On the use of sensorimotor coordinations for intuitive and ecological robotic assistance to gesture

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1.1 Healthcare robotics

Healthcare robotics, today, is a wide and expanding field of research and development. According to the definition given by the World Health Organization in 1946, *"Health is a state of complete physical, mental and social well-being and do not consists only in a lack of disease or disability"*. Consistently healthcare robotic does not only focus on providing technological tools to cure diseases, repair or assist the physical or cognitive impairments, but it now also investigates the possible improvement of the life quality of people in good health (for example by limiting physical stress or muscular fatigue) through robotic assistance. Different robotic platforms are thus being developed in research facilities and industry to provide value-added services to users of these devices, whether they are patients, clinicians or even workers in industry.

The applications of healthcare robotics (as shown in Fig.1.1) are numerous: surgery, medical imaging, rehabilitation, physical assistance (to both impaired and healthy users), telepresence, social or cognitive accompaniment, mediation, etc. The medical robots market is thus constantly growing (according to a Research and Markets report, the medical robotics market is projected to reach USD 12.80 billion by 2021).

Although some devices are already being commercialized, there remains numerous unresolved technological and scientific challenges which critically limit the performances and thus the usability of present systems, especially for the robots which are physically interacting with the human body, particularly those with sensorimotor disabilities.

These last devices are supposed to assist, support, correct, enhance, (or prevent

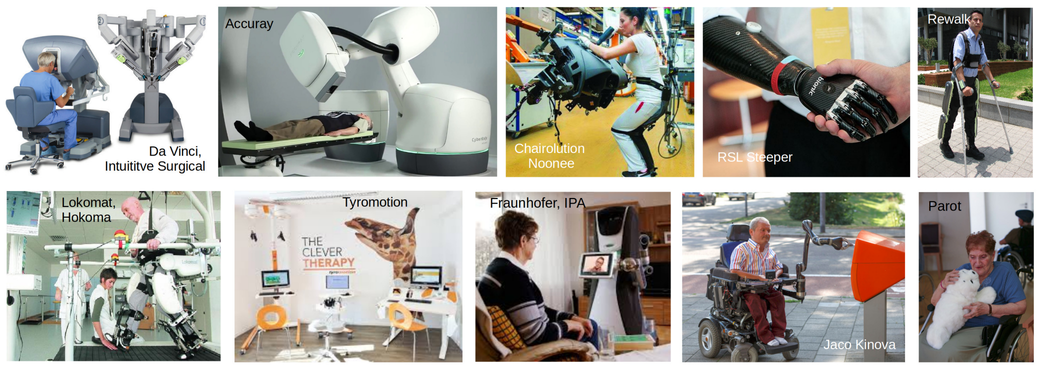

Figure 1.1: Overview of some healthcare robotic platforms for different applications

in some cases) the gesture of a user suffering from a sensorimotor disability (for example, an hemiplegic subject during a physical rehabilitation exercise, a paraplegic wearing an exoskeleton or an amputated user fitted with a bionic prosthesis). Those devices therefore need to decode finely the user's intention to provide desired assistance, and should not constrain user's perception and interaction abilities. The objective is indeed to offer an extended user experience in terms of control and perception and ultimately of appropriation and "body integration".

While a good progress has been made in the last decades on the hardware of these robotic devices (with new stiff and lightweight materials, biomimetic structures with an increasing number of active joints, improved electrical actuators and mechanical transmission technology, along with augmented embedded computation power, enhanced battery autonomy, etc.), offering users an intuitive and ecological[1] control over their "robotically assisted body" remains a critical challenge.

[1] "*Ecological*" in the sense of the ability to be used within a natural real-world environment (as opposed to a laboratory setting) to maintain the intrinsically coupling between the user and his/her environment, as in the definition of the "ecological perception" given by James J. Gibson [1]

The primary focus of the research work presented in this document is thus the development of better sensorimotor control approaches of physically interactive healthcare robots, and this, specifically for two principal clinical applications:

- *the upper-limb (UL) neuromotor rehabilitation of post-stroke patients* which aims at facilitating and maximizing the relearning of "body techniques" through supervised physical rehabilitation of brain-injured patients;
- *the assistance to gesture of upper-limb amputees* which aims at increasing the control capabilities of amputated subjects over their prosthesis and enhancing the body integration of these devices to improve their functional autonomy.

The context of these two clinical applications is briefly presented in the next section.

1.2 Context of the targeted clinical applications

Figure 1.2: Left: Neuromotor rehabilitation of a post-stroke patient through exercising in clinics with an exoskeleton (*Armeo® Power* from Hocoma, Switzerland) coupled to a gaming virtual environment. Right: Ergotherapist helping an arm amputee wearing her prosthesis (*Dynamic Arm* from Ottobock, Germany) to perform an Activity of Daily Living task (preparing meals) without exhibiting body compensation.

1.2.1 Upper-limb neuromotor rehabilitation of post-stroke patients

Hemiplegia following a stroke is one of the principal causes for acquired disability in adults [2]. Stroke (also known as cerebrovascular accident (CVA)), is a neurological disease occurring when the brain is not fed with sufficient blood flow for a period of time long enough to cause brain cell death and, as a consequence, persisting neurological deficit. A common issue for post-stroke patients is motor disability, that is moderate to severe impairments on both lower and upper-limb movements (hemiparesis), together with a loss of hand dexterity, that directly impede activities of daily living and limit their social participation. The principal goal of neurorehabilitation, is to thus induce neuroplasticity in stroke survivors, in order to recover voluntary control of movements.

For about fifteen years, the physiological knowledge on the mechanisms of the recovery and the rehabilitation techniques were turned upside down by the demonstration of a "activity dependent" cortical plasticity [3]. Thanks to this plasticity, more active, intense and targeted rehabilitation exercises can allow some recovery even long after the onset of stroke [4]. Technologies such as virtual reality and computer games help to better target rehabilitation exercises, intensify sessions, increase motivation (both phenomenons being identified as key factors in the motor recovery) and evaluate quantitatively the patients progress. Concretely, rehabilitation robots help to guide movements by physically interacting with patients. Robots can mobilize limbs of highly affected patients, but they are especially interesting for supporting the limb and strengthening active but weakened movements by automatically adjusting provided assistance in real-time. Robots can also work in resistive modes for patients who have already recovered well.
The first rehabilitation robots had a planar manipulandum kinematics (MIT Manus robot, now marketed by InMotion). Many studies have shown that rehabilitation with such robotic devices is effective but it is yet unclear if this efficiency is related to the intensity of therapy allowed by robotics (a few hundred movements in one session instead of a few tens) or if the control mode of the robot has a specific influence [5]. So far the human-robot interaction with this type of manipulandum was limited to actions over a handle, and thus was mostly focused on the rehabilitation of the end-effector (*i.e.* the hand) only, rather than a more global action over the different joints of the patient as a physiotherapist would do. Numerous exoskeleton devices have been designed in the last 10 years in order to consider rehabilitation at the joint level (see Fig. 1.2 left). Indeed, it is known that the disability of the patients is linked in part to a deficiency of the interjoint coordination between the elbow and the shoulder, and it is important to precisely train and correct this coordination [6]. However, despite the fact that numerous hardware platforms have been developed in recent years, few works focused on the actual use of this distributed physical interaction between the robot and the patient occurring at the joint level, and particularly on its effect over the patient motor behavior in the short and long term.

To sum up, while robotics use for rehabilitation seems promising, there is consequent effort to pursue for researchers to develop more versatile robotic platforms. Such devices should be able to assist patients with different level of impairment (and possibly adapt to it), especially patients who partially recovered and are able to mobilize, even if imperfectly, their limb (with the challenge of human-robot shared control and action). This will also requires the gathering of additional knowledge on the effects of the physical interaction with a robot on human motor control, in order to understand and maximize both motor adaptation and learning during rehabilitation, particularly for robots interacting at the joint level. Finally, there remains a lack of clinical evaluations of recent and more complex devices such as exoskeletons and of the possible outcome differences that may appear depending on the type of robot control (i.e. assistance) provided.

1.2.2 Assistance to gesture of upper-limb (UL) amputees

Patients with an upper limb amputation represent in France a group of over 12000 individuals [7]. These patients, most of them young active people, are usually fitted with a functional prosthesis (see Fig. 1.2 right) funded by the Social Security and composed of several active joints (hand, wrist and sometimes elbow), allowing them to regain a certain autonomy. While there have been improvements of prosthetic solutions over the last years, a significant number of amputees still consider that their prosthesis does not meet their expectations in terms of aesthetics, comfort or control [8]. Their control is indeed difficult to learn, being non-intuitive, and cognitively demanding. Moreover, these prostheses lack functionality and do not provide the expected assistance in Activities of Daily Life (ADLs) [9]. This leads to the development of compensatory strategies involving the rest of the body, causing shoulder, trunk, and contra-lateral limb disorders [10].

One of the current major issues, common to all levels of upper-limb amputation, is the growing gap between the available hardware of arm prostheses which are becoming more biomimetic with numerous active joints (e.g., polydigital hands), and the counter-intuitive and sequential control that limits their actual use [11]. For instance, the myoelectric control, which is the most common method to command an externally-powered upper limb prosthesis, relies on the use of ElectroMyoGraphic signals (EMG) from two antagonistic muscles of the residual limb (generally the biceps and triceps). An on/off strategy is applied by thresholding the input signals (amplitude and temporal variations of surface ElectroMyoGrams (sEMG)) that the patient needs to produce with the equipped muscles. Often, each active prosthetic joint that composes the substituting limb is sequentially controlled by the same control inputs. So, despite the potential possibilities offered by the new biomimetic prostheses like whole robotic arms [12] or polydigital hands [13], their control remains complex and limited [14]. And despite numerous recent developments in pattern recognition algorithm or neural signal interpretation, myoelectric control remains little robust and hard to master for patients [15].

The lack of active joints, the absence of sensory feedback, the complexity of the command and the consequent heavy cognitive load, lead to the abandonment of the prosthesis in more than 25% of upper-limb amputated patients [16]. For the ones still using their prosthesis, these issues limit the overall use of the device, and thus reduce their capability and autonomy.

An additional observation is that while a particular attention has been given to the case of hand and forearm amputation (with numerous advanced development of prosthetic hands and associated control) which is one of the most common level of amputation, fewer to no solutions have been proposed for higher levels of amputation (such as arm amputation or shoulder dis-articulation). This is problematic since people with an upper arm amputation represent a significant part of the major upper-limb amputees in western countries (for instance 33% in France [7] and 45% in the UK [17]). The issue here is not only due to aging hardware solutions for those joints but also to the lack of research on the control of multiple joints (intermediate joints and hand) in an intuitive and ecological way. Indeed, while dexterity and hand manipulation is crucial, the inability of arm amputees to correctly position and orient their prosthetic hand because of unsuitable and inefficient control of intermediate prosthetic joints is problematic.

1.3 Methods and objectives of my research

The approach chosen to tackle the challenges evoked in the previous section principally relies on the study, characterization and understanding of human sensorimotor control and on the integration of this knowledge in the design of the robot's control approaches to ease the intention decoding and improve their interactive behavior. More precisely the two principles of the chosen approach are the following ones:

- to focus on some control inputs that humans can easily and naturally control, feel and master: the movements. Humans can indeed easily control their movements, have numerous sensations provided in return (visual feedback, proprioception, along with tactile perception linked to skin strechting) and are particularly good at learning and mastering new movements skills, even if they are complex. Therefore rather than aiming at decoding motor intention from complex (and difficult to master) electrophysiological activities such as muscle contractions or cerebral states, using the body movements as principal control input has always been privileged.

- to consider the body as a whole, even when aiming at assisting only a part of the user's mobility. Therefore even when end-effector or distal actions are considered, the analysis framework should consider the movements of the proximal, support and redundant joints, and necessarily the sensorimotor coordinations that exists between the different body parts.

1.3.1 Using the knowledge on Human upper-limb motor control

Despite the great variability of human gestures, some invariant characteristics of the motor performance have been highlighted in the past years, especially for the end-effector kinematics. For example, the trajectory of the end-point (generally the hand or extremity of the grasped object) in a 3D space, follows either straight or slightly curved path, defined by a smooth "bell-shaped" velocity profile [18, 19]. Similarly numerous additional invariants do exist such as, for example, scaling laws which link the duration and the velocity of a movement with its amplitude and associated load [20].

At the joint level, while the increased kinematic dimensionality is making human gesture more variable and extending movement possibilities, there also exists some rather constant characteristics. Indeed, the presence of a large number of Degrees of

Freedom (DoF) allows the human upper-limb to potentially perform any movement in an infinite variety of joint configurations: this number of DoF (9 from scapula to the wrist, without considering the hand joints) makes the human arm kinematically "redundant" to most of the Activities of Daily Living (ADL) since those common tasks (e.g. pointing in the space, drinking and eating a meal, dressing, opening or moving boxes, etc.) require generally less DoF to be completed. This body redundancy provides human beings an extremely dexterous tool. However, the control of such a redundant system implies a complex set of control laws for the Central Nervous System (CNS). A classical hypothesis is that "synergies" [21], i.e. fundamental building blocks of motor control, are used by the CNS to decrease the apparent redundancy of the system. According to this concept, synergies (i) combine several elements, which share the same spatio-temporal properties and work together, and (ii) may be combined in a task specific way so that a limited number of synergies can give rise to a continuum of responses. However,there is still no agreement on the space in which synergies are encoded: joints or muscle level [22].

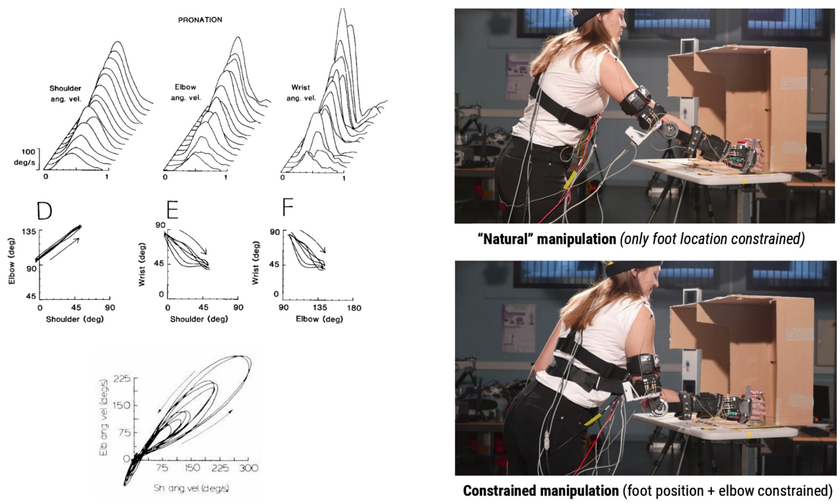

Figure 1.3: Left: typical shoulder-elbow-wrist postural and velocity coordination during a reaching task in healthy subject [23]. Right: Experimental comparison of the motor strategies used to reach a similar object in the case of a "natural" gesture (top image) and of a constrained manipulation leading to an important trunk compensation

In any event, these synergies, or synchronous coordination of the upper-limb joints, while subject-specific and task-specific are reproducible [24]. Such natural and rather constant motor interjoint coordinations are known to be found between the shoulder, elbow and wrist joints during reaching [23] (as shown in Fig. 1.3 left) or between the finger joints during grasping tasks [25].

It is also possible to consider that additional and even more global natural joint coordination schemes exist, when considering the body-compensatory strategies that humans typically exhibit when their natural kinematics is constrained or perturbed. Body-compensatory strategies can in a way be seen as "provoked" joint synergies, acting at the whole body level. The natural and unconscious enrollment, during a simple reaching task which normally only involves the elbow and the shoulder, of the scapulas, trunk, waist, knee and ankles joints to compensate for a constraint (for example an impaired joint as shown in Fig. 1.3 right, or a local obstacle) illustrates the existence of those whole body coordination schemes. Similarly it has been shown, that those motor coordinations are adjustable and that new schemes can be learned: the performance obtained with Body-Machine Interfaces (BMI) used to enable people with spinal cord injury to control a device by remapping their remaining body movements into the control space of the device [26] is a good illustration of the human CNS ability to learn new, unnatural and complex coordinations scheme. Similarly, amputees wearing a body-powered prosthesis that uses the movement of the contralateral scapula to control (through a cable) the opening and closing of their mechanical artificial hand, are able to learn and makes such new coordination scheme natural [27].

1.3.2 Objectives of my research

On the basis of the above, the objectives of my research project are :

1. **To study, analyze and characterize the natural motor coordination in humans, along with their reorganization provoked by whether the impairment, the use of tools or the interaction with robots**.
   Among others, my research has been yet focused on the characterization of *i)* the motor coordination and compensatory strategies in both healthy and patients suffering sensorimotor impairments, *ii)* the motor adaptation and learning in users interacting with an assistive robotic device and finally *iii)* the remaining or novel muscles coordination after amputation in upper-limb amputees, as illustrated in Fig. 1.4.

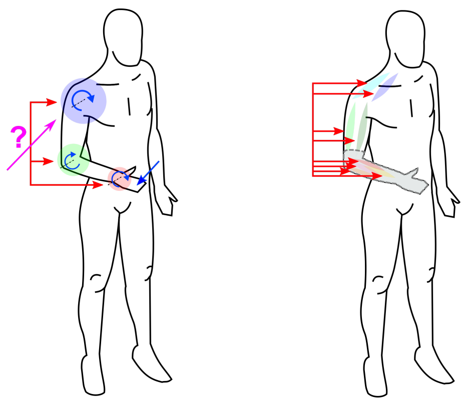

Figure 1.4: Phenomenons studied and used in the control of assistive wearable robots. From left to right: natural interjoint coordinations ("synergies"); adaptation of natural interjoint coordinations to force fields; persistance or evolution of muscles coordination schemes

2. **To use this knowledge to develop intuitive and ecological control of rehabilitation and assistive robotics.**

The objectives of these control approaches may be to *i)* minimize or maximize adaptation in human's motor control through interaction with a robot, *ii)* to make assistive robots better at decoding motor intention from natural or driven motor coordination reorganizations and *iii)* to make those devices capable of coordinating naturally with the human's body.

And finally, in parallel to these two principal technical objectives:

3. **To conduct this research in the light of the approach and knowledge of Sciences and Technology Studies.**
   In order to integrate my engineering research in a more global vision, to orient adequately my research directions and favor the development of useful, appropriable and acceptable technology for users, I am particularly interested in *i)* the multi-factor phenomenon of dody integration of technical assistances, *ii)* the ethics of research in assistive technology and *iii)* the challenges of technology communication and ideologies.

1.4 Ongoing research projects / Organization of the document

1.4.1 Understanding & improving neuromotor rehabilitation of upper-limb synergies with exoskeletons

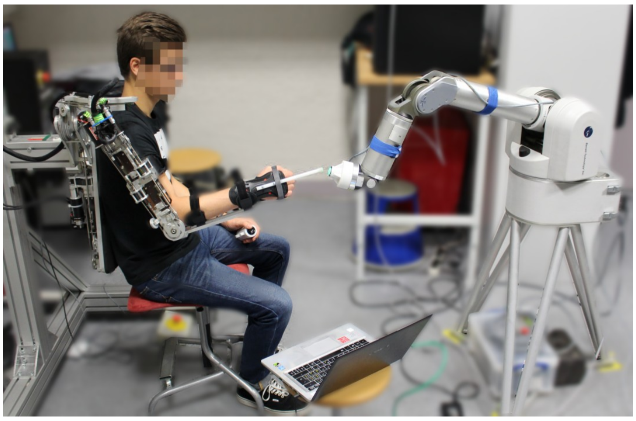

Figure 1.5: View of the experimental setup. On the left, a participant performing a repetitive task while a coordination constraint is applied by the ABLE exoskeleton. On the right, the WAM manipulator with the push button represent the variable target to reach.

Human ressources and collaboration context:
This historical research of ISIR started in 2009 with the ANR BRAHMA project in collaboration, among others, with the CEA-List (developer of the ABLE exoskeleton), the department of Neurophysics and Physiology of Université René Descartes

Paris, and later on with the Physical and Rehabilitation Medicine department of the the Pitié Salpétrière Hospital in Paris. The research I conducted, which partly pursued the former research work of Vincent Crocher (PhD student at ISIR between 2009 and 2012) on the rehabilitation of motor coordination in hemiplegic patients [28], was principally conducted during the PhD of Tommaso Proietti (2014-2017) that I supervised (direction: Agnès Roby-Brami).

This research was funded by a doctoral allocation from the region Ile de France (appel hors DIM 2013), and partly by the ISMES (Interfaces SensoriMotrices Embarquees pour la rééducation et la Suppléance) project (funded by the Labex-SMART, ANR-11-LABX-65 / programme Investissements d'Avenir ANR-11-IDEX-0004-02).

Research topic:

This research is dedicated to increasing the potentiality of rehabilitation robotics through a better understanding of human motor control and adaptation mechanisms, especially in the case of teaching "healthy" arm coordination to hemiplegic patients after a stroke.

