]. The aim of the work we present here is to evaluate the capacity and comfort of gradually contract upper limb muscles ipsi- and contralaterally for C6-C7 tetraplegic subjects in order to serve as interface for a device allowing to recover prehension movements.

II. MATERIALS AND METHODS

A. Subjects

Experiments were performed on 3 quadriplegic male subjects, who have a complete motor injury. Subject 1 is 33 years old, C6 and is paralyzed since 4 years. Subject 2 is 35 years old, C7 and is paralyzed since 13 years and has just sustained a muscle-tendon transfer. Subject 3 is 21 years old, C7 and is paralyzed since 6 months, all are AIS A. An information note explaining the purpose of the study was delivered and an informed consent obtained. The study was conducted at Propara neurological rehabilitation center (Montpellier, France) during scheduled clinical assessments. The studied muscles are: right and left superior trapezius, right and left middle deltoid, right and left biceps and right and left platysma for the subject 2. Superior trapezius, middle deltoid, biceps and platysma muscles of the ispilateral side of the dominant (right) upper limb were studied for the subjects 1 and 3.

B. Materials

Signals were recorded using an insulated National Instrument acquisition card NI USB 6218, 32 inputs, 16-bit (National Instruments, USA). BIOVISION EMG amplifiers

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(Wherheim, Germany) were used, the gain was fixed to 1000. The acquisition card was connected to a portable computer running on batteries. The acquisition is done at 2kHz. EMG data are filtered (high pass filter: 20Hz, four-folder butterworth filter, 0 phase) and RMS values calculated. Surface ECG BIOTRACE Electrodes (Controle graphique S.A, France) were used.

Fig. 1. Upper arm positioning during EMG recording

C. Methods

Surface-recording electrodes were positioned above the 4 muscles. The physician or the occupational therapist teaches and encourages movements allowing contraction of these muscles. Patients have not received any pre-training before these experiments. The upper arm is sustained by a forearm support (ERGO REST®), during the procedure and hand fixed around a cylindric object (cf. Fig. 1). Subjects had to perform a contraction as high as possible Peak activation levels of each individual muscle and hold it for 15 seconds. Then, each subject was asked to contract separately each individual muscle and to grade contraction (low, medium and high contraction) holding contraction for 5 seconds for each level of contraction. Visual and/or sound signals encouraged them to contract their muscles. Then, to evaluate proprioception, subjects repeated these same gestures with closed eyes. Tests are carried out on ipsilateral and contralateral sides of the dominant upper limb when possible. Subjects were then asked to choose the most comfortable muscle, i.e. the muscle which is the most easy to contract trying to sustain contraction at 3 different levels.

III. Results

Subjects were all able to contract, trapezius, deltoid and platysma muscles. Subject 1 was not able to contract his biceps brachii muscle unlike subjects 2 and 3 (Fig.2, 3, 4, and 5). Each subject was able to contract trapezius, deltoid and platysma continuously for at least one second. They were able to hold 3 distinct amplitudes during the graded contractions of these same muscles, even without visual feedback. For subjects 2 and 3, the maximal and graduated contraction of the 4 muscles is possible. The subjects 1 and 2 reported that the trapezius muscle is the most comfortable to be used as a control signal. The subject 3 having a number of active forearm muscles greater than 2 had no preference.

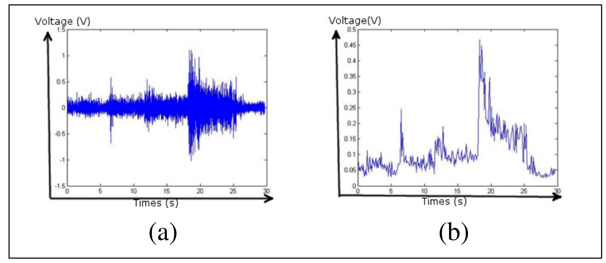

Fig. 2. Graded contraction of the upper trapezius muscle, dominant member, subject 1. (a) Raw signal, (b) RMS signal

We asked subject 1 to perform a graded contraction of his right upper trapezius muscle and hold each contraction for 5 seconholdds (Fig. 2). The subject could perform a graded contraction but has difficulties to hold it more than 1 second.