The initial observation is the following one: during physical rehabilitation, human physiotherapists naturally adapt to the patient capabilities by varying the interaction forces with the patients limb and the rehabilitation exercises; and while such assistance or correction is provided, the subject is also adapting his movements in return. This research thus aims at better understanding the process of reciprocal adaptation in a context of physical human-robot interaction, in order to develop innovative control strategies for rehabilitation robotics. The double goal is to develop efficient solutions to guide the adaptation of the robot with respect to the human performance, and to study, in return, the way the motor behavior is constrained and adapted when the robot controls action and the transfer of adapted behavior outside of the robot.

In this context, we first developed and tested a new adaptive controller, which assists the subject "as needed", by regulating its interaction to maximize the human involvement. The simplicity of this solution permits to implement this strategy with most of the existing controllers for exoskeletons. We further compared different signals driving this adaptation, to better following the functional recovery level of the patients.

We then studied extensively the human adaptation when exposed to perturbative/constraining applied over the joint coordination of subjects dealing with 3D movement. Indeed, as previously stated, the analysis of the upper-limb synergies is critical with stroke patients, due to the presence of pathological movement patterns. Therefore, we exposed human free motions to distributed resistive viscous force fields, generated by the exoskeleton at the joint level, to produce specific inter-joint coordination and to analyze the effects of this exposition. With healthy participants, we observed important inter-individual difference, with adaptation to the fields in 21% of the participants, but post-effects and persisting retention of these in time in 85% of the subjects, together with spatial generalization, and partial transfer of the effects outside of the exoskeleton context.

1.4.2 Coordination-based control approaches for prostheses

Figure 1.6: Left: Views of a subject who received a transhumeral amputation. Right: View of a a transhumeral amputated subject performing a reaching task with a 3 active Degrees of Freedom (DoF) arm prosthesis (elbow, wrist rotator and hand) attached to his body through the use of a conventional socket covering the residual limb and a harness responsible for keeping the socket in place.

Human ressources and collaboration context:

I started this research since my recruitment by the CNRS in 2012. This research was principally conducted during the PhD of Manelle Merad (2014-2017) that I supervised (direction: Agnès Roby-Brami), during the Master degree internship of Mathilde Legrand (2017) and Lucas Lavenir (2018) and with the technical support of both Etienne de Montalivet (engineer, recruited between 2015-2017) and Alexandre Peudpiece (technician, recruited between 2018 and 2019).

This research was funded by a MNRT doctoral allocation, and the PROCOSY ("Prothèse de bras à commande synergique") project (funded by the Financement Idex Sorbonne Université SUPER, programme Emergence) and partly by the funding ISMES (Interfaces SensoriMotrices Embarquees pour la rééducation et la Suppléance) project (funded by the Labex-SMART, ANR-11-LABX-65 / programme Investissements d'Avenir ANR-11-IDEX-0004-02).

Research topic:

As previously described, there is a gap growing between the prosthesis technological possibilities and the methods to control it, especially for high level amputees. Since most transhumeral amputees have a mobile residual limb, we developed an approach which aims at utilizing this mobility to control intermediate prosthetic joints, like the elbow, based on the shoulder/elbow coordination observed in healthy movements. This research thus investigated the possibility of controlling an active prosthetic elbow using the residual limb motion, measured with inertial measurement units, and knowledge of the human motor control. A primary focus has been targeting the reaching movement for which a model has been built using regression tools and kinematic data from several healthy individuals. The model, implemented on a prosthesis prototype, has been tested with healthy participants wearing the prototype to validate the concept, and with six amputated individuals. These participants also performed the task with a conventional myoelectric control strategy for comparison purpose. The results show that the inter-joint coordination-based control strategy is satisfying in terms of intuitiveness and reduction of the compensatory strategies.

1.4.3 Mobile phantom limb & muscles coordination based control of prostheses

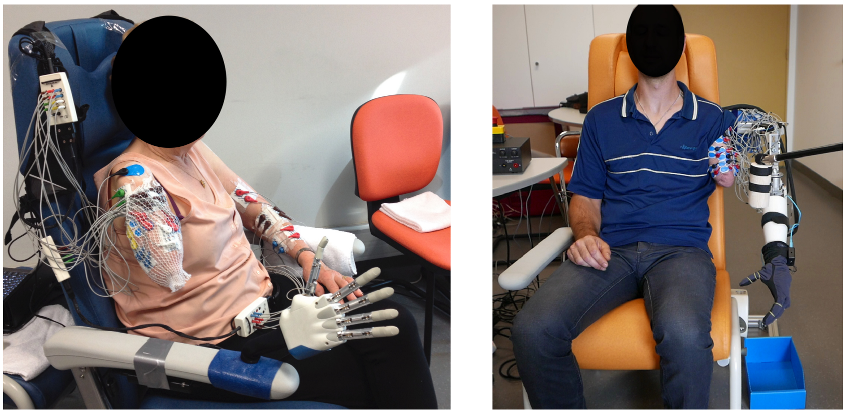

Figure 1.7: Experimental setups used to test, with transhumeral amputees, the control approach based on the decoding of the myoelectric patterns associated to the mobilization of the phantom limb, consequences of the neuromuscular reorganizations. Left: setup dedicated to the control of a polydigital hand. Right: setup dedicated to the control of an arm to perform functional tasks.

Human ressources and collaboration context:

This research started through a collaboration with Dr. J. De Graaf, neuroscientist, from Univ. Aix-Marseille, who was interested in understanding the origin of the electrophysiological manifestations of the mobile phantom limb and studying the possibility of using this phenomenon to control prostheses. We started this research together in 2013, in collaboration with the clinicians of the Institut Régional de Réadpataion (IRR Ugecam Nord-Est) in Nancy.

The scientific work of this research was conducted by myself, with the technical support of Etienne de Montalivet (2016-2017), engineer which participated in the development of a hardware embedded prosthetic control kit.

This research was initially funded by the project Reorgamp (2013-2015) funded by the DefiSENS from the Mission pour l'Interdisciplinarité du CNRS, by the project MOFACO (2015) funded by the CNRS JCJC INS2I, and finally by the project PhantoMovControl (2015-2019) funded by the ANR (project ANR-15-CE19-0008-02).

Research topic:

This research aims at using the knowledge on neuromotor reorganization and possible persistence of muscle coordination schemes following amputation in arm amputees to develop improved control strategies of prosthesis with multiple active Degrees of Freedom (DoF). The principal consequence of the neuromotor reorganization we focused on, is the existence of muscular contraction patterns associated to the voluntary movements of the phantom limb and which appear on proximal muscular groups of the stump that are normally not associated to the mobilization of distal joints.

While in the well studied case of below-elbow amputees the Phantom Limb Mobility (PLM) related electromyographic (EMG) activity is simply and strongly measured on the muscles that mobilized the fingers before the amputation (which are generally still present in the residual limb), the situation is quite different in above elbow amputees. Indeed, in the case of transhumeral amputation, PLM related EMG activity must be measured over muscle groups of the residual limb which -before amputation- were not mechanically acting on the joints of the missing limb. These signals, whether due to neuro-muscular reorganization or to remaining global supporting contraction schemes (proximal residual muscles acting in synergy with movements of the -now missing- distal limb), still seem to contain information regarding PLM. Yet, with the lack of research and knowledge on this phenomenon, the only way for above elbow amputees to increase their control capability is to receive a muscle reinnervation surgery[29] even if this remains a complex surgical procedure requiring an extended rehabilitation phase and offering a questionable risk/benefit balance.

This research is thus both focused on the quantitative characterization of this phenomenon among an extended representative population of amputated subjects (close to 100 participants) and on the development of a control approach for multi DoF active prostheses relying on the use of pattern recognition techniques.

1.4.4 Considering the ethical, legal and societal (ELS) questions of wearable assistive robotics

Human ressources and collaboration context:

This research started through a collaboration with Marina Maestrutti, lecturer in sociology from the CETCOPRA laboratory, from Panthéon-Sorbonne University, Agnès Roby-Brami, INSERM research director at ISIR from Sorbonne Université which led to the organization of an interdisciplinary workshop entitled *"Intégration corporelle de la technique"* and Guillaume Morel, professor of robotics, who pull bridges between medical robotics and sociology, over the last few years. It was later continued within the collective *"Corps & Prothèses"* (www.corps-protheses.org) which I co-founded in 2015 with Valentine Gourinat and Paul-Fabien Groud, socio-anthropologists from S2HEP laboratory of Université Claude Bernard Lyon 1,. *"Corps & Prothèses"* and gathers about ten academic researchers from different fields and aim at understanding the relationship between the body and (all) its prostheses, through experiences, uses and contexts. Twelve seminars were organized between 2016 and 2019 to study different aspects of this question. In parallel to the organization of workshops, a specific funded research project has recently being started by the collective on the use and abandon of prostheses, and particularly on two specific aspects: the experiential knowledge and the peer-learning.

The scientific work of this research was thus conducted by myself in close collaboration with the other members of the collective *Corps & Prothèses*, particularly V. Gourinat and P.F. Groud with who I co-directed the collective book *"Corps et prothèses"* published in July 2020 at the Presses Universitaires de Grenoble (PUG).

This research was initially funded by the DefiSENS - Mission pour l'interdisciplinarité of the CNRS, and then through several small fundings for the organization of workshops from the Maison des Sciences de l'Homme Paris Nord, the EREGE (Espace de réflexion éthique Grand Est), the GDR Robotique and the Labex Smart). More recently this research was supported by the project APADiP *(Analyse du processus d'appropriation des dispositifs prothétiques : pratiques des soignants, usages des patients et savoirs expérientiels.)* funded by the Fondation Janssen and the IRESP-CNSE.

Research topic:

Thanks to the numerous interactions I had with clinicians, patients and researchers in humanities throughout my research, and because of my personal interest in science and technology studies (STS), I am deeply convinced that providing efficient, suitable and acceptable assistive robotics tools does not only depend on quantitative specifications and technical performance. Indeed, as detailed throughout this introduction, while physical interaction with robots is becoming common and those are getting both more efficient and complex, an important number of those devices (especially the ones interacting closely with an impaired body) are not appropriated by their users and remain unused. In parallel, we observe a growing number of hopes turned into beliefs on the unlimited possibilities of technology to repair the human body, or even to enhance it ("trans-humans") to the point that a novel kind of human (a "transhuman" up to a "post-human") could be created. This last imagery, possible consequence of the convergence of popular science-fiction productions, the oversimplification of the media speech on science and technology, and the influential transhumanist ideologies, is so present and strong, that it starts raising ethical and societal questions that can not be avoided when developing robotic assistance.

For these reasons, I try to conduct a more "global" research capturing all the aspects of the body integration of technological devices, and particularly the socio-anthropological and cultural phenomena affecting the representation, appropriation and use of technical objects which interact with the body. I believe that considering these complementary points of views and theories in the design process of technical devices could be a way of improving their appropriation. It is also possibly a good approach to conduct an "ethical" technological research in this field.

Chapter 2

Understanding and improving neuromotor robotic rehabilitation of upper-limb synergies with exoskeletons

Sommaire

2.1 Improving rehabilitation robotics

Despite the numerous robotic devices developed in the last decades for neurorehabilitation, modern exoskeletons have so far not brought any major improvement to the results achieved with the pioneer generation of planar robots [30] or to the standard post-stroke therapy. Indeed the first and only results on a randomized controlled trial with the Armeo Power© (Hocoma, Switzerland) and 77 post-stroke patients did not produce significant improvements with respect to the traditional therapy [31], making the clinical relevance of robotics (and of complex systems such as exoskeletons) questionable.

Several causes to this lack of results can be given. The first one, as shown in a review we performed [32], remains the lack of innovative control strategies, adapted to multi-DOF joint space based devices. Indeed, most of the available controllers for exoskeletons are often implementation of 2D control laws on a 3D device. Robotic exoskeleton state-of-the-art almost completely lacks controllers addressing the upper-limb coordination, which is nonetheless heavily impaired in post-stroke survivors and strongly reduces the long-term motor improvements. Additionally, as stated in the introduction, there is a lack of understanding and consensual models of the human motor control at the joint level, along with a limited number of tools to characterize the interjoint motor coordination. This absence of knowledge clearly limits the possibility of developing innovative exoskeleton control approaches making use of human motor learning behavior such as the advanced ones developed for manipulandum (e.g. [33]) which could be real game changers for rehabilitation.

Another possible explanation lies in the fact that robots offers a very standardized therapy which cannot really deal with the necessities of different patients and particularly with the evolution in their motor capabilities through recovery. Having a fixed level of assistance or rarely adjusting it to the patient's state could limit the freedom of the patient's movements (i.e. the respect of their motor intentions), and consequently decrease their involvement in the action. Rehabilitation (similarly to teaching) is different from assistance [34]: indeed, because of the slacking of human motor behavior [35], providing too much assistance to the patients will encourage them to simply rely on the assistance instead of (re)learning to perform with their own body. Similarly, if the assistance provided is not sufficient (at some early recovery stages), patients could be unable to perform the exercise at all, reminding them of their disability and thus reinforcing the "learned non-use" [36] of the affected part of the body and an extended use of compensatory strategies.

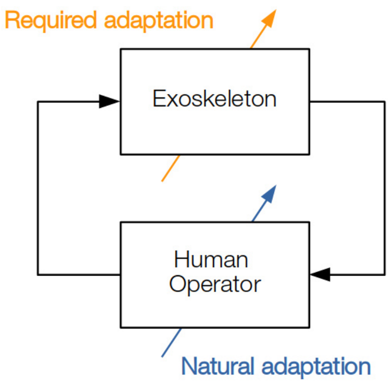

Figure 2.1: Representation of the reciprocal adaptation that should occur in an optimal rehabilitation session: robot is providing "assistance as-needed" to maximize the adaptation and learning of user's motor behavior

We thus realized that one major feature which could unleash the potentiality of robotics is therefore to consider the "reciprocal adaptation" as shown in Figure 2.1: adaptation of the robot action to the evolution of human motor behavior; and in return understanding the adaptation of humans to the application of joint force fields to maximize the (re)learning after the interaction with the robot. For this reason, during the PhD thesis of Tommaso Proietti, we studied those two aspects in parallel. On one hand, we tried to experimentally determine the optimal solutions to smartly guide the adaptation of the exoskeleton with respect to the human performance. On the other hand, we focused on characterizing the way human motor behaviour is constrained and adapt when an exoskeleton is applying a force field at the joint level, and how those motor changes remain when the robot is removed.

2.2 Adapting robotic assistance to the human motor performance

In the current literature, different solutions exist which discretely map the successive stages of the patient recovery (as shown in Figure 2.2), from "passive" control, which makes the robot fully stiff and in charge, to partial assistance (requiring some effort from the operator) up to "active" modes, in which the robot is transparent and only compensating for its weight (and friction). However, these remain separate controllers that the therapist has to select manually (when they are available on the rehabilitation robot) depending on patient capabilities, and which will hardly capture the fine, continuous and permanent evolution of patient's motor recovery. For all the previously listed reasons, there is thus a need for *"assistance-as-needed"* solutions, able to automatically and continuously adapt the robot behaviour throughout trials and sessions. While this idea is not new in the literature, we proposed a simple adaptation paradigm which can be implemented with most of the existing controllers for exoskeleton. At the same time, we compared different strategies and signals driving this adaptation, in order to better following the functional recovery level of the patients.

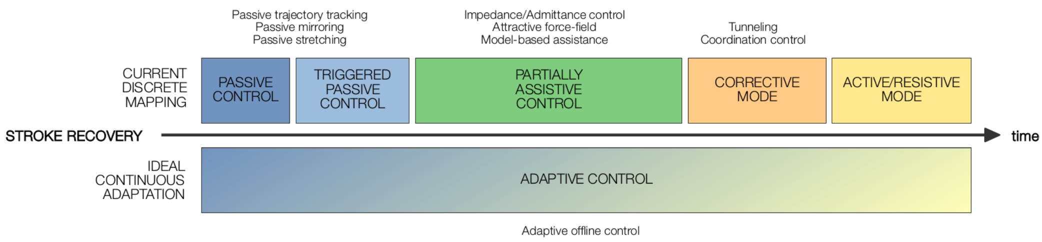

Figure 2.2: Optimal mapping between patient recovery stage and robot control strategies. As shown, the assistance provided by the robot is discretely, and generally manually, updated. An ideal adaptive controller would be able to finely continuously modify its level of assistance, better following the patient capabilities. Taken from [37].

The goal of an efficient assist-as-needed (AAN) control is to avoid over-assistance which would have negative effect over the rehabilitation process because of the slacking behavior of human CNS [38], while under-assisting the patient would lead to failure and a drop of involvement. During, T. Proietti we developed a simple version of an AAN inspired from human motor control adaptation.

2.2.1 Adaptive Control

2.2.1.1 Working principle

The principle is simple: the controller should be able to tune automatically and continuously its level of assistance based on the performance of the user of the exoskeleton across a session consisting of the repetition of a motor task. This last one is generally standard and predefined in a rehabilitation environment. Trial after trials, the performance of the user in completing the task with the robot will be used to modulate the level of assistance, from "full assistance" (passive mode) with a stiff robotic assistance along the good trajectory when the user is unable to perform, to no assistance with a fully transparent robot (active mode) only compensating for its own weight.

2.2.1.2 Control algorithm

Our AAN control strategy produces an output $w \in R_n$, where n is the number of joints of the robotic exoskeleton, which is composed of two terms $w = u + v$ where $u \in \mathbb{R}_n$ is a feedforward term (model-based gravity compensation balancing the robot's weight), and $v \in \mathbb{R}_n$ is a feedback control, and more precisely an adaptive proportional-derivative (PD) control, (i.e. an impedance control without inertial term):

$$v = K_p e + K_d \dot{e}, e = q_r(t) - q(t) \tag{2.1}$$

where $q(t)$ is the joint position vector, and error signals e and $\dot{e}$ are calculated with respect to the reference joint trajectory $q_r(t)$ and the reference joint velocity $\dot{q_r}(t)$. K_p, the stiffness term, and K_d, the damping term, are positive diagonal matrices of gains.

Based on some work on human stiffness modulation according to environment perturbation [39], and some implementation of this behavior for adaptive haptic exploration [40], the gains of the PD controller are adapted trial-by-trial, based on the former performance of the subject. Namely, at a given trial k, the controller proportional gain $K_{p,i}$ for the i-th joint of the exoskeleton is computed by:

$$K^k_{p,i} = K^{k-1}_{p,i} + \beta_i z^{k-1}_i - \gamma_i \tag{2.2}$$

where the learning parameter β_i and the decay γ_i are positive scalars, and z_i represents the reference parameter at trial $k-1$ to evaluate the performance of the i-th joint (i.e. similar to a performance error).

In addition, to avoid large increasing of the robotic stiffness and thus awkward feelings on the arm of the human operator, the stiffness variation increment was upper-saturated. Additionally, the damping $K_{d,i}$ was also modulated proportionally to $K_{p,i}$.

2.2.1.3 Performance metrics (adaptation signals)

The particularity of this simple implementation is that it can be used to produce different kind of robot adaptation (targeting certain aspects of the motor behaviour) by simply modifying the computation of the reference parameter z_i. We therefore defined four different error signals capable of driving the adaptation process of the i joints of the robot. First, two local adaptation rules:

- **Correction Amount Based adaptation**, using the mean of the absolute value of the feedback term v during previous trial as reference parameter z_i: if the robot controller has to correct a lot the trajectory, it will raise its stiffness at the next iteration.
- **Joint-By-Joint based adaptation**(JBJ) in which each joint being locally adapted based on the integral of its own error (position and velocity) at previous trial.

Then two global adaptation rules:

- **End-Effector Based adaptation** (EEB) in which all the joint are being adapted based on the integral error of the end-effector at previous trial. If the end effector trajectory is well followed, whatever the joint trajectories are, the robot will become transparent.
- **Single-Joint Based adaptation** (SJB) in which the error of one chosen specific joint drives the adaptation of the whole exoskeleton.

We believe that end-effector based adaptation can be the solution when functional recovery is needed (regaining of independence and functionality for performing activities of daily living). A joint-level adaptation could be more effective for impairment recovery, since it addresses the regaining of strength and muscle tone, range of motion, as well as joints arm coordination, for example to avoid unnatural joint synchronization and trunk compensation while extending the arm.

2.2.2 Experimental evaluation

2.2.2.1 Preliminary validation

Preliminary trials were conducted on six healthy subjects mimicking the relearning of a stroke patient undergoing rehabilitation. Participants attached to the exoskeleton, were asked to draw two times in the air, a 50 cm square, during 50 trials, and to exhibit different levels of participation (see top labels of Figure 2.3) to the achievement of the task throughout the trials. The Correction Amount Based adaptation alone was used for this preliminary assessment. Initial robot stiffness $K^1_{p,i}$ and damping $K^1_{d,i}$ were set to high values at the beginning (i.e. start in passive mode). The robot participation was measured across trials (as the total current consumption required by the robot during the task) along with the human participation (as the total muscle activity measured with surface electromyography on a set of 5 principal muscles of the arm attached to the exoskeleton).