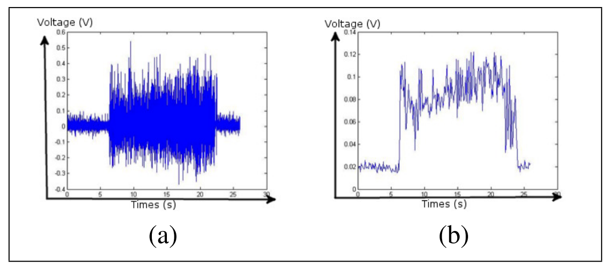

Fig. 3. Peak activation levels of the middle deltoid muscle, dominant member, subject 1. (a) Raw signal, (b) RMS signal

For the trial of Fig. 3 we asked the subject 1 to perform an isometric maximal voluntary contraction of his middle deltoid muscle for 15s. The subject was able to hold it for 15 seconds. Contraction is clear, amplitude of signal threefold.

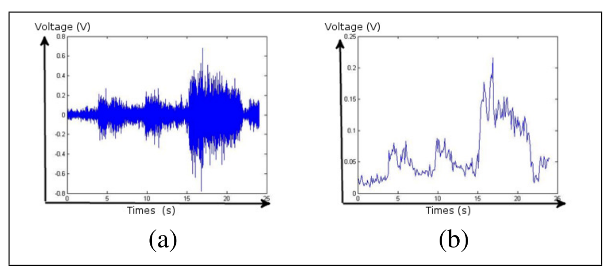

Fig. 4. Graduate contraction of the platysma muscle, dominant member, subject 1. (a) Raw signal, (b) RMS signal

We asked subject 1 to perform an isometric graded contraction of his platysma muscle and hold each contraction for 5 seconds (Fig. 4). The subject could perform a graduated contraction. The power of the EMG signal, shown by the RMS value increases threefold (53.7 $\pm$16.88 mV for the first contraction, 59.83 $\pm$14.3 mV for the second contraction, 135.83 $\pm$19.4 mV for the third contraction) during the contraction but the subject had difficulties to hold it for 5 seconds.

We asked subject 2 to perform an isometric graded contraction of his right upper trapezius muscle and hold each

TABLE I

EMG RMS VALUES FROM MUSCLES OF PATIENT 1, TIME FOR EACH CONTRACTION: 5S

Level of contraction	upper Trapezius (I)			middle Deltoid (I)			Biceps (I)			Platysma (I)		
	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)
1	75.33	18.87	0.32	72.93	9.51	0.6	NA	NA	NA	53.7	16.88	0.39
2	104	12.9	0.44	84.53	10.53	0.69	NA	NA	NA	59.83	14.3	0.44
3	237	59.9	1	122.13	12.87	1	NA	NA	NA	135.83	19.4	1

TABLE II

FOUR BEST EMG RMS VALUES FROM MUSCLES OF PATIENT 2, TIME FOR EACH CONTRACTION : 5S

Level of contraction	upper Trapezius (I)			middle Deltoid (C)			Biceps (C)			Platysma (I)		
	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)
1	50.94	7.81	0.22	273.3	59.9	0.52	110.9	8.07	0.39	73.7	2	0.35
2	96.36	3.87	0.42	370	73.2	0.71	164.8	30.8	0.58	157.5	14.5	0.74
3	226.97	211.51	1	522	61.1	1	285.8	50.5	1	213	51.6	1

TABLE III

EMG RMS VALUES FROM MUSCLES OF PATIENT 3, TIME FOR EACH CONTRACTION : 5S

Level of contraction	upper Trapezius (I)			middle Deltoid (I)			Biceps (I)			Platysma (I)		
	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)	Average (mV)	STD (mV)	Normalised value (%)	Average mV)	STD (mV)	Normalised value (%)
1	53.93	19.32	0.29	85.42	5	0.25	21.38	6.39	0.37	42.5	11.19	0.30
2	116.32	38.11	0.63	185	33.75	0.54	41.5	8.74	0.72	100	15.11	0.70
3	185	56.05	1	345	72.25	1	57.38	10.21	1	143.61	32.58	1

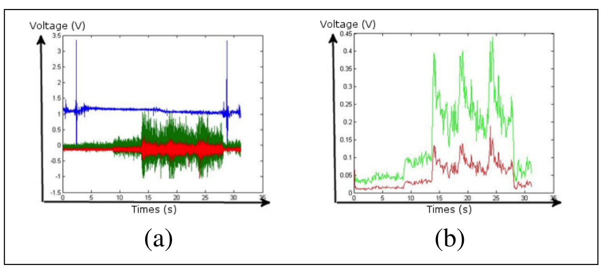

Fig. 5. Graded contraction of the upper trapezius muscle, dominant member, subject 2. (a) Raw signal, (b) RMS signal

contraction for 5 seconds (Fig. 5). The subject could achieve a graded contraction but had difficulties to hold the third contraction for 5 seconds.