The performance of the adaptative behavior with one representative participant can be seen in the Figure 2.3. The performance of the controller is the expected

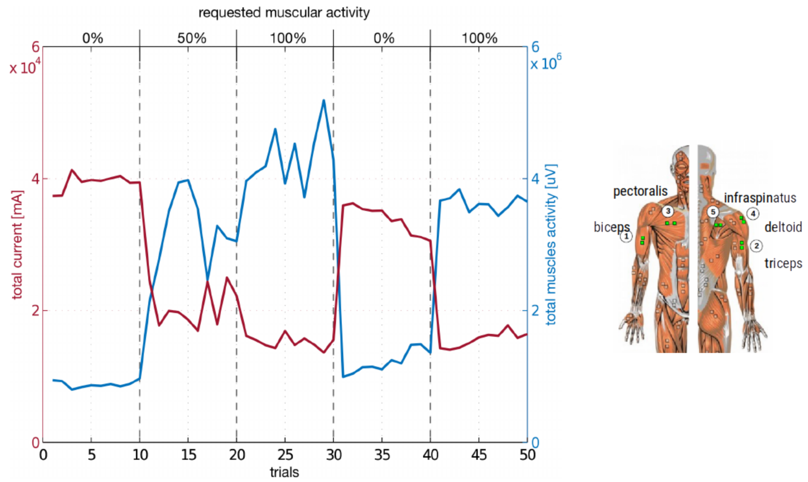

Figure 2.3: Robot adaptation with respect to the human performance. Total muscular activity (blue line) measured over the muscles indicated on the right, and total current from the adaptive PD controller (red line) over the 50 trials. On top of the figure, the percentage of participation (i.e. muscular activity) requested to the subject, trial-by-trial. Taken from [37].

one: it is able to reduce the stiffness of the robot while the subject is increasing his voluntary effort along the desired trajectory (thus his muscular activity) and it increases again the stiffness of the robotic arm when the human is relaxing.

Additionally, we validated the possibility of tuning the adaptation rate of the AAN controller by changing the parameters β and γ values, for example to adapt within the session (fast adaptation, for short-term performance) or within the therapy (slow adaptation, for long-term ones). This manual tuning of the adaptive parameter could allow the physiotherapist to control these strategies, in a simplified way, based on the necessities of each patient.

2.2.2.2 Comparison of different error signals driving the adaptation

To evaluate the ability of our controller to address different rehabilitation issues through the adaptation to several aspects of the motor performance, an additional experiment was conducted. We asked five healthy subjects to outline a 25x25cm foam-made rectangle, placed in front of them. Similarly to former experiment, throughout 40 trials, we asked the subjects for specific behaviours imitating different stages of motor recovery/abilities of post-stroke patients (see top labels on Figure 2.4.A) with robot starting in passive mode.

As expected, as shown in Figure 2.4.A, all the AAN controllers adapted correctly to the behaviour of the exoskeleton operators.

As illustrated in Figure 2.4.B, we observed differences in adaptation with, for example, EEB allowing different (but possibly wrong) joint coordination contrary to JBJ, or SJB (here computed on the shoulder opening angle) leaving more freedom on the inter-joint coordination.

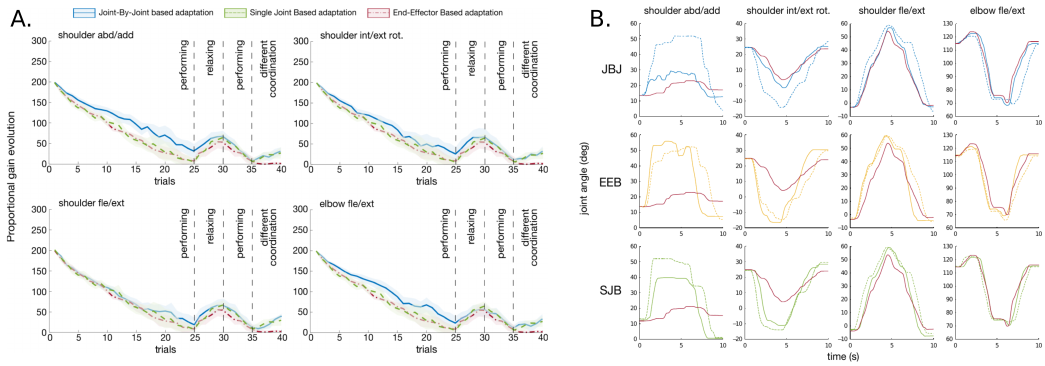

Figure 2.4: A. Evolution of the four $K_{p,i}$ during the experiment, averaged over the five subjects, for the three adaptive paradigms. For each condition, the shaded colored area represents the standard error. B. Joint trajectories for the three strategies. Each column is one of the four joints of the ABLE exoskeleton. For each plot, three trajectories are shown: in red, the desired joint trajectory, the 36th motion (dashed line) and the 40th trial (solid line). Taken from [41]

Overall, it seems clear that there is no a single optimal strategy to drive the adaptation in AAN controllers, and that the choice should be carefully made according to the type and phase of rehabilitation, with the risk of requiring again a human intervention to select the training parameters.

2.3 Understanding adaptation of human interjoint coordination

This work was reported in [42] shown in the Appendix

To study this phenomenon of adaptation at the motor coordination level, we exposed human free motions to joint resistive viscous force fields, generated by the exoskeleton to produce unnatural inter-joint coordination. We then characterized the effects of the exposure to joints distributed constraints on the upper-limb coordination during and after the experiment. This is a first step towards understanding the human-exoskeleton physical interaction, which could provide insights on the effect of robots on human coordination schemes, along with innovative ways to develop rehabilitation controllers for improving post-stroke motor recovery.

2.3.1 Motor adaptation and learning in humans

2.3.1.1 What is motor learning?

Motor learning is a complex process which can be decomposed in several sub-phenomenons (as shown on Figure 2.5). First, the **Adaptation**, which is the process of "the recovery of performance within the changed [...] environment" [43], then the **Post-Effects / After-Effects**, which is the modification of the motor behavior observed after the removal of a motor perturbation. It is usually followed by a

Wash-out, i.e. the disappearance of the post-effect and the return to natural (or earlier) motor behavior, or on the contrary by a **Retention**, which is the maintenance of adaptation/post-effects in time. Then **Generalization**, i.e. the presence of adaptation/post-effects along previously unperturbed spatial directions (or tasks) which were not exposed to the perturbation can be observed, or even some **Transfer**, that is to say the appearance of adaptation/post-effects in different activities or contexts.

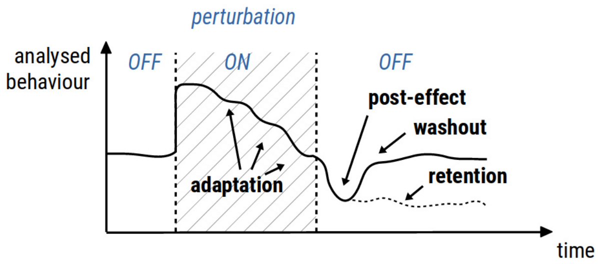

Figure 2.5: Chronology of motor adaptation and learning to perturbation. Adapted from [37].

2.3.1.2 Adaptation to robot physical action

One principal result on motor learning under robotic constraint was obtained by Shadmehr and Mussa-Ivaldi in [43], in which healthy subjects performed arm pointing tasks under the effect of a deviating force field produced by a planar robot. After initially failing, due to the force field, the users were able to learn how to complete the required task by progressively adapting to these disturbances. Once the force field was removed, participants temporary showed an over-shoot on the opposite direction of the field, as an after-effects or post-effects, as shown in Figure 2.6.A.

Unfortunately, little is known on similar effect of 3D or joint force fields on the overall motor coordination strategies and the management of redundancy by the CNS. Mistry et al. [44] investigated human force field adaptation using an exoskeleton. Authors observed that participants exposed to a force field applied on a single joint, behave, similarly to [43] at the hand level, but no adaptation at the joint level (which remained changed) was observed (see Figure 2.6.B). This indicates that the effect of perturbation or constraint on joints trajectories and thus on motor coordination is a more complex phenomenon.

Therefore a central question remains on the actual possibility of teaching motor coordination (or at least acting over it) with an exoskeleton and thus using this type of device for the clinical rehabilitation of "non-pathological" synergies. We thus decided to rigorously study and quantify the reaction of subjects being exposed to a viscous force field specially designed to modify the interjoint coordination.

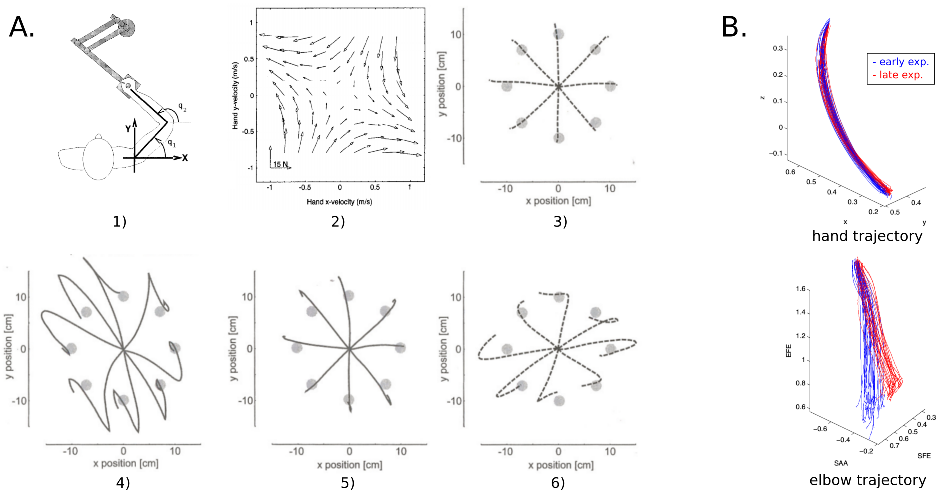

Figure 2.6: A. (left): View of the setup, of the perturbative force field and of the four typical consecutive phases of human motor adaptation and after-effects (from [43]). B. (right). View of end-effector and joint trajectories under exposure to joint force field (from [44]).

2.3.2 Experiment

We set up an experimental campaign to evaluate the possibility of modifying upper-limb synergies in healthy participants, by inducing adaptation and learning of joint coordination through the exposition to viscous force fields applied by an exoskeleton. A group of healthy subjects performed numerous randomized pointing tasks (with targets being designated by the end-effector of a WAM robotic arm manipulator fitted with a push button) as shown in Figure 2.7.

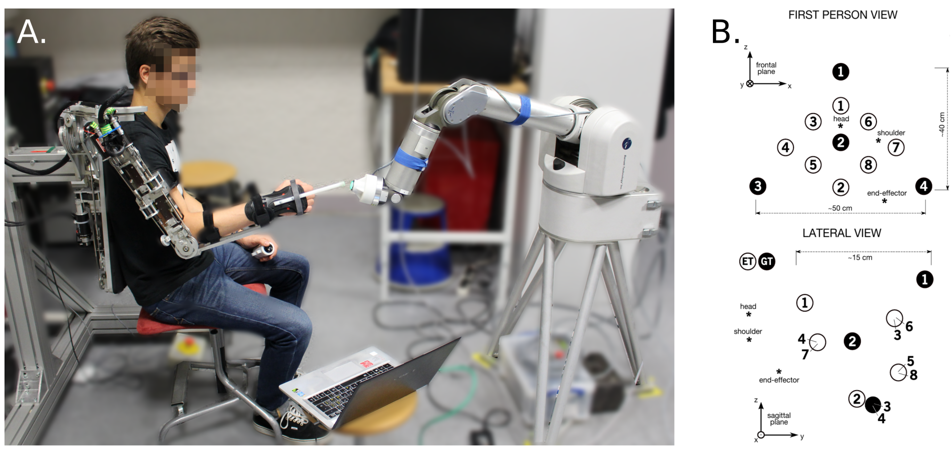

Figure 2.7: A: Experimental setup. On the left, a participant of the experiment within the ABLE exoskeleton. On the right, the WAM manipulator with the push button on top. B: WAM positions (targets). The 8 Experimental Target positions (ET) and the 4 Generalization Target positions (GT). The asterisks * show the mean position of head and shoulder, and the projection of the starting position of the elbow/end-effector.

2.3.2.1 Exoskeleton and controller

For this experiment, we used the 4 DoF ABLE exoskeleton [45] both to apply a force field to the participant arm joints, and to measure (thanks to its joint encoders) the kinematics of participant's arm when the constraint was applied or removed (exoskeleton being then set in "transparent mode").

We utilized two different control modes on the ABLE exoskeleton: a joint force field entitled *Kinematic Synergy Control* (KSC), to expose subjects to viscous force field that should perturb the joints coordination during movement, and a generic *Gravity Compensation* mode (considered as "transparent" mode) allowing unconstrained upper-limb motion. The KSC is a controller developed by Crocher et al. [46] which generates reactive viscous joint torques to impose specific patterns of inter-joint coordination without constraining the hand motion. This controller was here tuned in a way to provide a generic perturbing behavior (complex enough not to be easily predictable) pushing towards unnatural inter-joint coordination encouraging an over abduction while flexing the shoulder during forward hand movement.

The gravity compensation mode simply consisted in an always active feedforward gravity compensation of the exoskeleton to produce minimal resistance to the human motion, giving freedom of movement to the user [47]. This control mode can be seen as the situation in which the corrective force fields were inactive.

2.3.2.2 Experimental protocol

Twenty healthy individuals participated in this study: ten of them were asked to perform several pointing tasks (**GDM**, for Goal Directed Movements) while the ten others performed tracking tasks (**PCT,** for Path-Constrained Tracking) with the ABLE exoskeleton while sitting comfortably on a stool. The experimental protocol has been validated by the ethics committee of the Paris Descartes University (CERES).

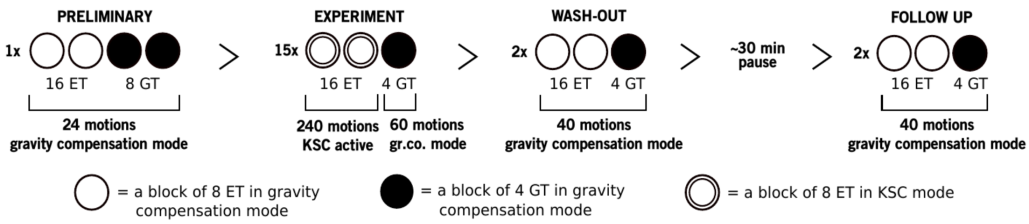

Figure 2.8: Phases of the experiment. Experimental protocol, showing the four consecutive phases, respectively preliminary, experiment, wash-out and follow up. Before the follow-up, the subject was resting, detached from the exoskeleton, for about 30 minutes. The number in front of each phase stands for the number of repetition of each pattern (1 repetition for PRE, 15 for EXP, and 2 for WAS and FOL).

After an initial training, subjects were asked to point different targets with the robotic exoskeleton. All the sequences of pointing tasks were performed by blocks of 8 ET trials (Experimental Targets, see Fig. 2.7.B) or 4 GT trials (Generalization Targets, see Fig. 2.7.B) presented in the same randomized order for each subject.

The experiment duration was between 90 to 105 minutes for each participant. The experiment chronology, as shown in Figure 2.8, consisted of 4 phases: preliminary (PRE), experiment (EXP), wash-out (WAS), and follow up (FOL). Before FOL there was a pause of about 30 minutes, during which the participants rested, detached from the exoskeleton. It is important to underline that the KSC was active only during EXP and only during the pointing tasks towards ET. Otherwise, the robot was controlled in gravity compensation mode. Therefore, as shown in Figure 2.8, the KSC was perturbing and correcting the subject free motion only during 240 movements over the 404 total movements of each experiment. GT movements were always unconstrained.

2.3.3 Principal results

The results showed that most of the subjects could learn from this unknown and unnatural interactive environment, meaning that their natural upper-limb coordination was exhibiting effects of the force fields exposition in terms of adaptation, post-effects, and generalization. The presence of after-effects was still observable after 30 minutes from the last constrained movements, during which time subjects were detached from the exoskeleton and rested. The main results obtained are detailed below.

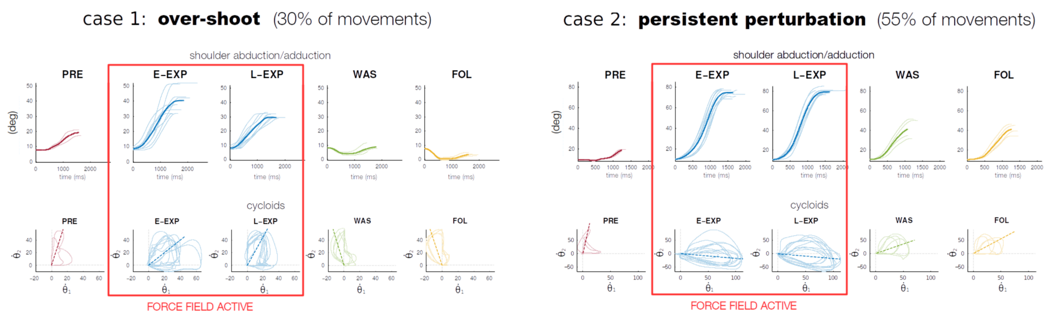

Figure 2.9: Two illustrative cases for two subjects, during GDM task. On top, the averaged trajectory of the the shoulder abduction/adduction (dark plots) and the single trajectories (lighter plots), when moving towards ET 4; on bottom, for the same target, the resulting cycloids when considering the ratio between the first two joint velocities (shoulder abduction/adduction versus internal/external rotation). In this case the light plots are the cycloids, while the dark dashed lines are the mean ratio. For the four graphs, data refer to the 5 phases of the experiment: preliminary (PRE), early exposition (E-EXP, first five repetitions of EXP), late exposition (L-EXP, last five repetitions of EXP), wash-out (WAS), and follow up (FOL)

A limited adaptation during interaction: Adaptation in participants who tended to minimized the effect of the perturbation induced by the robot, was only observed in 21% of the population. A majority of participants did indeed not adapt (i.e. react) to the robot's perturbation, similarly to the observation in [44].

Two distinct behavior in the post-effects: The major result of this study lies in the fact that we clearly observed two different types of motor behavior and therefore two distinct post-effects. Those post-effects were observed in 86% of the population. As shown in Figure 2.9 "Case 1", in a minority of cases (30%) in which adaptation occurred (variations between E-EXP and L-EXP), an over-shoot on the opposite direction of the natural original coordination (thus similarly to [43], but at the joint level rather then at the end-effector) was observed. And surprisingly it remained in the follow up period.
But as shown in Figure 2.9 "Case 2" the most common pattern (55%) consisted of, after no adaptation seen between E-EXP and L-EXP, a persistence of the perturbation during the wash-out and even the follow up period. This persistence of the perturbation could be the direct consequence of the CNS not globally optimizing the motor behaviour, but rather tending to repeat sub-optimal task-satisfying solutions, because of influenced by motor memory, as described by Growishankar et al. [48]. In the remaining 15% of the cases, we did not observe any significant post-effect.

Imposing or teaching novel joint coordination: Thanks to a joint coordination comparison metrics [49], we compared, for the two tasks GDM and PCT, the distance (i.e. difference) between the coordination exhibited by subjects when exposed to the exoskeleton and the natural one exhibited by subject in the PRE phase during which the robot was transparent.

This evolution in the difference of interjoint coordination with respect to their natural coordination was analyzed for both targets exposed to the force field (ET) to characterize adaptation, and for those which were never exposed (GT) to evaluate the generalization of the effects.
The result can be seen in Figure 2.10. By construction, the KSC should increase the difference between EXP and PRE (natural) coordinations, and decreases the difference with the coordination that it imposes. We can clearly see this consistent effect of the presence of the KSC during the experiment phase (bars in blue) for the two tasks (GDM and PCT. In fact these distances are large and almost constant for all the subjects, and very different from the natural synergy variability of healthy humans performing pointing tasks shown in red. The last four bars, respectively two for WAS and two for FOL, represent the post-effects of the force fields exposition. During these phases, participants were no longer under the constraints of the force field, but were instead performing with a gravity compensated robot, similarly to the PRE phase. Wash-out and follow up synergies, both in GDM and PCT exercises, show difference to the spontaneous variability value. This means that a different inter-joint coordination was still present, on most of the participants, even 30 minutes after having performed the last movements under the perturbation by the KSC. **The main result are thus that the exposition to the force field**

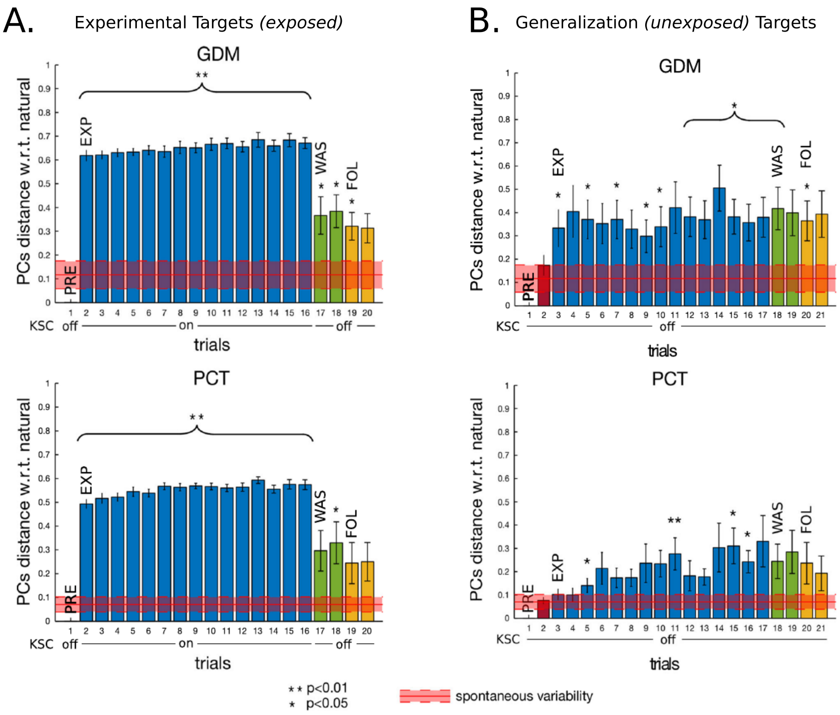

Figure 2.10: **A**: Difference of coordination (i.e. PCs distance) with the "natural" (PRE) coordination, on **ET** pointing task, for the two tasks GDM and PCT. **B**: Difference of coordination with the natural one, on **GT** pointing task, for the two tasks GDM and PCT. In red, mean values and standard deviation of spontaneous coordination variability within a transparent exoskeleton measured with 5 healthy subjects. Asterisks * mean significant difference w.r.t. spontaneous variability after non parametric one-sample sign test. A small value of the PCs distance indicates a similarity between interjoint coordination.

is effective, but with a rather poor adaptation of participants during the session, and that there is a visible and persisting after-effect..