Numerical results are presented in tables I II III (I: ipsilateral, C: contralateral). The 3 levels of contraction are clearly visible for all muscles for the patients 2 and 3. Indeed, for each level of contraction EMG signal increases by at least 20%. Distinction between level 1 and 2 for patient 1 is almost impossible; for instance, the average value for the middle deltoid increases by 15% (from 72.93±9.51 for level 1 of contraction to 84.53±10.53 mV for level 2 of contraction). Moreover, he failed to contract biceps.

IV. DISCUSSION

This study enabled us to target potential control strategies and to assess the relevance of using myoelectric signals in quadriplegic patients as a possible discrete control mean for future assistive devices. Our preliminary results show that myoelectric activity of muscles under voluntary control could be used to drive a FES or prosthetic hand with a limited number of contraction levels (3). The use of these different levels of contraction can be either to select a hand function or a different level of torques. 3 of the 4 muscles tested here, both on ipsi- and contralateral sides, could serve as interface for the control of assistive devices. The biceps brachii does not seem adaptated to be used for subject 1. We have not recorded in our study any electrical activity from under lesional muscles unlike [8] where authors observed electrical activity in sub lesional muscles in the lower limb in complete paraplegic subjects. Nevertheless, we cannot exclude that it is not present. Indeed, activity from forearm muscles is not very important compared to the muscles of the lower limb, particularly when we used surface electrodes.

Strong STD refer to patients who were not able to hold contraction at a stable level, or even worst during 5s. Patient 2 was unable to achieve correct stable contraction third level with his upper trapezius so that this muscle is not a good target. Finally, given that placement of electrodes for each subject is different and the medical assessment is also different, a comparison of the power developed by inter- and intra-individual muscles is irrelevant. The more a muscle is proximal, the more it will likely be controllable by the subject. Selection of muscles to be used for assistive device control has to be decided according to the subjects level of injury and remaining capacities. The 3 subjects were able to hold 3 distinct levels during the graded muscle contraction. Subjects were able to grade their muscle contractions and hold it for at least 1 sec. This duration sounds sufficient to assess a voluntary contraction and to processed the signal in order to induce a response (for instance, trigging of an hand opening or closing). Subjects are also able to contract and grade their contraction when they close their eyes. This observation proves that they are able to position their upper limbs with each other and in space (proprioception). In the presented trials, only a single contraction of the trapezius muscles, deltoid, biceps and platysma was requested. A subsequent study will help us to determine if subjects are able to contract voluntarily two or more muscles simultaneously. Thus, if the subject can both perform individual and simultaneous contraction of two or more muscles, it may possible to generate another function mode. For instance, contraction of the deltoid only could allow the opening of the hand while contraction of the trapezius could allow its closure. The simultaneous contraction of these both muscles could allow to move from a palmar grasp to a lateral grasp and vice versa. Thus, each individual could produce several movements from a limited number of active muscles. In case where a co-contraction is not possible or acceptable for the subject, the subject's ability to grade his contraction can be used instead.

V. Conclusion

EMG signals from sus-lesional muscles could allow complete quadriplegic subjects to control an assistive device for hand motion rehabilitation with a limited number of states that may refer either to few torque level of a given movement (in open loop mode) or selection of a movement among a small set of predefined functions. An EMG-based interface appears to be a solution to achieve this type of control motion in a comfortable manner.

Acknowledgements

The authors wish to thanks the subjects who invested time in this research, Mrs. Sonia Henkous, occupational therapist for her help in this study and Axonic / ANRT support the PhD grant, CIFRE N2013/0867

References

[1] K. D. Anderson, "Targeting recovery: priorities of the spinal cord-injured population," *Journal of neurotrauma*, vol. 21, no. 10, pp. 1371–1383, 2004.

[2] P. Krause, J. Szecsi, and A. Straube, "Changes in spastic muscle tone increase in patients with spinal cord injury using functional electrical stimulation and passive leg movements," *Clinical rehabilitation*, vol. 22, no. 7, pp. 627–634, 2008.

[3] N. Bhadra, P. H. Peckham, M. W. Keith, K. L. Kilgore, F. Montague, M. Gazdik, and T. Stage, "Implementation of an implantable joint-angle transducer," *Journal of rehabilitation research and development*, vol. 39, no. 3, pp. 411–422, 2002.

[4] T. Keller, A. Curt, M. R. Popovic, A. Signer, and V. Dietz, "Grasping in high lesioned tetraplegic subjects using the emg controlled neuroprosthesis," *NeuroRehabilitation-An Interdisciplinary Journal*, vol. 10, no. 3, pp. 251–256, 1998.

[5] R. Thorsen, D. Dalla Costa, S. Chiaramonte, L. Binda, E. Beghi, T. Redaelli, E. Occhi, and M. Ferrarin, "A noninvasive neuroprosthesis augments hand grasp force in individuals with cervical spinal cord injury: The functional and therapeutic effects," *The Scientific World Journal*, vol. 2013, 2013.

[6] W. D. Memberg, K. H. Polasek, R. L. Hart, A. M. Bryden, K. L. Kilgore, G. A. Nemunaitis, H. A. Hoyen, M. W. Keith, and R. F. Kirsch, "Implanted neuroprosthesis for restoring arm and hand function in people with high level tetraplegia," *Archives of physical medicine and rehabilitation*, vol. 95, no. 6, pp. 1201–1211, 2014.

[7] M. DiCicco, L. Lucas, and Y. Matsuoka, "Comparison of control strategies for an emg controlled orthotic exoskeleton for the hand," in *Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on*, vol. 2. IEEE, 2004, pp. 1622–1627.

[8] C. W. Moss, K. L. Kilgore, and P. H. Peckham, "A novel command signal for motor neuroprosthetic control," *Neurorehabilitation and neural repair*, vol. 25, no. 9, pp. 847–854, 2011.

DOCTORAT DE L'UNIVERSITÉ DE MONTPELLIER

RAPPORT DE SOUTENANCE

Nom et prénom du doctorant : TIGRA Wafa
Date de la soutenance : 14 décembre 2016
Président du Jury : André CROSNIER

Mme Wafa Tigra a présenté son travail intitulé "Assistance à la préhension par stimulation électrique fonctionnelle chez le patient tétraplégique". Dans ce travail, elle a proposé une approche qui associe d'une part la stimulation sélective nerveuse à l'aide d'une électrode gouttière multi contact, dans le but de rétablir des mouvements de préhension chez des participants tétraplégiques, et d'autre part l'utilisation de signaux émanant de muscles supra lésionnels pour le contrôle de cette stimulation. Le sujet étant très vaste et complexe, la candidate a dû surmonter de nombreuses difficultés rencontrées, en particulier, au cours de la mise en place des protocoles per opératoires.

Le jury a trouvé la présentation très claire et très pédagogique. Le choix du plan de la présentation a aussi permis d'apporter un éclairage complémentaire à celui proposé dans le manuscrit. Par ailleurs le jury a souligné que la candidate a su mener à bien un travail conséquent sur un sujet fortement pluridisciplinaire, relevant des domaines de la neurophysiologie, de la robotique ou encore du traitement de signal. Aux nombreuses et diverses questions touchant aux différentes disciplines abordées, elle a répondu de façon honnête et pragmatique.

Le jury a félicité Mme Wafa Tigra d'avoir mené son projet jusqu'à la réalisation de deux expériences per opératoires, et à l'unanimité lui a décerné le grade de Docteur de l'Université de Montpellier.

Les membres du jury :

Nom	Signature	Nom	Signature
Christine AZEVEDO COSTE	[signature]	Agnes ROBY-BRAMI	[signature]
Yannick AOUSTIN	[signature] Y.A.	André CROSNIER	[signature]
David GUIRAUD	[signature]	Jozina DE GRAAF	[signature]

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Rapport sur le manuscrit de thèse de doctorat présenté par Mme. Wafa Tigra

Le manuscrit présenté par Mme. Wafa Tigra développe ses travaux de thèse de doctorat réalisés au sein de L'INRIA sous la direction de Christine Azevedo Coste et David Guiraud. Le manuscrit est intitulé : **Assistance à la préhension par stimulation électrique fonctionnelle chez le sujet tétraplégique**.

Ce mémoire de 173 pages est rédigé en Français. Il est composé d'une table des matières, d'une table des figures, d'une liste des figures, d'une introduction, de sept chapitres, d'une conclusion de trois annexes et d'une liste de références. Le mémoire est agréable à lire et bien structuré. Le style et les illustrations sont irréprochables.