Unfortunately, while participant exhibited different coordination after being exposed to the joint force field of the exoskeleton, the subjects did not learn the desired synergy, as it can be seen in Figure 2.11: the KSC was able to correctly constrain the participants to perform the desired synergy (EXP phase) for each mode, but the post-effect of WAS and FOL phases does not seem to correspond to the effective constraints on the joint coordination.

Spatial generalization of effects: An interesting result is that generalization phenomenon did occurred in participants, since the results observed in targets exposed to the force field (ET, see Figure 2.10.A) were also observed in targets never exposed to the force field (GT, see Figure 2.10.B), with an increased adaptation observed in PCT task.
This is promising for rehabilitation since training the coordination for one gesture type toward a limited number of targets (as it is the case in a rehabilitation environ-

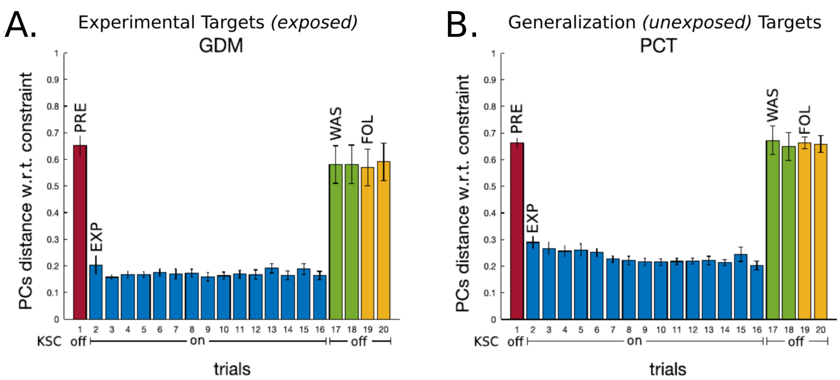

Figure 2.11: **A**: Difference of coordination (PCs distance) with the one imposed by the KSC, on ET pointing task, for the two tasks GDM and PCT.

ment) could be sufficient to generate a global improvement of motor coordination (at least for one given task).

Transfer of the post-effects outside of the robot: An additional experiment was performed to evaluate the generalization of this motor behavior modification to another environment. This would be fundamental for rehabilitation efficacy, to ensure that patients would generalize,an even transfer the motor strategy "learned" with the robot in a clinical environment, to movements performed out of it at home, and without the device. We therefore ran an experiment on one healthy participant who perform the same protocol, but the "natural" movements and coordination (at the PRE, WAS, and FOL) were recorded outside of the exoskeleton, with an optical motion capture system. Additionally follow up was performed 2 hours (instead of 30min in previous protocol) after the wash-out and second follow up was added (FOL2), after a short additional interaction phase. Similar results were obtained as

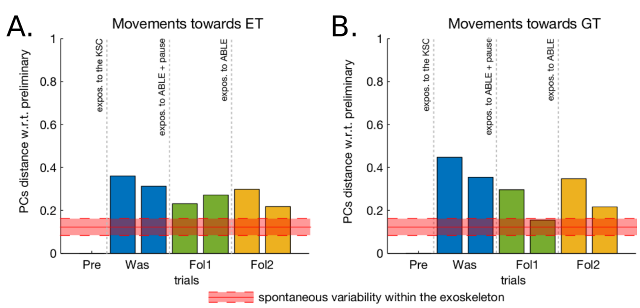

Figure 2.12: **A**: Difference of coordination (PCs distance) with the natural one (measured during PRE), on ET and B. on GT targets for the GDM task, for one subject with assessment phases performed outside of the exoskeleton with MOCAP

shown in Figure 2.12 showing that a difference in interjoint coordination was still visible, in the wash-out and follow-up phase, and remained visible 2 hours after the experiment. This indicates that the adaptation and learning effect seem to be generalized enough to be visible in a different context and type of interaction (i.e. outside of the robot). While encouraging, those results remain preliminary since they were conducted on one subject only. Longer and more repeated protocols will thus be necessary to provide stronger conclusions.

2.4 Conclusions and perspectives

2.4.1 Robot adaptation

The proposed AAN approach is a simple solution that can easily be implemented on numerous exoskeleton since those generally use impedance controllers (even if a good level of back-driveability and transparency may be needed to offer low impedance behaviours). The limited number of tuning parameters could make it easily customized to the patients by the physiotherapist. Additionally, the use of different adaptation strategies depending on the type of targeted exercise may provide a wide range of rehabilitation solutions: some (as EBE) for functional training focused on the end-effector, some (as JBJ) for strength and coordination training, or to focus on physiologically relevant features such as a defective joint strategy (with proposed SBJ). Nevertheless, it would be also necessary to develop additional adaptation strategies using, instead of an error requiring a predefined (and thus constraining) trajectory, other performance metrics such as the level of muscle activation level, the type of inter-joint coordination, etc.

Overall, while being encouraging, these experiments clearly need to be conducted on post-stroke patients within a rehabilitation to ensure of the real performance of the proposed method with pathological motor behaviors and slower, and more unstable evolution.

While performing experiments with patients in a clinical environment is becoming particularly difficult to organize (for ethical and safety reasons) with complex experimental research devices such as exoskeleton (a CPP has been already been submitted several times but did not succeed because of the lack of certification and CE marking of our experimental exoskeleton), we also plan to study within the next years, the possibility of using our AAN approach in a different context, the one of assistance to healthy operator in industry. Within the new research project ANR EXOMAN (started in October 2020) piloted by B. Berret from Univ. Paris-Sud, we will, among other aspects, evaluate the possibility of using this AAN controller to modulate and personalize, based on motor performance, the physical assistance of the exoskeleton when used for repetitive tasks.

2.4.2 Human adaptation

A better understanding of human motor adaptation at the joint and inter-joint coordination level is a mandatory step for exoskeletons to be concretely usable in rehabilitation. Although adaptation did not occur in the majority of the cases, the presence of different after-effects was rather persistent in time which represents a

new result with respect to classical motor adaptation experiments with robots. One reason of this long lasting effects could be the consequence of the particular unexplicit nature of the constraints imposed by the exoskeleton. Our protocol, because of KSC, indeed explored the idea of "implicit learning" [33], with participants performing an end-effector task and not focused (and aware) on the perturbation at the joint level. At the same time, this kind of "implicit learning" strategy may be the only one possible in therapy with post-stroke patients having trouble in monitoring simultaneously both their hand and intermediate-joints movement.
Beyond that, several major issues remain, in particular the fact that we were able to modify (at least alter) the coordination but not to teach one, which is required for the targeted clinical application. Also, the important inter-individual difference which was observed has yet no clear explanation.

Several aspects will thus have to be addressed in a near future to reinforce these preliminary observations and hypotheses. First from an analysis point of view, studying new metrics to characterize more precisely the inter-joint coordination seems necessary. Also the investigation of experimental data in the light of new motor control models such as the Uncontrolled Manifold (UCM) principle [50] may provide valuable insight to understand the variability observed in adaptation. Additional analyses and experiments will also have to be conducted to reinforce these preliminary observations. Exposition to the robot force field should be extended in time and possibly repeated across multiple sessions over several days to study the role of motor memory. Additional experiments on the transfer of learning effects outside of the robot should also be performed with more subjects. Comparison with different types of joint force fields, some acting more explicitly (both at the joint and end-effector level) or of different nature (elastic, assistive, etc.) or more locally (similarly to [44]), would ne necessary. This would also allow to possibly generalize our results and compare them with those of other teams. Finally, conducting experiment on an impaired population which would be trained with the exoskeleton to perform "more natural" gestures, in addition to being the final applied objective of this research, would allow us to study the potential reinforcing effect on learning when teaching a "beneficial motor strategy".

Chapter 3

Improving the control of prostheses in transhumeral amputee with motor coordination-based control approaches

Sommaire

3.1 State of the art of upper-limb prosthetic control

Progress in mechatronics and robotics has facilitated the production of prostheses with an increasing number of active joints, like the 10 DoF Luke Arm for upper limb amputation [51]. Unfortunately, the gap between hardware improvements and control developments has been growing in parallel, limiting the overall benefits for amputees. Myoelectric control has become for the last decades a common control method of prosthetic end-effector [52, 53], but its current implementation with only two electrodes (with sequential control and complex set of contractions pattern to master) is poorly adapted to the control of numerous active DoF. That is why most transhumeral amputated individuals are often fitted with only a myoelectric hand, and eventually a myoelectric wrist, but almost never with a (commercially available) myoelectric elbow, choosing instead a cable-driven or manually-locked joint.

To sort out this control limitation, numerous methods like discrete control based on myoelectric pattern recognition strategies (developed for over 40 years [54]), continuous regression control (see Fig. 3.1.A), or neural signal interpretation have been developed [15] to improve the users possibilities with myoelectric control. However, sEMG signals, often described as unreliable [55], are impeding the implementation of advanced processing techniques. Several studies have investigated alternative control methods to myoelectric signals, such as sonomyography [56, 57] (see Fig. 3.1.B), mechanomyography [58] or myokinetic signals [59] (see Fig. 3.1.C), among others. But yet, the need for simultaneous and easy control strategy over artificial joints still remains.

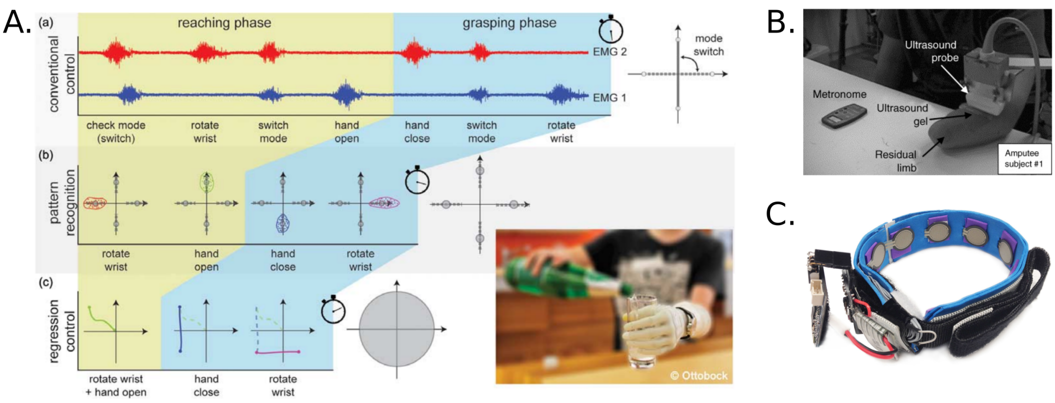

Figure 3.1: A. Vizualization of the control sequence to grasp a bottle and pour a glass with 3 myoelectric control methods: a) conventional dual site control, b) pattern recognition, c) regression control (taken from [14]). B. Sonomyography setup used on a forearm stump (taken from [57]). C. FSR bracelet for myokinetic signal-based control (taken from [59]).

Indeed, the current approach of prosthetic devices is based on the association of one (generally neural) signal to a unique prosthetic DoF, while natural limb movements are explained by a coordination between joint kinematics, result of a synchronous control of muscle groups by the central nervous system [60]. Consequently, healthy movements are task-centered, whereby one focuses on object or hand motion without explicitly controlling each muscle or joint motion. Previous studies have shown evidence of invariant kinematic characteristics in upper limb movements [61, 49] proving the coordinated aspect of joint movements, and especially of the shoulder/elbow coupling [62, 23].

Replicating a human-like control strategy whereby joint motion is coupled onto a transhumeral prosthesis is a promising solution. Thus, residual limb mobility, that most transhumeral amputees have, can be used to drive automatically the elbow joint, as originally presented in Gibbons et al. (1987) [63]. If the inter-joint coordination relationship is known, then distal joint motion (e.g., elbow flexion) could be predicted from measurement of proximal joint kinematics (e.g., shoulder). In addition, performing movement is natural, provides numerous sensory feedback and is thus easier to produce and master, than controlling our muscular activity.

Several studies have shown that these synergies can be modeled, and thus, used to derive distal joint movements from measurements of proximal joints kinematics [64, 65, 66, 67, 68, 69]. The study by Kaliki et al. [66] showed for example that the elbow flexion angle and the forearm rotation angle could be predicted using offline measurements of shoulder and scapula posture, and an artificial neural network-based model of the upper limb joints motion for a reaching task. Yet, most of the previous works have been tested in lab context with precise motion capture (and not wearable movement sensors), limited number of subjects (and thus of motor variability) generally in simulation or virtual environment. And, overall, the proposed developments have never been tested on prosthetic devices and in clinical environment with amputees.

This is what we tried to address within the PhD thesis of Manelle Merad, and what we will summarize in this chapter.

3.2 An automatic control based on model of interjoint coordination and IMUs

3.2.1 Concept

For numerous ADL task, elbow control as a distinct joint, "separated" from the end-effector control, is not suitable. In a generic gesture such as pointing or reaching an object, which are fast actions, the user should be only focusing on the hand displacement within the task space and not on the intermediate joint action (within the joint space). While myoelectric control maybe suitable for the control of the grasping function of the prosthetic hand, it is a bad candidate for allowing a quick and simple positioning and/or orientation of the hand in space.

The objective is thus to automatize the movement of those intermediate artificial joints, to allow the user to focus and his/her end-effector and the task. To do so we developed an automatic control of those joints based on a model of interjoint coordination, which could drive the movements of some prosthetic joints based on the ones of the user remaining body segment (i.e. the residual limb), as illustrated in Figure 3.2. Since interjoint coordinations (i.e. synergies) are task-dependent, this model of interjoint coordination should be identified from experimental data captured on subjects performing the targeted task (i.e. pointing/reaching). This model could be defined as:

$$\dot{\beta} = f(\dot{\psi}, \dot{\theta}, \dot{\phi}) \qquad (3.1)$$

with, $\dot{\beta}$ the elbow joint velocity and $(\dot{\psi}, \dot{\theta}, \dot{\phi})$ the three shoulder angular velocities

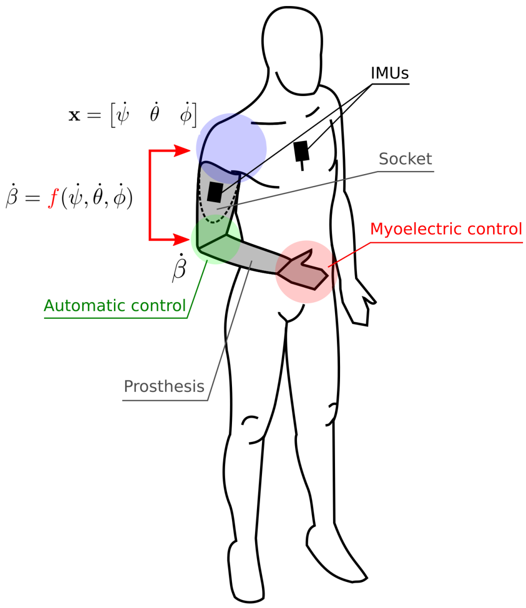

Figure 3.2: Proposed control scenario: while the hand remains myoelectrically and voluntarily controlled, the prosthetic elbow joint is automatically piloted by a model of interjoint coordination f, which computes the elbow joint velocity $\dot{\beta}$ in function of the shoulder ones $(\dot{\psi}, \dot{\theta}, \dot{\phi})$, measured by worn IMUs

(derived from Euler angles) measured with respect to the user's trunk. We chose to use a model based on joint velocities to also avoid any dependence on the initial position.

Since the interjoint coordination is known to be generally constant for one given type of task (such as "reaching", "moving the hand" or "bringing to mouth" for example), the advanced concept of our approach should rely on different interjoint coordination models (one per type of task), and a high level control layer able to load the proper coordination model. Ideally, this global framework, shown in Figure 3.3, should automatically select the appropriate model through real-time monitoring of human motor behaviour and online task recognition. The user could also possibly indicates, through a dedicated interface, the type of task he is going to perform to solve the complex challenge of online real-time detection. While the long term goal would be to develop such a multi-task control framework, we focused first on the most common reaching/pointing model as a starting point.

Additionally, some technical choices were made: the kinematics measurements should be made with embedded/worn sensors (i.e. IMUs since we essentially wanted to measure orientation of limb segment in space) so that the solution could realistically be embedded in a prosthesis and could work in a real life environment outside of the lab. Also we made the simplifying hypothesis that this model could be build from the kinematic data taken from the limbs of asymptomatic subjects: the objective being to have the residual limb - prosthesis coordinate the same way the arm segments of a non-amputated subject would.

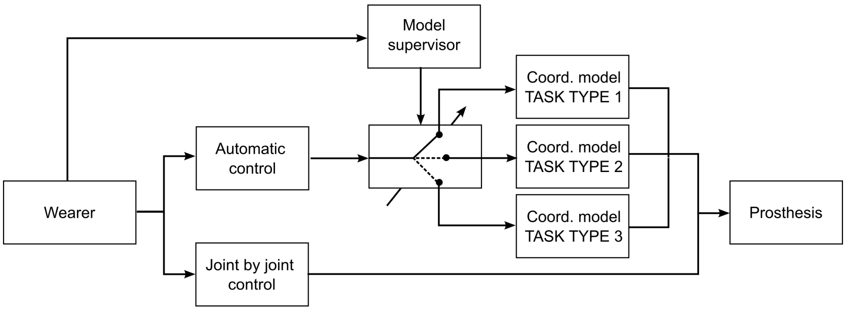

Figure 3.3: Global generic framework representation: when automatic control is used, a model supervisor should be able to automatically load the appropriate coordination model for each type of considered task such as, for example, "reaching", "manipulating", "displacing an object" or "bringing to mouth".

3.2.2 Prosthetic prototype

To assess realistically our model, we developed a dedicated 2 DoF prosthetic prototype from commercially prosthetic components like a conventional electronic wrist rotator (model 10S17, Ottobock©), and a modified E-TWO electric elbow (Hosmer©, Fillauer©) and a custom electronics. The prototype mounted on participants is shown in Fig. 3.4. An i-Limb Ultra from Touch Bionics© was generally used as end-effector. A Raspberry Pi 3 with a dedicated shield, was used to read sensors, control the hand electronics and a dedicated motor controller in charge of elbow's and wrist's motor position and speed closed loop control. The prosthesis prototype could be connected to conventional myoelectric electrodes which are generally located within prosthesis socket over the residual biceps and triceps groups. The prosthesis controller also read the data from two IMUs (x-IMU, X-IO Technologies©), placed on the participant's trunk (located at the sternum level) and arm (placed on the socket of the prosthesis). Finally, the controller piloted the prosthetic joints according to the input signals from IMUs and myoelectric electrodes, and the control mode in which the prosthesis was set.

As shown in Figure 3.4, specific adaptation parts were developed so that the prototype could be mounted on conventional amputee socket, osseointegration implants (metal bone rod implanted in the residual limb's bone [70]), or even non-amputated participants through the use of a dedicated elbow orthosis (blocking the natural arm and placing the prosthesis in parallel to the subject's forearm).