Introduction : Elle présente la cadre de la thèse. Notamment elle propose comme alternative l'utilisation de la stimulation électrique fonctionnelle (FES) invasive ou non ou de la robotique d'assistance lorsqu'une chirurgie de transfert n'est pas disponible.

Chapitre 1 : Système neuro-musculaire, lésions de la moelle épinière et stimulation électrique. Ce chapitre offre une description très fine et didactique du système neuro-musculaire, des différentes lésions de la moelle épinière. Il se termine par une présentation du principe de la stimulation électrique fonctionnelle (SEF) fonctionnelle pour palier ces lésions. L'objectif souhaité de la suppléance fonctionnelle par SE est qu'un muscle électriquement stimulé puisse se comporter comme s'il était naturellement activé par le système nerveux central SNC. La stimulation électrique permet parfois aussi de limiter l'atrophie musculaire.

Chapitre 2 : État de l'art des neuroprothèses du membre supérieur. Ce chapitre débute par une présentation très détaillée des neuroprothèses actuelles du membre supérieur. Ces dispositifs stimulent des muscles de l'avant bras, dont l'innervation périphérique est intacte. Cette stimulation induit des contractions de muscles pour permettre des efforts de pincement. Les neuroprothèses peuvent être implantées (systèmes Freehand ou FES-Mate) ou non-implantées (systèmes ETHZ-ParaCare, ActiCrip, Bionic Glove). Ce chapitre met bien en relief les difficultés respectives de mises en oeuvres de ces différentes techniques : mise en place du matériel, acceptation/tolérance par le patient, mise en évidence de la pertinence de ces technologies pour recouvrer l'autonomie selon le niveau de la lésion médullaire, volonté des industriels du domaine à investir dans les techniques de stimulation, etc. Il est montré que les électrodes de surface sont moins sélectives, plus encombrantes et nécessitent plus d'énergies que les électrodes implantées. Le placement quotidien du dispositif peut nécessiter l'aide d'une tierce personne. Elles sont toutefois adaptées pour des patients ayant subi un accident vasculaire cérébral ou pour des exercices de renforcement musculaire. Les électrodes implantées, malgré l'épreuve de l'intervention chirurgicale, pallient les inconvénients des électrodes de surface. Nous pouvons remarquer que pour les dispositifs implantés il existe deux méthodes de stimulation : La stimulation par une électrode qui est placée autour d'un nerf près des branches musculaires d'un groupe de muscles et la stimulation par une électrode qui est placée sur chacun des muscles. L'inconvénient de cette dernière méthode est d'augmenter le nombre d'électrodes nécessaires avec le niveau lésionnel du patient. La principale conclusion de ce chapitre est que les dispositifs qu'ils soient non-implantés ou implantés restent peu utilisés.

Chapitre 3 : Pertinence d'un programme de stimulation électrique implantée du membre supérieur de la personne tétraplégique. L'objectif de ce chapitre est de comprendre pourquoi les neuroprothèses restent si peu utilisées. Il s'appuie donc sur une enquête menée auprès d'un échantillon de personnes tétraplégiques. Il en ressort que les mouvements de préhension sont la priorité de récupération des patients tétraplégiques. L'acceptabilité d'une chirurgie est très importante. Afin d'augmenter cette acceptabilité des modifications apportées aux dispositifs actuels sont nécessaires comme par exemple : un système totalement implanté, une diminution du nombre de composantes, une réduction de la consommation en énergie. Je pense que ce chapitre est la clef de voûte de ce mémoire. Cette philosophie d'aller s'enquérir des vrais besoins, aspirations des patients avant de définir une quelconque stratégie est tout à fait remarquable. Et d'ailleurs ce chapitre à lui seul fait l'objet d'une soumission d'un article aux *Annals of Physical and Rehabilitation Medicine*.