3.2.3 Modeling of upper-limb synergies

3.2.3.1 Collecting the data to build the model

To build and train the coordination models, data of motions from asymptomatic subjects were collected from 15 participants who performed pointing movements with their natural arm. Again, two IMUs, one located on the arm, the other on the trunk (as seen on Figure 3.5) were used to capture the shoulder kinematics. Specific

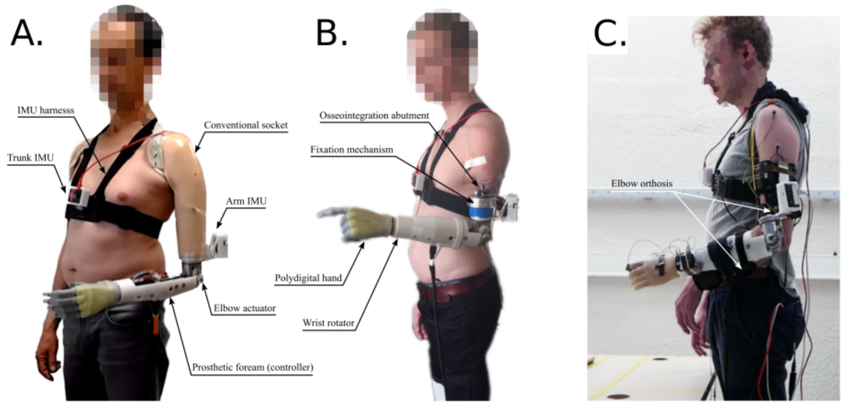

Figure 3.4: A. amputated participant wearing the prosthesis prototype with a conventional external socket. B: amputated participant with the prosthesis prototype plugged to an osseointegrated participant. C: non amputated participant wearing the prosthesis mounted on an elbow orthosis as a substitution arm.

projections through quaternions were used to extract the Euler angular velocities $(\dot{\psi}, \dot{\theta}, \dot{\phi})$ of the shoulder in the trunk frame. Additionally, during this step an optical motion capture was used to additionally capture the elbow kinematics.

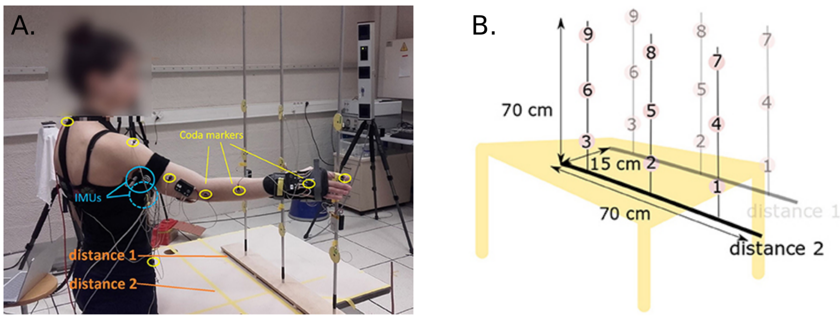

Figure 3.5: A. Experimental set-up for training data recordings: one participant performing natural reaching movements toward 18 targets (9*2 distances). B. Localization of the targets to reach.

Subjects had to reach (several times) nine targets at two different distances (18 targets in total), whose height and position were adapted to subjects' morphology. No specific instruction were given to the participants, to let them move naturally. Only the initial position was imposed: subjects were asked to start with the humerus along the body and the elbow flexed at 90°.

The shoulder kinematics (measured by IMUs), and the elbow trajectories (measured by MOCAP) were recorded, filtered and used to train a regression model of the shoulder-elbow coordination function f previously defined in 3.1.

3.2.3.2 Regression models

Since there is not one accepted regression method to model the shoulder-elbow coordination, and since the validation of published models were generally performed offline, through simulations, or in a virtual reality environment, we developed several models through different regression techniques, and decided to evaluate experimentally their prediction ability and performance when used to drive the control of a prosthetic [71] to select the most pertinent solutions. We focused on three relatively simple methods: RBFN, the simplest ANN, which was shown to correctly model shoulder-elbow synergies in preliminary works [72, 73]; Principal Components Analysis (PCA), to test the prediction ability of a linear regression technique; and Locally Weighted Regression (LWR).

The three models were built with the data collected on non-amputated subjects. First, based on the collected data, a standard offline analysis of the prediction ability of the different models in reconstructing precisely the elbow trajectories based on the shoulder ones. This analysis showed that the three models yielded good prediction results but did no allow to conclude. Additionally, an online control experiment was conducted to evaluate models performance and more particularly their robustness. Ten non-amputated participants, who did not contribute to the collection of training data, participated in this experiment. Those participants, equipped with the prosthetic elbow prototype substituting to their natural arm (as shown in Fig. 3.4.C), were asked to use the prosthesis to reach the same targets as for the preliminary experimental session. Different metrics among which the precision, the shoulder/elbow desynchronization, the curvature and the smoothness as shown in Figure 3.6 (along with a quantification of body compensations), were used to evaluate the performance of those three models used within the control, in comparison with the characteristics of natural movements.

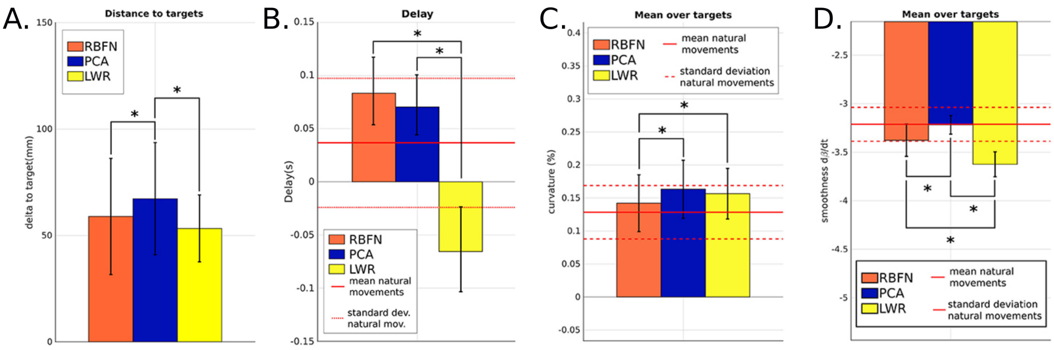

Figure 3.6: For the three regression models, (averaged over targets and participants): A. Final end-effector position error; B. Delay between the shoulder and the elbow motions; C. Curvature of the movements; D. Spectral arc length of $\dot{\beta}$ characterizing the smoothness (the more negative, the less smooth). *indicates a statistically significant difference ($p < 0.05$).

Analysis revealed that, while RBFN offered better overall performance than PCA and LWR (particularly in terms of synchronization and smoothness), none of the models outperforms significantly the others. What was observed is that the regression technique used to model joint synergies may not be a key factor to improve prosthetic movement-based control, but rather is the dataset used to build the model (important inter-subject variability). Yet, based on those analyses, the simple RBFN-based regression model was chosen for the rest of the experiments.

3.3 Clinical evaluation of automatic elbow control with transhumeral amputees

After a preliminary successful test with one transhumeral amputated individual [74], we conducted, with the same model and prototype, a larger clinical evaluation of this automatic elbow control strategy on a group of transhumeral amputees, in comparison to a conventional myoelectric elbow control strategy [75] which is shown in the Appendix .

3.3.1 Material and methods

Participants: Six amputated participants were recruited, all of them users of myoelectric prostheses. They were organized in two groups. The first group (Group Harness) was recruited at Centre Louis Pierquin in Nancy. Their own prosthetic equipment included a conventional external socket maintained by a harness, as illustrated in Fig. 3.4.A. The second group of participants (Group Osseo) was recruited at the Biomechatronics and Neurorehabilitation Laboratory (Chalmers University of Technology, Gothenburg, Sweden), among participants of an ongoing experiment on osseointegrated prosthetic devices. These participants had undergone surgery consisting in inserting a titanium implant into their residual humerus bone [76]. Any prosthetic device can be fixed to the end of the percutaneous rod, without needing a harness to hold it, as illustrated in Fig. 3.4.B.

Prosthetic control: The prosthetic was controlled during the experiment whether with standard biceps/triceps myoelectric control (ME-Mode) with participant's own electrodes (whether located in their socket or implanted) and with automatic elbow control (A-mode), i.e. the control mode relying on the previously described RBFN model of the shoulder-elbow coordination trained on healthy participants' data.

Protocol: Participants, after a 5 minutes training, performed the pointing task once with the prosthetic elbow driven successively by each of the two control modes: during the first session, the ME-mode (conventional dual-site myoelectric control strategy) was used, then, during the second session, the participants used the A-mode (automatic elbow control strategy).

3.3.2 Results

Functional assessment: All the participants could reach the targets with both modes with similar final precision errors (1.5 cm ± 1.3 cm with the ME-mode and 1.7 cm ± 1.8 cm with the A-mode, in comparison with an average precision error of 1.4 cm ± 1.9 cm in non-amputated participants). Nonetheless, considering the

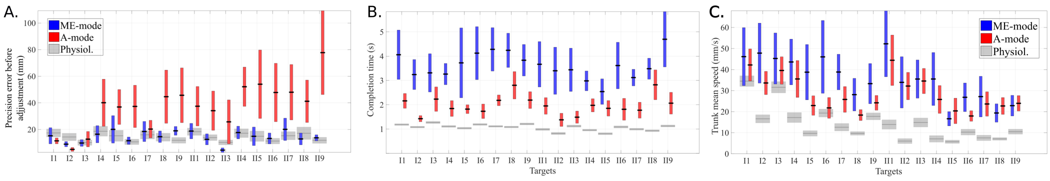

Figure 3.7: Precision errors (A), task completion times (B) with the ME-mode (blue bars) and the A-mode (red bars) for all targets. Small black lines represent the mean value, and bars represent the standard deviation. Values are calculated before final (body) adjustment movements. Grey lines and shaded areas represent the averaged precision errors and completion times, and the corresponding standard deviation, of some averaged non-amputated participants

precision error before final adjustments (i.e. before the final correction usually made by body or residual limb movement and not by the prosthesis) showed larger errors with the A-mode (as shown in Figure 3.7.A) revealing issues with the prediction of the coordination model used. The reaching gestures performed with a prosthesis were longer than healthy movements but the movement duration was clearly reduced when using the A-mode (Fig. 3.7.B).

Movement strategy assessment: Unsurprisingly, the participants' overall motor strategy was different depending on the prosthetic elbow's control mode. A typical reaching movement is illustrated in Figure. 3.8.A, which shows the initial and final postures taken by one participant performing the reaching movement toward one target with both control modes.

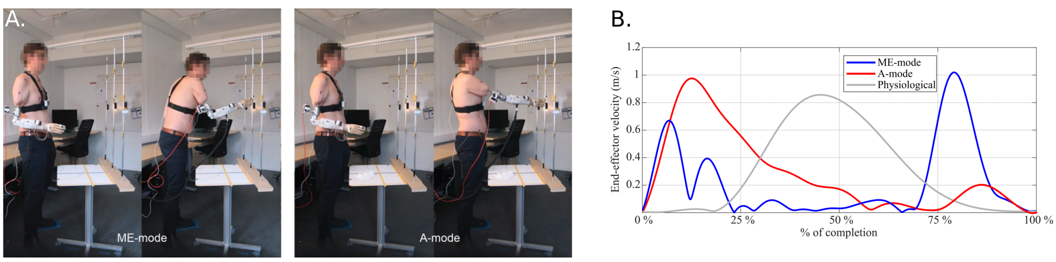

Figure 3.8: A. Reaching movements with initial and final postures towards Target 5 (Distance I) with the ME-mode (left) and with the A-mode (right). B. Example of filtered end-effector velocity profiles, calculated as the norm of cartesian velocity. Blue (resp. red) line represents the velocity profile of one participant's reaching gesture towards Target I.8 with the ME-mode (resp. A-mode). The grey line represent the velocity profile of a non-amputated individual's reaching gesture towards the same target.

Such variations in reaching strategies can be also be seen at the end-effector level. Figure. 3.8.B. depicts the typical velocity profiles of the end-effector for the two control modes for one amputated participant, and a physiological velocity profile. With the ME-mode, most participants positioned the prosthetic elbow (first blue peak) before performing the reaching movement by moving only the residual limb and the trunk (second blue peak). With the A-mode, participants performed directly the reaching movement by simultaneously moving the shoulder and the elbow (first red peak), and some performed a final adjustment movement by moving the residual limb to reduce the distance to the target error (second red peak). However, most participants stopped their motion after the main reaching movement as they were close to the target.

Analyzing the joint motor strategies revealed that the A-mode restored larger (and more natural) range of use of the elbow joint (43.2 deg ± 15.2 deg) for A-mode, 17.1 deg ± 19.7 deg for ME-mode), as a non-amputated subject (34.9 deg ± 10.1 deg) would do, but generated a slight overuse of the shoulder elevation (but without reaching uncomfortable postures) possibly to compensate for over-extension generated by the A-mode in some closer targets.

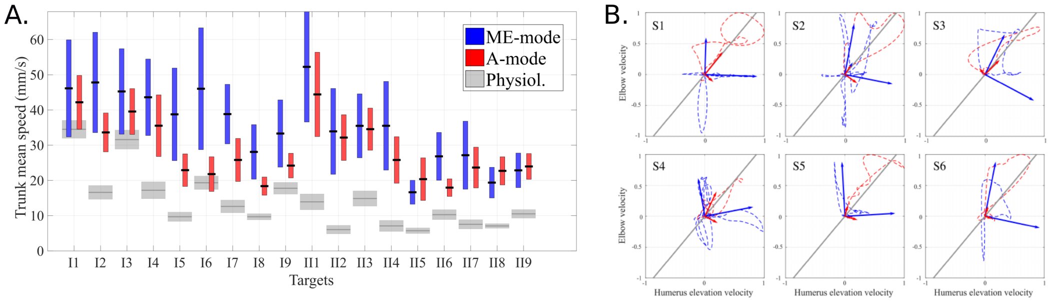

Figure 3.9: A. Averaged trunk mean speed (i.e. trunk cumulative trajectory normalized by the completion time) with the ME-mode (blue bars) and the A-mode (red bars) for all targets. Small black lines represent the mean value, and bars represent the standard deviation. Grey lines and shaded areas represent the values for averaged physiological reaching movements. B. Example of the shoulder/elbow synergies, expressed in terms of angular velocities of the humerus elevation angle and elbow flexion/extension angle, of the 6 amputated participants for reaching movement towards one target with the ME-mode (dashed blue line) and the A-mode (dashed red line).

Some reduction of the trunk compensation in the sagittal plane were observed for most targets (except for some of closer targets) in all the participants, as shown in Fig. 3.9.A. A-mode also seemed to lead to a reduced deviation of the trunk among the tested population compared to ME-mode.

In terms of interjoint coordination, the automatic elbow control strategy (A-mode) restored a shoulder/elbow synergy close to a physiological one, whereas shoulder and elbow movements were decomposed using myoelectric control, as illustrated in Fig. 3.9.B.

Finally, from a subjective point of view, the A-mode, was appreciated by all the participants who described it verbally as an intuitive control method.

3.4 Extension to multiple prosthetic joints control

During the internship of Lucas Lavenir, we adapted the previous architecture to predict the shoulder (humeral) internal-external rotation in addition to the elbow movement. Indeed, when the pointing task used in this study is performed by healthy subjects, an amplitude of 58° of humeral rotation was measured highlighting the important role of this mobility.
Transhumeral amputees using a conventional socket are generally loosing their humeral rotation capability [77]. On the prosthesis, this DoF is generally replaced by a passive frictious joint which has to be adjusted manually by the other arm. Since this is constraining and unpractical, amputees tends to rather compensate with their trunk torsion.
Our hypothesis was that this joint also follows a synergic scheme for pointing gestures and could be automatically controlled with the proposed approach. We therefore developed an updated RBFN model using both shoulder and trunk rotations as inputs to be able to predict both humeral and elbow rotations. We also designed a one DoF motorized humeral rotation DoF specifically. As shown on Figure 3.10,

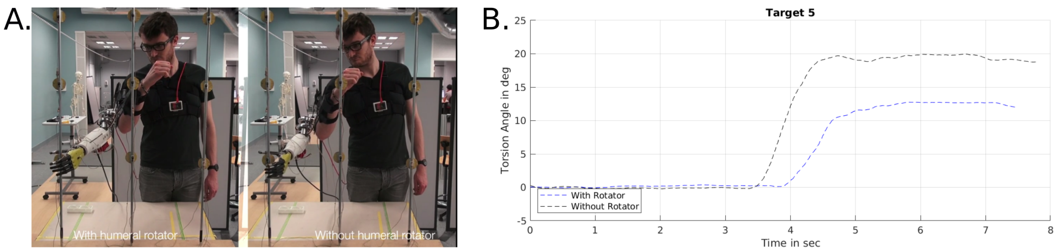

Figure 3.10: A. View of a subject performing a pointing task with the 2 active DoF prosthesis. On the left, in addition to the elbow joint, the humeral rotator is active and controlled automatically by the RBFN model while on the right it is locked, leading to more compensatory trunk torsion and bending. B. Trunk torsion during the pointing to one target, when the humeral rotator is active and controlled (in blue) while locked (in black).

preliminary experiments were performed on one healthy subject wearing the prototype and showed that the 2 DoF A-mode, allowed to performed the task while at the same time minimizing the trunk torsion compensatory movements of about 5 to 10° compared to the case in which this DoF is locked.

3.5 Conclusions, limitations and perspectives

Throughout this research, several important results were obtained. We were able to show that a model of the shoulder-elbow coordination could be built from healthy subject and used by amputated patients to control a prosthesis using a wearable kinematic measurement solution (IMUs). This is the first time such approach was tested in real-time with real users and prosthesis, and without motion capture. We showed experimentally that performing pointing tasks with an automatically-driven elbow was possible. This control was appreciated and beneficial to the users, with fast and fluid movements, with reduced compensatory strategies and cognitive load (focus on the hand only), and a possible simultaneous elbow and end-effector control.

3.5.1 The difficulty in personalisation and (task) generalization

Unfortunately several fundamental issues and limitations were raised throughout this work. First, the important amount of inter-individual variations between participants, even stronger between amputated and non-amputated users highlights the limitation of building and using a fixed generic model of interjoint coordination. And the resultant lack of model's precision lead to limited performances and remaining undesired compensations of users. Indeed, in addition to variations of morphology and individual preferences in motor strategy observed in humans, the residual limb movements of amputees tend to be kinematically different from healthy upper limb movements. This is due to numerous parameters: prosthetic extra weight and different mass balance, constraints generated by the socket fixation, partial paralysis of the residual limb observed in some transhumeral amputees, etc. There is a clear need, yet unsatisfied within our work, for modeling methods and control personalisation, to identify the interjoint coordination model of a given user, or tune a generic model to fit the user's behavior and need. Some interesting work has been recently conducted in this direction in [78] which proposed an online adaptation method able to personalize the model through iterative optimization while compensating for variations due to human motor control adaptation phenomenons. Also, considering again the global architecture presented in Figure 3.3, to be used in real-life scenarios, a complete control framework should be able to provide the right prosthetic movement completion for different motor tasks, and thus to manage multiple and different interjoint coordination models. Considering the complexity observed here for the "simple" pointing task considered alone, building an architecture able to (quickly) recognize the task initiated by the user and load the adequate (and hopefully personalized) coordination model appears to be particularly challenging, if not impossible. Additionally, one could think that a discrete and reduced catalog of coordination models, will hardly capture the multiplicity of kinematic body strategies to perform a task.

3.5.2 Towards a novel approach exploiting body compensations

During the PhD thesis of Mathilde Legrand (started in 2017 and directed by G. Morel), after several unsuccessful attempts to build the intended control framework, we finally decided to explore a fundamentally different control alternative, which exploit more global body coordination schemes: the body compensations. This ongoing work proposes to build a more generic, robust and intuitive control which does not rely on precise models of human motor behavior, but rather enslaves the prosthetic movements to the body compensations of the user [79]. The role of this new control approach is to modify (at a smaller frequency than the one of human movements) the prosthesis posture in order to minimize the body compensations of the user (such as the trunk bending). The results is a natural and efficient coupling between the user and the prosthesis, without any training of the user, and without the need for the prosthesis to know the task. This approach is currently being intensively investigated and will constitutes our new research path for the incoming years.

Chapter 4

Improving the control of prostheses in transhumeral amputee thanks to the mobile phantom limb phenomenon

Sommaire

4.1 Introduction and concept

As stated in the previous chapter, numerous researches in the field of bionic prostheses aim at developing more intuitive and efficient control approaches for already available advanced hardware. While a growing number of research groups have been recently exploring movements-based control approaches, most of the researches are currently rather focused on improving the myoelectric control to adapt it to the growing complexity of prosthetic devices.

To overcome the limitations of the conventional "dual-site" myoelectric control (see introduction or Chapter 3 for extended description), pattern-recognition approaches have been developed since the late 60s/70s [54, 80, 81] aiming for a more precise decoding of myoelectric signals in order to improve the recognition of different muscle activation patterns and thus to control more types of movements. This requires the use of multiple recording sites, a precise extraction of signal characteristics (not only amplitude) and a multidimensional classification architecture. While well established and extensively studied in research institutions, such approaches have only very recently been applied commercially to prosthetic control (see the COAPT system, http://www.coaptengineering.com/), notably due to issues with limitations in clinical robustness [82] (pattern variability, noise in the measurement, sensitivity to numerous external factors like muscle fatigue, electrode shift or skin characteristics variations, etc.).

The classical way of feeding pattern recognition myoelectric control is to rely on sEMG activities of the residual limb associated with **phantom limb movement (PLM)** execution. Voluntary phantom limb movements have recently been shown to be “real” motor execution [83, 84, 85], with underlying neurophysiological mechanisms different from those of motor imagery [86, 87]. The associated muscle activity varies with the type of executed PLM [84, 86] even for different finger movements in above-elbow amputees. This approach has been quite extensively studied for below-elbow amputees whose residual limb usually still contains **the muscles that mobilized the fingers before the amputation**, and, therefore, provide an adapted measurement site together with relatively strong myoelectric signals. While numerous adaptation of these approaches were made to above-elbow amputees from the 70s to the 90s [88, 89, 90], it is the development of targeted muscle reinnervation (TMR) approaches [91] which made this technique more viable and concretely transferrable to patients [92]. **In the case of transhumeral amputation, without artificial reinnervation, PLM related myoelectric activity has to be measured over muscle groups of the residual limb which, before amputation, were not mechanically acting on the joints of the missing limb**. These signals, whether due to neuro-muscular reorganization [93] or to **remaining global supporting contraction schemes (i.e., muscle contractions of the proximal residual muscles acting in synergy with movements of the -now missing- distal limb), still seem to contain information on PLM**.

The objective of the research we conducted in close collaboration with neuroscientists from Aix-Marseille university and clinicians from IRR Nancy / UGECAM Nord-Est, was therefore first to characterize this little-known PLM phenomenon and its related myoelectric activity (especially in transhumeral amputees). We then tested the possibility of exploiting it to offer a more natural and efficient control of prosthetics, without requiring TMR surgery.

4.2 Characterization of the PLM phenomenon

4.2.1 Epidemiology

The presence of voluntary PLM in most patients has been reported since the middle of the last century [94]. Yet, since then, PLM has received limited attention in the literature for several reasons. First, the phantom limb is widely considered as associated to phantom pain [95] and mostly studied as such [96]. Second, the patients are not encouraged by the rehabilitation staff to explore the mobility of their phantom limb through fear of disturbing prosthesis control [97]. Third, a belief still exists among many patients and health professionals, that PLM are the "fruit of a highly active imagination", reflecting "the non-acceptance of the limb loss" [97]. PLM are still often considered as imaginary movements despite recent neurophysiological evidence for the contrary [86]. For these reasons, no quantitative information is available on the percentage of patients with voluntary control of their phantom limb, on the kinematics of its mobility, nor on the evolution of phantom mobility over time.

We conducted a series of semi-directed interviews about their phantom limb on a group of seventy-six below- and above-elbow amputees with major amputation [98]. The types, characteristics and potential influencing factors (amputation level, elapsed time since amputation, chronic pain and use of prostheses) of upper limb PLM were extracted from the interviews. Thirteen different movements were found involving the hand, wrist and elbow. Seventy-six percent of the patients were able to produce at least one type of PLM; most of them could execute several. Amputation level, elapsed time since amputation (which varied from 1 month up to 50 years), chronic pain and use of myoelectric prostheses were not found to influence PLM.

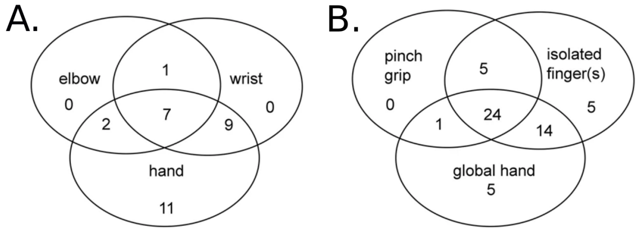

Figure 4.1: **A.** Number of patients with PLM at the indicated phantom limb level(s)for the above-elbow amputees. **B.** Results for the phantom hand for all below and above-elbow amputees (except for 3 patients with only phantom finger abduction and adduction movements). Note that no patient had PLM exclusively at the wrist or elbow. Taken from [98].

As shown in Figure 4.1, eighty-four percent of the interviewed transhumeral amputees (37 participants) were able to perform PLM, with 78% of them being able to move the phantom hand, 46% the phantom wrist, and 27% the phantom elbow. Additionally, we observed that some participants reported of having the sensation of being able to act over the phantom joint while the latter was not moving (and thus considered in the report).

The high percentage we observed of amputees with this condition clearly encouraged us to investigate further the development of PLM-based modes of prostheses control.

4.2.2 Characterization of the phantom kinematics

Since our long term objective was to associate the kinematics of the prosthesis to the one of the phantom limb, we performed an experimental campaign to quantify the PLM kinematics and relate these to the one of participant's intact limb and also to the time elapsed since amputation [99].

Six upper arm and two forearm amputees with various delays since amputation (6 months to 32 years) performed phantom finger, hand and wrist movements at self-chosen comfortable velocities. The kinematics of the phantom movements was indirectly obtained via the intact limb that synchronously mimicked the phantom limb movements, using a 15 DoF Cyberglove for measuring the movements of the fingers and an inertial measurement unit for both the movements of the wrist and the elbow.

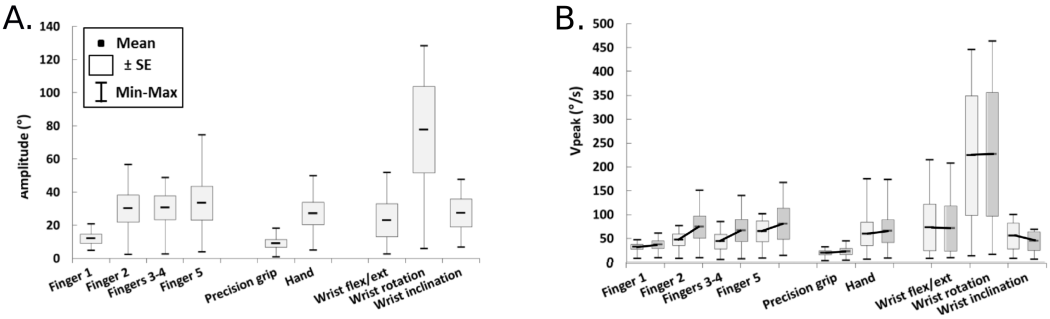

Figure 4.2: PLM kinematics values obtained for each patient (averaged over cyclic repetitions). **A**. Amplitude (in degrees) (averaged over all patients). **B**. Corresponding mean peak velocities (Vpeak, deg/s), separated for the two phases of each type of phantom movement (i.e., flexion/extension or closing/opening). Taken from [99].

The results (some of them visible on Figure 4.2) show that the execution of phantom movements is generally slow and perceived as "natural" but effortful. The types of phantom movements that can be performed are variable between the patients but they could all perform thumb flexion/extension and global hand opening/closure. Finger extension movements appeared to be faster than finger extension movements. Neither the number of types of phantom movements that can be executed nor the kinematic characteristics were related to the elapsed time since amputation, highlighting the persistence of post-amputation neural adaptation. One hypothesis is that the perceived slowness of the phantom movements is related to altered proprioceptive feedback which lacks recalibration through vision during phantom movement.

The results of this study highlighted the variability of PLM kinematics between subjects, along with their possible (depending on participants) difference in terms of amplitude or speed with respect to the movement of the intact limb. Because of the differences observed between the mobilities of the phantom and the intact limb, mapping directly the kinematics of the phantom would be little functional and thus unsuitable, even with using a gain in the mapping. These results comforted us in the necessity of using a classification architecture (discrete recognition of PLM action) rather than a regression one (continuous recognition of PLM state). The discrete behaviour of classification appeared more suitable: the participant would perform a specific PLM which would be recognized (in a discrete binary way) and would create a velocity on the same joint of the prosthetic, which would be maintained as long as the PLM is performed (as well as the associated myoelectric contraction pattern).

4.3 Phantom-based prosthetic control in transhumeral amputees

Based on the promising scientific results obtained in characterizing the phantom limb mobility, we conducted a step by step implementation of a PLM control-based arm prosthesis for transhumeral amputees.

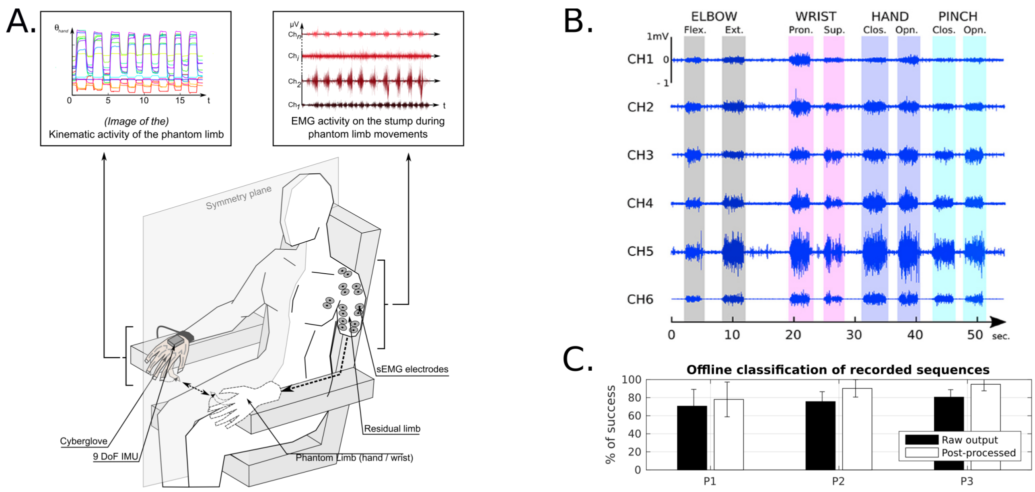

Figure 4.3: **A**. Global view of the experimental setup during recording session for offline classification. Examples of kinematic measurements recorded by the gloves and associated sEMG activity of one participant are shown. **B**. Typical sEMG patterns associated to the voluntary mobilization of the phantom limb recorded by six selected pairs of electrodes when performing successively 8 different phantom limb movements. **C**. Plot of the percentages of classification success. Top: Success rate (averaged over all movements) obtained during offline classification of prerecorded sequences for each participant, with (white) and without (black) post-processing.

4.3.1 Classification of phantom limb movements with surface EMG

This work was presented in [100]. As shown in Figure 4.3.A, a dedicated electrophysiological signal-recording system (Eegosports from ANT-Neuro) was used to record sEMG activity of participant's residual limb, while the phantom hand, wrist and elbow kinematics, mirrored by the intact limb during the recordings, were recorded with a Cyberglove glove (15 DoF measurement of fingers kinematics) and a dedicated IMU (for wrist and elbow movements).

This allowed us to verify that, in accordance with literature [86, 101], the mobilization of different joints of the phantom limb generated particular/typical sEMG patterns over the residual limb, as shown in Figure 4.3.B.

Thanks to this setup, we first performed an evaluation study of phantom finger, hand, wrist and elbow (if present) movement classification based on the analysis of surface electromyographic (sEMG) signals measured by multiple electrodes placed on the residual upper arm of five transhumeral amputees with a controllable phantom limb who did not undergo any reinnervation surgery. We developed a dedicated state-of-the-art pattern recognition architecture using a linear discriminant analysis (LDA) classifier [102] relying on specific filtering and an optimized set of features (including in particular the sample entropy [103]).

We conducted a first recording experiment on 5 transhumeral amputees performing repeated sets of PLM and showed that it is possible to correctly classify those recordings of phantom limb activity (for sets of 12 possible movements) with an important average success (78% to 94.8% according to the participant with a 10% decrease without post-filtering), as shown in Figure 4.3.C.

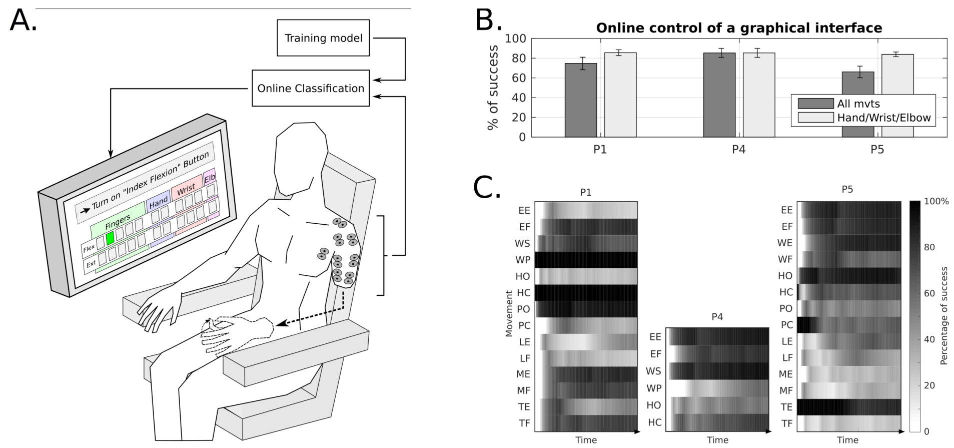

Figure 4.4: **A**. Global view of the experimental setup for online control of a graphical user interface through the mobilization of the mobile phantom limb and the real-time classification of associated sEMG pattern on the residual limb. **B**. Success rate obtained during online control of a graphical interface for each participant averaged among all possible movements and averaged among six movements of the three main phantom limb part (hand opening/closing, one wrist movement and elbow flexion/extension, in light grey) C. Online control performance as a function of the time. The color scale increases from white to black as a function of increasing classification rate.

To further evaluate the PLM control possibilities, we then used the pattern recognition algorithm output to provide online control of a device (here a graphical user interface) to three transhumeral amputees, as shown in Figure 4.4.A. As illustrated in the plots of the Figure 4.4.B, participants were also able to perform online control with similar success percentages over 80% if considering basic sets of six hand, wrist and elbow movements. Additionally, we observed a relative stability of participant performances and thus of these PLM associated myoelectric patterns, at least for a short time period of use (30 minutes sessions approximately) as shown in Figure 4.4.C.

4.3.2 Phantom-mobility-based arm prosthesis control

This work was reported in [104] shown in the Appendix .

Based on these encouraging first results, we conducted another experimental campaign to evaluate the possibility for transhumeral amputees to use a PLM-based control approach to perform more realistic functional grasping tasks. We also wanted to see if those could be able to manage (in terms of perception and control action) simultaneously their limb in a "phantom world" and a "connected" prosthetic and task both in the "real world".

Two transhumeral amputated participants were asked to repetitively grasp one out of three different objects (a wood cylinder, a foam ball and a clothespin) with an unworn eight-active-DoF (elbow, wrist and polydigital hand) prosthetic arm and release it in a dedicated drawer, as shown in Figure 4.5. The prosthesis control was based on phantom limb mobilization and previously defined myoelectric pattern recognition algorithm, using only two repetitions of each PLM to train the classification architecture. This time, a reduced set of only six surface electrodes pairs were used.

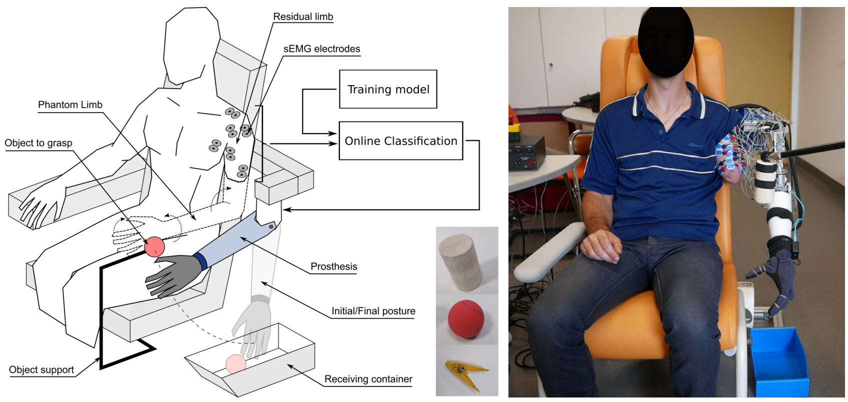

Figure 4.5: (Left) Global view of the experimental setup during one of the functional tasks of grasping an object (here the foam tennis ball) and releasing it in the dedicated container, with the arm prosthesis controlled through the associated mobilization of the phantom limb. (Middle) The objects used for the grasping task. (Right) Photo of the setup being used with P2.

As shown in Figure 4.6.A, the participants were successfully able (over 85% of classification success, with main confusions between hand an pinch actions) to use their PLM to control the eight possible movements of the prosthesis evaluated in a preliminary session similar to the previous experiment but with a limited set of 6 electrodes.

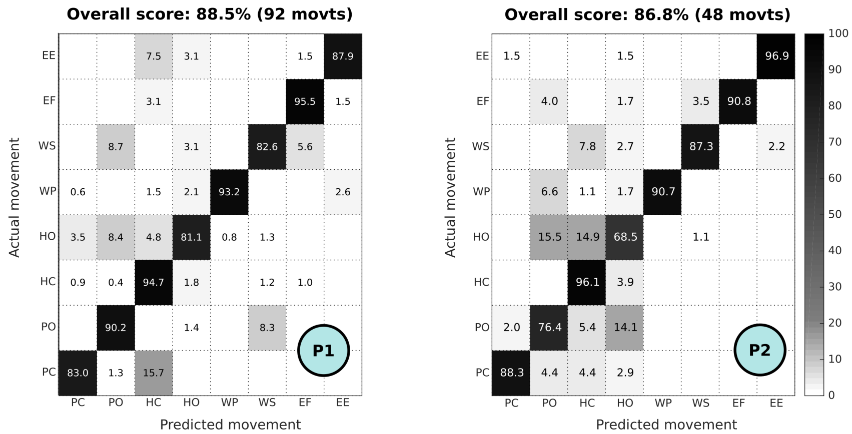

Figure 4.6: Confusion matrix of online control of the prosthesis for both participants. Confusion matrix color scale is normalized across methods and increases from white to black as a function of increasing classification rate.

The results of the functional experiment show that the task could be successfully achieved for the three objects with rather optimal strategies and joint trajectories (see Figure 4.7.B), even if the completion time was increased in comparison with the performances obtained by a control group of asymptomatic participants using a simple GUI control (mouse-operated), and the control strategies required numerous corrections (see Figure 4.7.A).

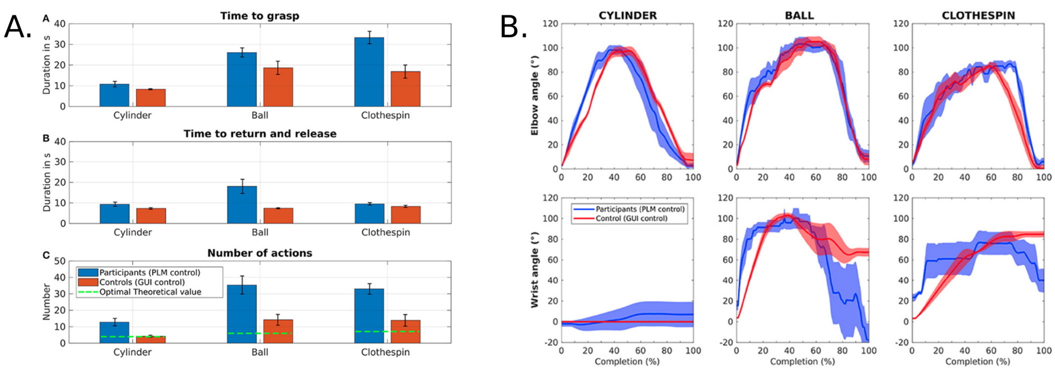

Figure 4.7: **A**. Top: Averaged time (± standard error (SE)) to grasp the three different objects for the. Middle: Averaged time (± SE) to return and release the three different objects for the two groups. Bottom: Averaged number of actions for completing the 3 "grasp and release" tasks. **B**. Plots of the averaged joint kinematic profiles of both elbow and wrist joints, normalized in time and averaged between repetitions and participants and the three objects. Standard error is represented by the transparent envelopes around the curves. (In blue: amputated participants, in red: healthy participants).

The obtained results show that amputated participants were able, after a very short appropriation of all task requirements to manage the rather complex interaction between their PLM, the associated actions of the prosthesis and, through it, their physical interaction with objects and the environment. Additionally, the PLM-based control revealed to be rather intuitive. While numerous limitations related to robustness of pattern recognition techniques and to the perturbations generated by actual wearing of the prosthesis remain to be solved, these preliminary results are promising. We believe that it could possibly be a viable option in some transhumeral amputees to extend their control abilities of functional upper limb prosthetics with multiple active joints without undergoing muscular reinnervation surgery.

4.3.3 Phantom-mobility-based polydigital hand prosthesis control

This work was reported in [105]. In parallel to studies focused on the practical control of the elbow-wrist-hand complex, we also investigated the possibility of using PLM-based control approaches to offer more dexterous control over polydigital hands. Several participants to our experimental campaign indeed reported the ability to perform individual phantom fingers movements.

With the previously developed pattern-recognition architecture and using a set of 12 electrodes, three transhumeral amputees were able, without specific training, to initiate up to 12 movements of a robotic hand (including individual finger movements) as shown in Figure 4.8.A.