Chapitre 4 : Vers un nouveau système implantable. L'auteur, à partir des résultats de l'enquête présentée au chapitre 3, définit ici "un cahier des charges" d'un nouveau système de stimulation. Il faut qu'il soit sélectif par l'activation de différentes fonctions et/ou muscles, indépendants tout en réduisant la fatigue musculaire par l'activation alternative de muscles agonistes. Ce système de stimulation doit s'appuyer sur un nombre limité d'électrodes implantés. Il doit conduire à un temps raccourci de la procédure chirurgicale et une plus grande acceptabilité de la part du patient. Enfin il doit être adapté le mieux possible au niveau de lésionnel du patient. La stimulation d'un nerf est privilégiée. Ce chapitre commence donc par une étude comparative et très documentée des différentes électrodes, intraneurales et extraneurales, couramment utilisées pour la stimulation des nerfs du membre supérieur. Il s'ensuit une presentation de ce qu'est un nerf et un descriptif du réseau nerveux d'un bras humain. A partir des connaissances actuelles l'utilisation d'une électrode gouttière multipolaire semble être le meilleur compromis haute sélectivité/invasivité. Dans le cadre de cette thèse un stimulateur a été développé. Il possède 12 sorties qui peuvent être activées indépendamment. Il offre donc la possibilité de 2^{12} configurations de stimulations différentes exploitables. Toutes ne sont pas pertinentes. Un travail de modélisation a été effectué pour déterminer les configurations les plus pertinentes. Plus de détails sur ce travail de modélisation des configurations auraient été les bienvenus car il me semble déterminant. Toutefois une référence relative à ce travail est donnée. Il est apparu que cinq types de profils de stimulation émergent. La légende de la figure 4.9 pourrait être plus précise. Néanmoins les choses s'éclaircissent au chapitre suivant. Il est observé qu'il faut non seulement activer indépendamment des contacts transversaux mais également des contacts longitudinaux. Ce chapitre introduit et justifie bien la nouvelle stratégie de simulation sélective nerveuse grâce à des électrodes gouttières placées autour d'un nerf. L'objectif est le rétablissement de préhensions latérale et palmaire chez le patient tétraplégique.

Chapitre 5 : Méthodologie. Ce chapitre s'applique dans un premier temps à bien définir un protocole de tests qui vise à rétablir deux types de préhension par SEF. Les critères pour définir de groupe d'appartenance des patients suivis sont définis selon les éventuelles pathologies, le niveau des lésions, l'âge, etc. Ce protocole a reçu l'autorisation du comité de protection des personnes Sud méditerranée IV. Ensuite l'auteur définit des critères d'évaluation des résultats, un indice de sélectivité, un indice d'efficacité et un indice de robustesse. L'auteur présente ensuite le système de stimulation per-opératoire et le déroulement de l'étude. Ce protocole n'a pas été appliqué dans sa globalité chez l'homme dans le cadre de la thèse. Ce qui est tout à fait compréhensible. C'est pourquoi ce protocole de tests des différentes configurations de stimulation a été validé sur le nerf sciatique du lapin. Une expérimentation qui me semble nouvelle et vraiment originale est définie dans le paragraphe 5.3. L'objectif est de déterminer si des muscles immédiatement supra-lésionnels peuvent être utilisés par des patients tétraplégiques pour commander une main robotique. En l'occurence il s'agit de la très belle main Shadow. A ma connaissance sa cinématique est quasiment identique à celle de la main humaine. Je trouve cette idée extrêmement intéressante et prometteuse pour l'avenir. Une question toutefois : de par sa conception les actionneurs de la main Shadow se trouvent dans l'avant bras. Il doit donc y avoir des frottements dus notamment aux câbles au niveau du poignet. Est-ce que cela ne représente pas une difficulté d'exploitation des signaux EMG pour des personnes dont le système musculaire est déjà affaibli ?

Chapitre 6 : Résultats. Ce chapitre est d'abord dédié aux résultats obtenus à partir des expériences de stimulation du nerf sciatique sur l'animal, le lapin. Plusieurs études sont menées : les intensités nécessaires au recrutement des muscles, le recrutement relatif des muscles en fonctions des configurations des électrodes gouttières, les intensités nécessaires en fonction du recrutement, etc. Il semble qu'une configuration "Anneau Bipolaire" soit la meilleure combinaison pour stimuler un nerf de façon non sélective à une intensité minimale. Le deuxième volet des résultats est dédié à la stimulation humaine. Une difficulté majeure a été le recrutement des patients pour l'étude de stimulations per-opératoires. Un seul patient a été inclus dans le protocole per-opératoires. Et quelques limitations du matériel (carte graphique) et signaux trop faibles des EMG ont entravé l'étude lors de stimulations humaines per-opératoires. Toutefois les observations per-opératoires ont prouvé que des configurations déterminées peuvent assurer une activation sélective.

Plusieurs patients ont participé à l'étude de l'EMG en vue de la commande d'une main robotique. il est montré que des sujets ont été capables de contracter sur demande les muscles évalués pendant quelques secondes. Un résultat extrêmement intéressant est qu'il est possible, malgré la fatigue de provoquer la fermeture de la main robotique pendant cinq secondes.

Chapitre 7 : Discussion. Ce chapitre est à la fois un résumé et une liste des enseignements de cette thèse et des perspectives. Ainsi l'orientation du courant provoquée par les nombreux pôles de l'électrode gouttière a permis l'activation sélective de muscles antagonistes. L'électrode gouttière a induit des mouvements chez un patient stimulé en per-opératoire. Parmi les nombreuses perspectives j'en retiens une. Il a été observé que des muscles sous lésionnels chez certains patients tétraplégiques pouvaient délivrer des signaux EMG. Ces signaux éventuellement amplifiés peuvent être eux aussi utilisés pour la stimulation, voire la commande de prothèse robotique. Cette main robotique peut aussi être un moyen d'évaluer les capacités d'un patient avant tout implantation d'un système de stimulation.

Il est évident que Madame Wafa Tigra, sous la direction de Mme Christine Azevedo-Coste et Mr David Guiraud, a bénéficié d'un environnement exceptionnel. Cette thèse a été effectuée au sein d'une équipe de l'INRIA réputée pour la qualité de ses travaux, en collaboration étroite avec une équipe médicale spécialisée pour les pathologies tétraplégiques. Il n'empêche que par la qualité et la variété de ses propres contributions Mme Wafa Tigra a effectué un travail original et conséquent. Certaines de ses contributions ont été valorisées par une conférence internationale et deux articles en revue. Un troisième article de revue qui porte sur le questionnaire est en préparation. En conséquence mon avis est très favorable pour la soutenance de cette thèse en vue de l'obtention par Madame Wafa Tigra du grade de Docteur de l'Université de Montpellier.

Fait à Nantes, le 17 novembre 2016

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Rapport pour la soutenance de thèse de Wafa Tigra.

Assistance à la préhension par stimulation électrique fonctionnelle chez le sujet tétraplégique.

ED« Information structures systèmes » Université de Montpellier

Sous la direction de Christine Azevedo-Coste et de David Guiraud

Le mémoire de thèse

Le mémoire de thèse s'articule en 7 chapitres, précédés d'une table des matières et de listes des figures, tableaux et abréviations et suivis de trois annexes.

L'introduction définit la problématique de l'intérêt de la stimulation électrique fonctionnelle chez les patients qui présentent une tétraplégie à la suite d'une lésion spinale.

Le premier chapitre est une revue de la littérature sur la physiologie du système moteur, en particulier l'excitabilité des fibres nerveuses et musculaires, la structure de la moelle épinière et la stimulation électrique fonctionnelle. Ce chapitre gagnerait à être complété par un rappel de l'anatomie fonctionnelle du membre supérieur et par plus de détails sur les classifications des lésions spinales (ces deux aspects figurent plus loin dans le manuscrit).

Le second chapitre est un état de l'art très complet sur les neuroprothèses du membre supérieur, externes ou internes en insistant les aspects techniques et cliniques du système « freehand ». Comme le système « freehand » a été commercialisé et implanté chez de nombreux patients ce chapitre est également une mise au point clinique sur les risques et les bénéfices de ce système ainsi que sur les types de préhension restaurées par le freehand : « key grip » et prise palmaire de force. Ce chapitre présente également les développements ultérieurs des neuroprothèses implantées : modes de contrôle alternatifs au joystick externe (EMG, goniomètre du poignet implanté, accélérométrie), améliorations techniques. Ce chapitre se termine par les possibilités de stimulation par électrodes gouttière. Deux autres systèmes implantés sont également présentés : le « Fesmate » et le « Stimugrip ».

Les cinq chapitres suivant présentent le travail personnel de Wafa Tigra.

Le troisième chapitre présente l'enquête par questionnaire menée par la candidate auprès de 40 patients tétraplégiques dont 31 ont été retenus. Cette enquête présente les besoins considérés comme prioritaires et les critères d'accessibilité d'une neuroprothèse implantée. Cette enquête montre la pertinence de neuroprothèse implantée pour les patients tétraplégiques.

Le quatrième chapitre expose le rationnel visant à développer des électrodes implantées sélectives. Ce chapitre comporte une revue sur les types d'électrodes implantées et sur la structure fine des nerfs périphériques qui aurait été plus à sa place dans les chapitres 1 et 2. Le type d'électrode retenu est une électrode gouttière. La méthode proposée consiste à tester différentes conditions de stimulation à partir d'électrodes gouttière à 12 points de stimulation. Le test comporte une partie de simulation pour limiter le nombre de configurations à tester et une partie expérimentale effectué chez l'animal (nerf sciatique du lapin) puis chez l'homme.