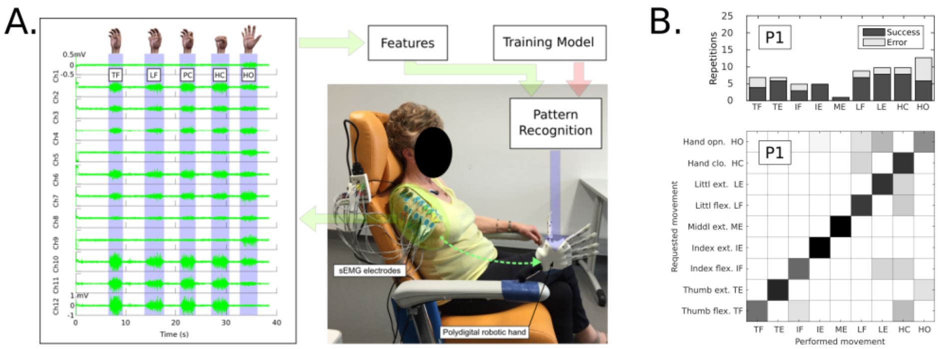

Figure 4.8: **A**. Global view of the setup along with the myoelectric activity associated to the voluntary control of phantom hand (measured with 12 sEMG electrodes placed over the residual limb of one participant). Phantom hand movements are named the following way: TF stands for Thumb Flexion, LF for Little finger Flexion, PC for Pinch Closing, HC for Hand Closing and HO for Hand Opening. **B**. Control of all possible phantom movements for one participant. Top: Number of repetitions performed during for each possible type of phantom movement and the associated ratio of successful classification (in black). Bottom: Confusion matrix for the PLM of participant P1.

When considering the whole range of phantom movements (i.e., 9-12 different movements), the obtained individual rates varied from 57.1 to 71.6% of successful reproductions (as shown for one participant in Figure 4.8.B.). Yet, some movements being never correctly recognized by the classifier, practically, the participants were able to control -with limited results- 5 to 9 different movement of the polydigital hand. These mixed preliminary results indicates that, with current sEMG technology, and without optimized filtering and extended additional training of participants, the only practical approach would be to only use a reduced set of hand gestures to limit both classifier and participant confusions.

4.4 Training participants in mobilizing their phantom limb

A persistent influencing factor was identified in all the experiments and feedback from amputated participants: the training in performing PLM. First, since PLM do not have (yet) a particular use, numerous participants whether discovered their ability to perform PLM or reported having initial difficulty in mobilizing their phantom. Additionally, we observed that participants also have trouble in mobilizing their phantom limb in an optimal way, i.e. to minimize the confusion of the classification architecture. We therefore conducted several studies to evaluate the improvements permitted by the training of participants and to develop tools to facilitate this "exploration" of the phantom limb mobility.

4.4.1 Characterization of PLM training

While in our research, we principally focused on the spontaneous ability of amputees to mobilize their phantom limb, we also studied the effect of training over the kinematics and perception of PLM. Several participants in our experiments in [99] suggested that training would make their PLM execution easier. Additionally recent literature, such as [106], reported a positive effect of training over phantom pain.

Five above-elbow amputees (without phantom and residual limb pain) were therefore enrolled in a phantom-movement training program, and the PLM was compared before and after a daily training period of 1 to 2 months [98].

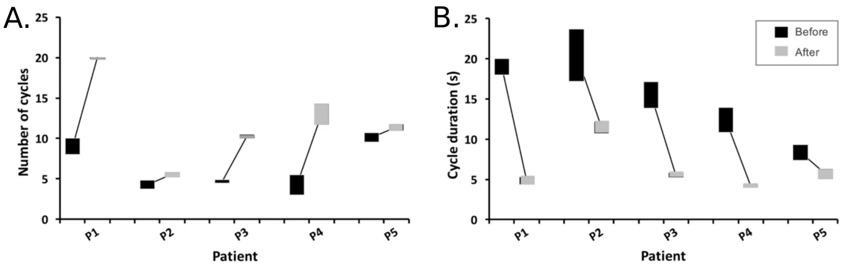

Figure 4.9: Results concerning the daily PLM-training. **A** Number of cycles that could be executed subsequently before movements blocked due to fatigue, averaged over all types of PLM for each patient (the vertical size of the bars represents the standard error). **B** Cycle duration averaged over all types of PLM for each patient (the vertical size of the bars represents the standard error). Taken from [98].

As shown in Figure 4.9, all the participants consequently increased both the endurance and speed of their PLM which is encouraging for a potential real (and thus repetitive) use of their phantom to control a prosthesis in daily life.

4.4.2 Guiding the training of users with biofeedback to improve myoelectric pattern recognition

Across experiments we also realized that behind the discrete label used to describe one class of PLM, there was generally numerous ways for participants to perform the given movement. For example the action *"Closing the hand"* could be done with or without finger adduction, or with or without thumb rotation. And what we observed is that the way one gesture is performed can have a direct consequence over the pattern recognition result: performing a "close the hand" action in a certain way can reduce the confusion with another close class such as "close the pinch". Because of participants relatively limited perception of their PLM, encouraging them to explore different way of performing PLM, and to do so relatively to the classification algorithm performance was particularly challenging. Our objective is not to train participants in performing more repeatable PLM, but rather in exploring different phantom mobilization strategies to enhance the difference between classes (separability) of PLM and consequently improve the classification.

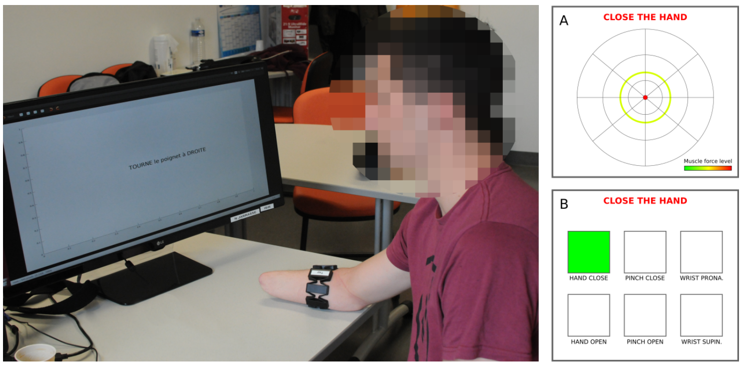

Figure 4.10: Left: amputated participant equipped with the MyoBand during the experiment. Right: View of the two different graphical interfaces used during the experiments. Top: Pattern Similarity Biofeedback GUI used with Group A (PSB-group) and amputated participant. Bottom: Raw-output feedback GUI used with Group B (RF-group).

We thus developed an intuitive pattern similarity biofeedback which can be easily used to train amputees in mobilizing their PLM (or in contracting their residual limb muscles) and allow them to optimize their muscular contractions to improve their control performance. Basically, our biofeedback shows a circle which diameter is proportional to the difference of the muscular contraction patterns performed with respect to the patterns of the other classes to be classified. And during training, participants have, through exploration, to find a way to maximize the circle size.

Preliminary experiments were conducted on twenty able-bodied participants and one transradial amputee. Their performance in controlling an interface through a myoelectric PR algorithm was evaluated; before and after a short automatic user training session consisting in using the proposed visual biofeedback for ten participants (PSB-group), and using a generic PR algorithm output feedback for the others ten (RF-group), as shown in Figure 4.10.

As shown in Figure 4.11, participants who were trained with the proposed biofeedback (group A) increased their classification score for the retrained gesture (by 39.4%), without affecting the overall classification performance (which progressed by 10.2%) through over-training and increase of False Positive rate as observed in the control group. Additional analysis indicates a clear change in contraction strategy only in the group who used the proposed biofeedback, with an increase in class separability.

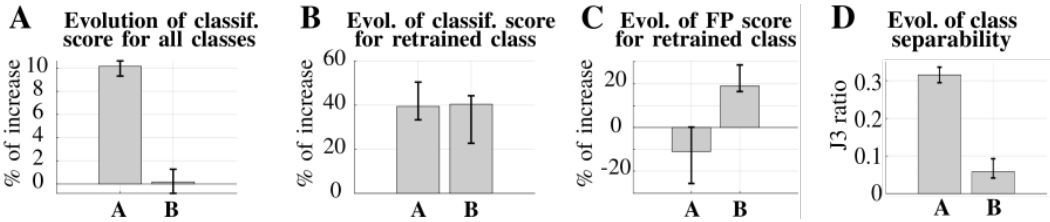

Figure 4.11: Averaged classification score variation, for the two groups A (Pattern Similarity Biofeedback) and B (Raw-output feedback), after training with representation (as error bars) of the 95% Confidence Interval, for all movement classes (A.) and for the retrained class only (B). C: Evolution of False Positive percentage for the retrained class. D: Variation of averaged class-separability ratio index (J3).

The amputated participant who used the proposed biofeedback improved similarly as shown in Figure 4.12. While the evolution of classification score was rather reduced, an important variation of the muscular strategy to perform the retrained class was observed, indicating a change in PLM strategy.

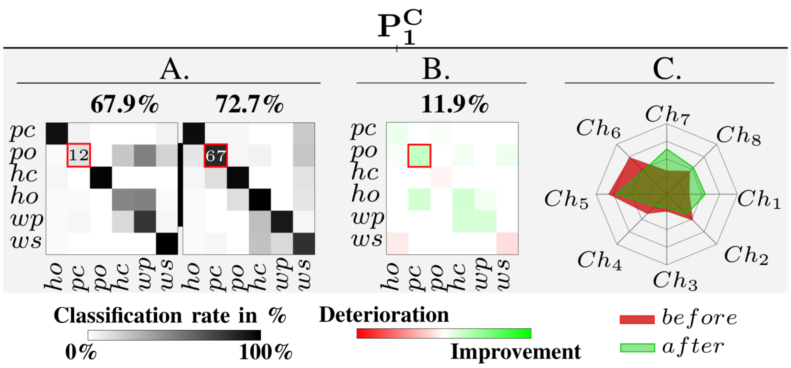

Figure 4.12: Results of the amputated participant. A: Confusion matrices before and after training with the Pattern Similarity Biofeedback (the percentage over each matrix indicates the average global classification score). B: Variation of the overlapping between clusters after the retraining of a class (marked with a red square). C: average muscular contraction (normalized RMS of sEMG signals) pattern for the retrained movement, before and after training.

These preliminary results highlight the potential of this method which does not focus so much on over-optimizing the pattern recognition algorithm or on physically training the users, but on providing them simple and intuitive information to adapt or change their motor strategies to solve some misclassification issues. This could be an interesting tool for the exploration of PLM by amputees and improve robustness of classification in future more practical implementation of PLM-based control.

4.5 Conclusions and perspectives

4.5.1 Conclusions

We saw in this chapter that using the myoelectric patterns associated to Phantom Limb Movements, which are actually rather common among high level amputees and appears to be trainable could be a valid approach to offer transhumeral amputees an improved control over their prosthesis. While more fundamental researches would need to be conducted to determine if those patterns are related to preserved muscle synergies scheme or to neuromuscular reorganization, we showed that a rather generic an simple (i.e. with a low computation cost) classification architecture and a limited set of electrodes (six instead of two) could be used to decode them. We also show that one key might not be so much the improvement of decoding algorithms but rather the training of participant, which suggests great potential for improvement.

These results are promising since the proposed approach could be a viable alternative to "invasive" approaches requiring nerve re-routing surgery (Target Reinnervation or biceps neurotization), which until now was the only solution being considered for arm amputations,but remains a complex, expensive and in fact unthinkable track for many amputees.

However, there are still a number of hurdles to overcome which will guide the future research directions.

4.5.2 Addressing limitations

The principal incoming challenge will be to move to the case of a worn device, with electrodes placed within the socket of the prosthesis. Preliminary experiments on one participant with a worn device and an embedded pattern recognition architecture definitively suggest some interesting possibilities.

However, additional developments would have to be made to filter out parasitic muscular activities related to movements of the residual limb, and the possible mechanical effect of the sockets over the sEMG measurements. Robustness of the classification will have to be increased by both integrating recent developments in myoelectric signal filtering, by understanding and modeling the evolution of those phantom related myoelectric activities because of time and fatigue (both muscular and central) and finally by massively focusing on the training of participants. This training should both be dedicated to stabilize and enhance the PLM, but also to refine classifiers (avoiding False Positive is a major requirement) and to improve amputees skill in using such complex technology.

4.5.3 Extending the concept

Among experiments and interviews conducted with participants, we also gathered a lot of feedback and information on phantom sensations. As reported in the literature [107], we observed that in numerous case it is possible to create sensory stimulation to the phantom limb, by stimulating some areas of the residual limb in particular ways. In some case touching some areas of the residual limb generate similar touch sensation to specific part of the phantom. Providing feedback from the prosthesis (not controlled by the phantom though) through the generation of phantom limb sensations (by electrically stimulating the amputated nerves via implanted electrodes) was recently tested on lower-limb amputees and showed improvements in several aspects (walking speed, metabolic cost and phantom pain) [108].

We believe that such paradigm could also be available with non-invasive stimulation approaches, and that it could had particularly strong effect in our case. Being able to "close the phantom loop" by both mimicking the phantom limb action with the prosthesis and simultaneously conveying the sensory stimulation measured by the prosthesis back to the phantom limb might deeply enhance the control, and in a longer term, the appropriation and body integration of the prosthesis. This, will probably represents one topic for a novel collaborative research project to be proposed in the incoming years with the research team of the ANR PhantomovControl project.

Chapter 5

Considering the ethical, legal and societal (ELS) questions of wearable assistive robotics

Sommaire

5.1 Body integration of technical assistance : a multi-factor phenomenon

This work was reported in [109] shown in the Appendix

5.1.1 The need for an interdisciplinary approach

While physical interaction with robots is becoming common in many domains, numerous devices are not appropriated by their users and remain unused in the cupboard. This phenomenon is particularly observed with robotic devices which interact closely with the body, especially if they are designed to compensate for a loss of sensory or motor capacity. While this may be due to technology imperfection, it is impossible to believe that this is the only reason. The anthropology of technology, among other fields, has shown for a long time that many phenomena other than technical performance, condition the appropriation and use of a technical device, particularly when the device is designed to interact with the body. Prostheses are a perfect example to highlight those socio-anthropological, psychological and cultural phenomena affecting the appropriation and use of technical objects. Indeed, viewed in the light of the works in anthropology of techniques, the prosthesis can be considered as an ultimate technical object: it is "part of the body" which necessitates the learning of new “body-technique”, it is both intimate and visible (to the others), and used intensively by "non-technical" people.

For technical staff (engineers and researchers), considering these complementary points of view and theories in the design of wearable assistive robotics could be a way of improving their appropriation and a mandatory condition to design usable and acceptable technology. That is why I tried to analyse and understand the prosthesis and its ecosystem from a global interdisciplinary way.

5.1.2 Beyond technical performance

5.1.2.1 Disciplinary compartmentalisation

In the field of assistive robotics, there is a general lack of consideration for the fundamental work from humanities and social sciences on body and techniques. For example, considering M. Mauss vision of "body-techniques" and [110] holistic approach broaching the biological, psychological and sociological aspects of human beings; the work of A. Leroy-Gourhan [111] on the technical, psychic and psychological relationships between man and tools during prehistoric periods; the vision of G. Canguilhem of the body from the perspective of its relationship with its environment [112] rather than a simple mechanistic view; or the work of G. Simondon [113] on the cultural and “human” existence of technical objects. Considering the prosthesis in the light of all those visions and established knowledge, and taking into account its multiple roles and complex ecosystem is a key to develop useful and acceptable technical devices.

5.1.2.2 Versatility and technical popularization of performance

Another important phenomenon related to the appreciation of assistive technology for the body is the discrepancy that exists between the versatility of the human body and the popularization of technical performance. The body can carry out a fantastic number of motor actions. However, this versatile nature of the body, its capacity to carry out so many different tasks (with more or less success), is often forgotten. Versatility is a scarce performance index in the different fields of engineering, for example robotics. In addition, the performance of those technical devices to perform the (only) task they have been designed for, is generally inflated by scientific popularization. The latter tends to extrapolate and generalize technology local capacity and to compare them to the efficiency of human beings (for example an AI for playing chess perceived as a "strong" AI smarter than humans).

Prostheses, like other technical objects, incur this phenomenon: while occasionally more efficient that the human body for one given specific task, they tend to impede the realization of others (i.e. the versatility). But the image of human enhancement remains strongly present in the public mind. This popularization of an overrated technical performance and the forgotten versatility which is the primary characteristic of the human body induces a certain amount of perplexity in amputees and tends to increase their dissatisfaction with their (even advanced) prostheses.

5.1.2.3 Levels of perception of technical objects

Another influent phenomenon relates to the differences in the perception of technical objects between different groups within the population, as well as within each group. The prosthesis as a technical object can indeed be viewed from many angles: users, technical staff, "public", all will use different semantics and images to characterize a similar object. Additionally, perceptions vary greatly within the same group. The person's personal history, their amputation, family, social and professional life are all elements which participate in the definition and shape of a person's relationship with his/her prosthesis. Thus, within the group of prosthetic-users, some will view their prosthesis as part of their body, and others as a quite separate work tool. For those with aesthetic prostheses, there is also ambivalence between its nature as a “mask” and the “stigma” which is quite present.

Thus, even if it is tempting to organize and to categorize the phenomena of representation, the large number of studies carried out on labelling theory [114] and on stigmatization reminds us of the limits of such -but common- simplifications. The validity of categorizing people in groups as is sometimes proposed in simplifications of prosthetic specifications can be questioned. Beyond quantitative facts and the group within which the person is categorized, it is the whole-person which needs to be considered in order to foresee and understand the appropriation or not of a prosthesis.

5.1.2.4 Use, conception and acceptance

The questions evoked above, regarding certain simplifications of the representation of the "end-user" in the process of the conception of prosthetics highlights the fact that there are several problems with the definition and conception of this technical object. First is the fact that the approach to conception is ill adapted, tending to consider the object and its technology rather than the user and his/her related technique or use [115]. This is particularly problematic in the case of prosthetics.The lack of consideration of these issues in the conception process, leads to compensation by calling upon humanities and social sciences at the last minute. The concept of acceptance to which the designers of technical objects refer, is thus more often than not an a posteriori sterile justification rather than a prior-to-conception real consideration of the needs and uses of the user and related anthropo-socio-cultural issues [116]. Lastly, the complexity of the questions raised, once again, highlights the importance of the consideration of the results of psychological and anthropological studies in the conception and design of prosthetics, as much as those from quantitative/statistical sociological approaches which can appear more easily exploitable in engineering processes because of their “mathematical” content.

5.1.2.5 Integrity and integration

Beyond anthropological and social issues, a number of phenomena related to psychology and the neurosciences influence the appropriation of prosthetics. Two important questions can be posed when proposing prosthesis for an amputee: that of the physical integrity of the amputated body, as well as the physical integration of the technology. The amputated and thus "diminished" body questions the notion of physical integrity: the damage made to the sacred envelope which is the human body alters the representation which the subject has of himself and can harm his self-perception. Above and beyond the fear of pain, complex symbolisms relating to the “invasiveness” of a prosthetic device which crosses (recent prototypes use implanted elements) or comes very close (surface electrodes) to the symbolic barrier of the skin can directly affect the user’s psyche.

The phenomenon of the physical integration of technology thus has psychological aspects but in order to fully understand it, one must also look to the neurosciences and social sciences. Indeed, when different research communities are questioned on the conditions required for the integration of prosthesis in the body image, opinions differ, and even the possibility of complete integration is questioned. For neuroscientists, the relationship between sensory-motor loops and physical integration appear obvious, which supports the growing number of research on artificial sensory feedback. Beyond these neuro-physiological phenomena, it is impossible not to consider the conditions required for the incorporation of the technical object in the light of work from social integration theories such as [117]. The manner in which society perceives, considers and judges the prosthetic-user is also indirectly responsible for the level of personal appropriation of this technical object which, like amputation, remains a stigma. Integration of the prosthesis by the amputee is therefore directly conditioned by the integration of the prosthetic-user in society (see next section on the *myth of human enhancement*), another demonstration of the “holistic” nature of this phenomenon.

5.1.2.6 Temporality and instantaneity

One society-driven myth is that of instantaneity. Socio-cultural productions promote, as well as the image of a hybrid body, the (utopic) idea of instant integration. The direct consequence of this myth is the negation of the difficulty to learn body techniques and the time scale required: this comes to forgetting the number of years it took us to master our bodies even for basic tasks such as walking or grasping. With regard to prosthetics, this utopia of instantaneity has a negative effect both on users as well as the designers of technical devices. The amputee is thus usually surprised at the difficulty he has to learn to control his prosthesis, and this lag between myth and reality can be discouraging in some cases, pushing him to request a simpler device. This negation of the temporality of the learning process leads the prosthetic designer to sometimes conceive technical objects requiring body techniques which are so new and/or complex that the learning time is longer than the lifespan of the device itself (temporal incompatibility between learning and obsolescence).

5.1.2.7 Ethical questions

A large number of studies have been carried out by different groups regarding the ethics of technology, in particular, when the aim is interaction with the body. Several ethical think-tanks have produced norms and legislation regarding these questions, such as the ones from the European Ethics Group on science and new technologies. These legislative points are not to be ignored, however, they should not be considered alone, disconnected from technical reality and anthropo-socio-cultural phenomena: the impact of techniques on human beings is more complex than the legal questions and biomedical aspects which are generally at the forefront of this type of work.