Le cinquième chapitre décrit les méthodes employées pour les deux principales études personnelles. La première pour tester la faisabilité d'utiliser des électrodes gouttières sur les nerfs médian et radial chez l'homme tétraplégique en per-opératoire. Les contraintes importantes de cette expérience sont décrites, en particulier l'exigence éthique : un CPP a été obtenu. La seconde étudie la possibilité d'utiliser l'EMG pour commander la main, en prenant une prothèse robotique pour objectiver l'ouverture-fermeture.

Le sixième chapitre présente les résultats. Tout d'abord le test des différentes configurations de stimulation chez le lapin qui confirme la possibilité d'obtenir des excitations sélectives de différents muscles. Un seul essai a pu être effectué chez l'homme en per-opératoire sur le nerf médian ce qui a permis d'analyser les grandes difficultés de ce type d'expérience et de proposer des solutions. Les résultats de la seconde étude chez cinq patients tétraplégiques montrent qu'il est possible de détecter de façon utile des activités EMG sus lésionnelles (ou même de muscles peu fonctionnels) pour commander l'ouverture-fermeture d'une main. Un CPP a été obtenu pour étudier la commande de sa propre main par FES à partir d'activité EMG.

Le septième chapitre est une discussion des résultats et une mise en perspective de la FES par rapport aux autres solutions potentielles pour restaurer la fonction du membre supérieur (chirurgie, exosquelette).

Le mémoire se termine par une conclusion. Il est enrichi d'annexes : A et B les questionnaires et C, les courbes obtenues chez les 5 lapins et d'une bibliographie de 128 références.

Impact de la thèse.

Le travail de thèse a donné lieu à deux publications en 1er auteur dans des journaux internationaux (lIEEE Trans Neural Syst Rehabil Eng. 2016 et Eur J Transl Myol) et deux communications dans des conférences internationales.

Le manuscrit est dans l'ensemble clair et détaillé avec des illustrations et des tableaux nombreux et pertinents et de bonne qualité. Il serait préférable dans le titre et le texte de la thèse de remplacer le mot « sujet » par « patient ». Le manuscrit présente toutefois des signes d'inachèvement. Le plus gros problème tient à la numérotation de la bibliographie qui ne correspond pas à la liste, ce qui fait qu'il est impossible de s'y référer. Le plan aurait pu être plus lisible, en regroupant les revues et état de l'art au début du manuscrit et en regroupant les méthodes et résultats des deux études principales plutôt que de détailler d'abord deux méthodes très différentes. Il existe de nombreuses coquilles et fautes d'orthographe. L'annexe montre toutes les courbes expérimentales, ce qui n'est pas utile, mais des commentaires pour les interpréter auraient été plus utiles.

La soutenance pourra donner lieu à des discussions sur certains aspects du travail.

- La description des modes de stimulation avec les électrodes gouttière (p 63-64) demande à être clarifiée lors de la soutenance. De plus, dans quelle mesure est ce que les résultats obtenus pourraient être généralisés à d'autres nerfs ou d'autres espèces ? La présentation des résultats est très analytique mais il manque une conclusion de synthèse des très nombreuses expériences effectuées.

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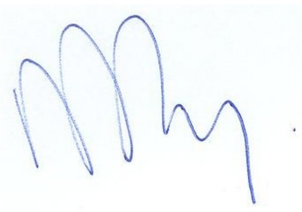
- Au sujet de l'utilisation de l'EMG pour la commande : quelle était la consigne donnée aux patients, est ce que les mouvements étaient exécutés de façon isométrique ? Le problème étant que la contraction volontaire d'un muscle isolé peut être problématique dans le cas de patients tétraplégiques avec une paralysie des muscles antagonistes. Dans quelle mesure ces commandes pourraient être utilisées pour déclencher des prises fonctionnelles chez les patients tétraplégiques ?

Au total : Il s'agit d'un travail conséquent permettant de progresser dans le domaine des neuroprothèses pour le membre supérieur chez des patients tétraplégiques : d'une part pour la validation de l'activation sélective de muscles par électrodes gouttière, d'autre part pour la commande de la FES via l'EMG. Ce travail n'a pu être validé que chez un patient en raison de la grande difficulté du recrutement et des contraintes liées à l'expérience per-opératoire.

Je donne mon accord pour la soutenance publique de la thèse.



Agnès Roby-Brami

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