5.1.3 Conclusions

As briefly analyzed in this document, progress in technology alone will not solve the issue of appropriation and integration of assistive robotics, especially when they interact closely with the human body. Most of these considerations can be applied to other robotic devices dedicated to pHRi (surgical robots, exoskeletons, wheelchairs, cobots, etc.). I strongly believe that an awareness of this multitude of phenomena, symbolisms and points of view could help us, technology researchers, to produce better adapted technological devices. Moreover, at a time in which there is an increase in studies relating to the ethics of research on robotics, this analysis pushes us towards another “ethical” question: that of the technical deontology of the creators of these objects. Indeed, only the adoption of a global or “holistic” point of view, which neither neglects nor denies any aspects of the problem, and which results in a concrete, ecological approach to co-conception, could be considered truly ethical.

5.2 Ethics of research in assistive technology

5.2.1 Context

The question of the ethics of assistive robotics generally raises the major concerning question of the potential danger of human enhancement. One common belief is indeed that technologies that repair the body could easily (and will) be used for augmentation of unimpaired users. This question of the enhancement, is actually so strong in the societal debate that it tends to overshadow more real possible ethical issues.

But, as we saw through the different literature review of this document, the state of the art of technology to "simply" repair the body is already rather mixed. Indeed, while there was some recent progress in the hardware, numerous scientific barriers remain and limit the real possibilities of those devices. A majority of devices remain complex (significant cognitive cost of use), with extended learning time periods while providing a rather limited sensory-motor assistance and daily-life experience. And the growing number of promising invasive technologies (implants, electrodes, etc.) are not always tilting the benefits/risk balance in the right direction. The question of the "enhancement" and its consequences is thus yet hardly questionable.

Nevertheless, numerous ethical questions are already raised by the current state of those technologies, because of its relation to health, and of the close connection between human body and (possibly flawed) technology: inviolability of the human body along with its physical and psychological integrity, respect of human dignity, specification of the finality and proportionality and relevance principles in research, free and informed consent, respect of data privacy, along with major questions such as the respect for human life and its diversity or the question of non-discrimination and equity.

Some legal and ethical framework already exist about those questions and their future developments. For the legal aspects, some conventions and declarations already partially cover some of the evoked points: the Oviedo convention [118], the Universal declaration on the human genome and human rights [119] or Charter of Fundamental Rights of the European Union among others. From an ethical point of view, the work, for example, of the European Group on Ethics in Science and New Technologies (EGE) such as the report on ICT implants [120] or national initiatives such as the UNESCO-COMETS report on ethics of robotics [121] or on neuro-enhancements from the CCNE [122] also already provide directions.

5.2.2 New ELS challenges in wearable assistive robotics

While those frameworks exist, the rapid evolution of technology is challenging possibilities and raising new ethical questions, or new issues to be considered.

- **Shared-control and respect of patient autonomy**: the question of the shared control between a human and a subject may raise some questions about the loss of liberty, the loss of autonomy, and possibly the manipulation of will power. This question can be hardly perceptible when analyzing a simple assistive device compensating for a limited autonomy loss, such as a simple prosthesis. But when considering the case of users with important impairment relying on assistive devices to act over their environment (tetraplegic user on a wheelchair controlling an assistive robotic arm) or to communicate with others (locked-in patients relying on eye-trackers or brain computer interfaces), the risk of loosing the control becomes greater and the possible consequences more serious. This also raises the question of the security of those assistive devices with respect to the risk of external manipulation or takeovers.

- **Dependence on technology and technological sustainability:** Restoring autonomy in a patient suffering functional impairment is now possible with several technologies. Those could possibly deeply affect in a positive way the autonomy and life of the patients who might feel "repaired" or "cured". It is therefore mandatory for companies producing the technology to ensure of the long term viability of their devices, and to plan as much as they can the possible issues patients might meet in case of product discontinuation, or worse, of company bankruptcy. Especially if the device is implanted or required (possibly irreversible) surgery. The dependency on efficient assistive technology may be total for some users, and they might feel "handicapped again" the day the technology is no longer available. One could also see a connection with the current debates on the planned obsolescence and the "right to repair" [123] for devices on which patients' lives depend so much. While such situation is already partly managed for critical implanted devices (such as pacemakers or implanted insulin pumps) with interoperability of systems, this aspect should be more carefully considered for future assistive robotics devices.

- **Precautionary approach and risk minimization:** One major current trend in the field is towards the development of invasive technologies. A growing range of solutions are being proposed to interact with the peripheral or central nervous systems [124]: Brain Computer Interfaces (BCI) with implanted electrode arrays, cuff measurement electrodes or intrafascicular stimulation ones, spinal cord stimulators, etc. The installation of those electrodes generally also requires an extensive surgery. Considering the current benefits-risks balance for those invasive solutions might raise some interrogation with respect to the precautionary principle and the principle of proportionality [120]. The overall picture gets bleaker with current limited long term visibility on the robustness and physiological effects of those technologies and the reduced understanding of biocompatibility phenomenon such as the gliosis [125]. Although research should obviously be continued and encouraged toward this direction, the promotion and transfer of invasive technologies should definitively be done with reason and restraint.

- **Promoting a certain vision of impairment:** Comparing the current trend in the development of exoskeletons to allow paralyzed people to move around, with limited efforts and results of the policy measures to make cities and buildings more accessible to people within wheelchairs, highlight a possible ethical dilemma. In the last decades, the way society considered and managed handicap evolved from an "integrative model" (for example in France with the "Loi n° 75-534 du 30 juin 1975 d'orientation en faveur des personnes handicapées"[1]) which encourages the adaptation of "different" individuals to a "normal" system, toward an "inclusive model" (for example in France with the "Loi n° 2005-102 du 11 février 2005 pour l'égalité des droits et des chances, la participation et la citoyenneté des personnes handicapées"[2]), which rather pushed for changes from the society to include all individuals. One might think

[1] https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000333976/

[2] https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000809647/

that, indirectly, robotic assistive technology is pushing toward an integrative model which puts pressure over individuals and continue to spread a rather outdated model of normality [126].

5.2.3 Conclusions

While some ethical and legal framework do exist, the rapid evolution of technologies (especially invasive ones such as neuroprotheses [127]), the appearance of novel use case scenarios and the diversion of tools dedicated to body reparation towards potential "enhancements" is slowly raising novel ethical questions which might require additional expertise from classical ethical committee, along with new reflections and propositions such as the one proposed in the guide on the Ethics of Research in Robotics" released in 2015 [128]. Thus I believe that the education and empowerment of future engineers and researchers in technology regarding those (and incoming) ethical questions may be one of the major keys to the ethical "regulation" of this field.

5.3 The challenges of technology communication and ideologies

As stated before, the ethical questions related to human enhancement have yet no reason to be particularly addressed. But, the human enhancement along with other myths (such as the one of the "cyborg") and beliefs conveyed by technology ideologies such as the Transhumanism(s)[3] are, to my opinion, already raising several concrete ethical concerns.

I am here referring to the concept of ideologies, as defined by R. Boudon, i.e. the *"false ideas which social actors possess because of their material interaction"* [130].

5.3.1 The dual existence of healthcare robotics

What is rather particular to healthcare robotics (and particularly to assistive robotics) is that, while being popular it remains rare and unknown to wide audience. The common "knowledge" of the technical reality and its performances is in fact acquired through scientific popularization, technology ideologies, cultural products (science-fiction), non-academic channels and companies advertisement. For society, these technologies are more present in the discourse than in the reality. Thus they exist for people by the communication on them rather than for their real performance or provided service. Healthcare robotics thus has a "dual existence", oscillating between the collective representations (myths) and reality.

[3] A plural is here voluntarily used here. Indeed, according to the multiplicity of ideological movements within this label, with no consensus over numerous fundamental aspects of the philosophy of technics, the philosophy of minds or the moral and political philosophy, it is not possible to describe this movement in a singular unified way [129]

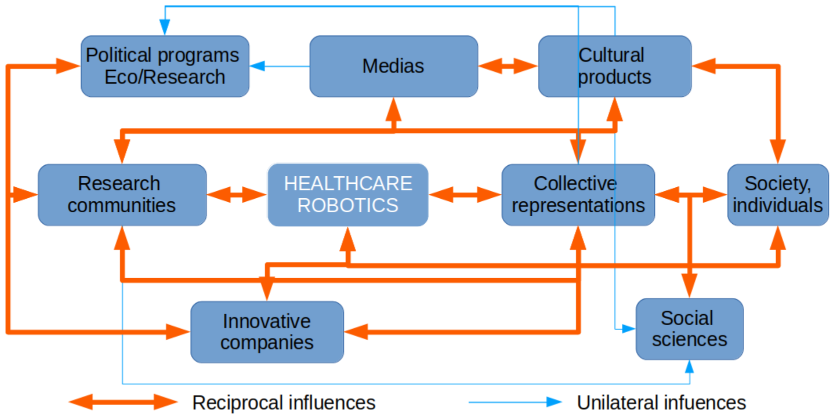

Figure 5.1: Schematic of the complex ecosystem of Healthcare robotics with communication as the principal vector of influence between groups.

Considering the complex (as for any "technoscience" [4] ecosystem of those robotic technologies, as shown in Figure 5.1, it becomes clear that those representations have in return a strong influence over individuals, society, companies and even research institutions.

As defined by D.N. Dobrin, *"Technical communication is the process and product of communication -written, visual, multimedia, etc.- from an expert to a non-expert. It is designed, both in form and content, to accommodate the understanding and tasks of the non-expert"* [131]. Technical communication has a critical role, since it can be be a source of false hope, disillusionment, even ideological, economical or political manipulation, and raise some questions (up to some crisis) about the role of scientific research, especially medical research, in our society [132].

5.3.2 Manipulation of communication in healthcare robotics and its consequences

I've been working for the last few years to identify some manipulations of communication through numerous interaction with non-technical actors, from patients to entrepreneurs up to ideologists or politicians. I tried to study those and understand their mechanisms and consequences, principally to be able to refine my own communication about my technical research. Below is an overview of some of the observed phenomenons:

- **Making up novelty and reinventing technology**. Numerous devices (such as polydigital hand prostheses or exoskeletons for example) are advertised as new or futuristic while actually being already available (at least in research laboratories and with extra constraints of use) since the 70s. Possibly to appear more modern, there is a tendency to ignore or forget technology history.

[4]Disciplines in which technology and science are viewed as mutually interacting, or as two components of it.

- **Creating beliefs on provided service**. For example, the company Intuitive Surgical commercializing the Da-Vinci surgical robot is pushing the idea that being operated by a robot is better for patients while this device, which is a teleoperating system and not an autonomous device, provides a very discussed added value for the patient but rather for surgeon's comfort, and is mostly used as hospital's technological showcase [133]. The company is doing so by bypassing the experts through intensive marketing and by relying on technology perception bias by myths (here the myth of autonomous robotics).

- **Modulating the perception of technology added value**. Prosthetic company are for example using the aesthetic codes of science-fiction (i.e. a "cyborg" look) to visually communicate an idea of "High-Tech" and of a technology able to efficiently repair (or even enhance) the body. In reality, those provide a rather limited value in terms of performance, and such practice may in the end rather satisfies the society neophilia rather than the patients real needs. Additionally, patients will have to manage an ambivalent role, acting publicly as "enhanced" humans while being aware they are not [126] which may create additional psychological pressure.

- **Minimizing the role of human users in technology performance**. By communicating on chosen "similarities" of devices with human limbs (number of DoF, grasping force or speed for artificial hands) rather than underlining the major differences and their consequences on the usability in daily life, the belief that is indirectly maintained is that reparation is instantaneous and technology use is natural (a simple "swap" of body pieces). A growing number of companies are also relying on selected "ambassador's" users to communicate through social networks an ideal image of simplicity and efficiency. In reality, patients are the ones who -in private- are paying the high cost of extended learning time, energy and concentration to make the technology work.

- **Neglecting the risks associated with some technologies**. Considering again the current trend of invasive technologies (osseointegration [70], implanted electrodes [124], etc.), several minimization or the hiding of some information can be observed: the required -possibly damaging- surgical procedures, the possible non-reversibility or safe removal and the unknown lifetime of devices, among others. This creates the belief that implanted devices are common and safe objects. Additionally, the stereotype myth of the body-machine fusion of an implanted technology which by nature would be more efficient than an external one is partly covering for the increased risks associated to those devices.

In general, what we observe is that two principal methods are used to manipulate communication. First the modulation of contents necessary for judging technology, with for example the omission of information necessary for appreciating technology, a biased contextualization, a double communication (verbal and visual) or by hiding behind the mythological representation. The second method consists in bypassing the classical path of communication of technical information to end-users or wide audience.

5.3.3 Conclusions

As a consequence, manipulating technical communication is creating and maintaining ideologies on healthcare robotics and more dangerously is manipulating opinions on these technologies and possibly their relation to humanity and society. Communication and the representations it creates or maintains indeed directly participate in the forging of human identity, as much as technical reality itself.

These bias on the reality could on the long term encourage or stop some research directions, create new lost hopes, expectation and even fears up to rejects from the society toward some scientific researches. The risks could also be the collapse of the representations (after a technology related crisis or spectacular accident) and then in the long term, a loss of confidence in technology and in its research community. Based on this analysis, even the critical notion of "informed consent" may be examined in a different way.

There is thus a real need for a certain ethics of technical communication in healthcare robotics guaranteeing the notion of "informed consent" on these technologies. Among possibilities are the regulation of biased technical communication of end-users and medical experts with an economical conflict of interest (ambassadors and consultants), the training of academics in the field of technical communication or an effort in a more skeptical communication on the limits rather than the possibilities.

This should both lead to an improvement of the quality and objectivity of information transmitted to society, and also to help citizens better appreciating the potential (individual or collective) impact of these technologies.

Chapter 6

Conclusions and perspectives

Sommaire

6.1 Summary

This manuscript describes the different aspects of my research activity on the use of sensorimotor coordinations (and of a multidisciplinary approach) for intuitive and ecological robotic assistance to gesture.

After an introduction to the field of healthcare robotics and the numerous challenges of the targeted clinical applications, the chapter 2 presents some contributions to the field of human-robot adaptation in the context of neuromotor rehabilitation. We first proposed a generic Assist-As-Needed (AAN) method to adapt the exoskeleton behavior to the performances of the participants and their evolution. In parallel, we tried to characterize and understand the adaptation of movement and coordination in participants interacting with a constraining force field applied at the joint level during an extended time.

In chapter 3, we used the knowledge on motor coordination to reduce the control dimensionality of an arm prosthesis and complete the residual arm movement with those of the prosthesis. To this aim we built models of interjoint coordination allowing to automatize the movement of an artificial elbow based on the ones of the remaining shoulder of participants. This approach was evaluated on amputated participants on a specifically developed prosthesis prototype and partly generalized to control additional prosthetic joints.

In chapter 4, the use of remaining muscle coordination schemes activated by the phantom limb mobilization allowed us to develop a new myoelectric control approach of prostheses for transhumeral amputees. A characterization of the phantom limb mobility and its physiological expressions allowed us to build a dedicated pattern recognition architecture offering extended myoelectric control of prosthesis with multiple DoF, yet in some controlled conditions, with results promising enough to question the generalization of nerve surgeries to extend the control abilities in upper-limb amputees.

Finally in chapter 5, some summaries of the interdisciplinary researches I am exploring in parallel of my technical contributions are shown. The multifaceted question of body integration of technical assistance is evoked, along with some of the novel ethical questions that those technologies are raising, and the implications of technical communication on creating ideologies. Those aspects all highlight the need for a more global vision of technology beyond engineering aspects.

6.2 Perspectives

6.2.1 A deeper understanding of the adaptation in human motor control caused by the interaction with an exoskeleton

As reported in Chapter 1, there is yet no real understanding on the effects of the exposition to generic joint force field (such as friction, viscosity, elasticity or inertia) on the human adaptation or motor learning phenomenon, while such understanding would be crucial to improve the quality of physical assistance or to prevent the possible appearance -in the long run- of pathological motor behaviors, not only in patients during rehabilitation but also in industrial operators who are starting to use such exoskeletons to assist their gestures and supposedly preserve their health by preventing the development of musculoskeletal disorders. During the PhD of Tommaso Proietti, we performed a first analysis but relied on a particular reactive joint force field, and a reduced number of repetitions limiting the possibility of deeply study the motor variability. The overall objective of future research, which will be part of the EXOMAN project ("Towards exoskeleton-human symbiosis: investigating how humans interact with an upper-limb robotic exoskeleton") funded by the ANR AAPG 2019 supervised by B. Berret from Université Paris-Sud), will be to study, characterize and understand more systematically the adaptation of human participants performing simple tasks within an exoskeleton exhibiting different standard and simple interactive behaviors (i.e. joint force fields). Those tasks will be inspired by standard cobotics applications such as "pick and place" or "displacement" of more or less heavy objects, which are typical scenarios of the industrial application of assistive exoskeletons.

The three major scientific topics to be studied within this project will be i) the retention of coordination patterns imposed by exoskeleton joint control and particularly its influencing factors (to identify most effective force fields); ii) the identification of individual characteristics (i.e. movement preferences such as vigor, physical or psychological factors) predicting for specific adaptation profiles; and iii) the development of novel metrics for characterizing patterns of upper limb motor coordination. Indeed, the two first topics requires a precise quantitative analysis of inter-joint coordination, and usual kinematic metrics applied on endpoint trajectory (direction, velocity profile, smoothness) are clearly insufficient. The use of additional frameworks, such as principal component (PC) analysis, or Uncontrolled Manifold (UCM) paradigm to quantify adaptation in both the task and the null spaces will be studied, along with the possible development of novel metrics to quantify correlations between signals.

6.2.2 Improving upper-limb prosthetics

While I mostly plan to pursue my works on the control of prostheses, I also envisage to extend my research to other related research aspects. Indeed, along with the difficulty in controlling the device, three other major phenomenons limiting the performance and adoption of these devices were identified: the insufficiency of the mechanical performances (lack of DoF, limited power, stiffness and non-backdriveability of joints) which tends to limit the control possibilities; an insufficient perception of the internal state of the prosthesis (proprioception) and of its interactions with the environment; and finally the difficulty and duration of learning sensory-motor behaviors integrating both the body and the prosthesis. I therefore plan to address those different aspects within the next years.

Concerning the mechatronics, we plan to develop a compliant robotic prosthesis with remote actuation. We have started to develop advanced prototypes of an arm prosthesis with more degrees of freedom (at the wrist and shoulder levels) with embedded actuation and a dedicated control architecture. Within the next years, we wish to go further and deport the actuators (thanks to flexible transmissions), batteries and electronics in the user's back. Also since the rigidity of the prosthesis making certain interactions complex, we will study the development of an actuation allowing, when desired, a certain joint flexibility.

For the control aspect, within the framework of the BYCEPS ("*BodY-ControllEd robotic ProSthetic for arm amputees*") project funded by the ANR and the PhD thesis of Mathilde Legrand, we have recently developed and patented an innovative control mode, the "Compensation Cancellation Control" or C.C.C. in the continuity of our previous work on movement-based control, which focuses on another type of coordination, namely the body compensations. This C.C.C approach proposes to enslaves the movements of the prosthesis to the body compensations of its user, measured by movement sensors [79]. The first evaluations of this control on an elbow joint elbow joint for the realization of simple tasks (pointing and tracking) have highlighted the efficiency and simplicity of use as well as a great capacity to relieve the user of the control of the intermediate joints. We now wish to go further and develop a complete control mode dedicated to a multiple DoF prosthesis, mixing myoelectric (possibly phantom-based when available) for the only control of the hand grip, with this C.C.C. approach which would drive automatically and in a coordinated way the intermediate joints (elbow and wrist) responsible for the position and orientation of the hand in space.

Considering the sensory feedback, we recently started to study with Malika Auvray the possibility of transmitting sensory feedback on the orientation of the prosthesis

by means of tactile vibrations. The encouraging results suggest an performance improvement, especially in terms of motion preparation [134]. In the extension of this work, we will try to develop tactile artificial sensory feedback generated by vibrators and mechano-tactile stimulators distributed in the socket and the strap of the prosthesis, able to transmit chosen information of touch, force and proprioception in an intuitive and efficient way.
Finally, regarding the learning of using the prosthesis, we will develop an environments and tools to train and guide the users in mastering their prosthesis. Recently, we explored the use of a simplified visual feedback of the muscle activations used during the execution of the movement to guide the the learner towards a co-adaptive strategy with the classification algorithm [135]. We will extend preliminary results to develop co-adaptive interactive tools integrating the modeling of learning mechanisms in the context of prosthesis control and user interface that facilitate the interpretability of these systems and their appropriation. In collaboration with B. Caramiaux, we will also explore, within the ARCOL ("*Interactive Reinforcement Co-Learning*") funded by the ANR, the possibility of using algorithmic methods to guide users and optimize their learning program under the formalism of reinforcement learning where the tasks chosen are those on which are those on which the learner makes the most progress [136].

6.2.3 Generalization of the approach to other applications

I also plan to extend the use sensorimotor coordinations to develop intuitive robotic assistance to two novel applications:

6.2.3.1 Lower-limb exoskeleton for paraplegic users

Within the CIFRE PhD thesis of Omar Mounir Alaoui, in collaboration with the french exoskeleton company Wandercraft, we started working on using the coordination that naturally exists between the upper and lower part of the body. Our objective is to decode the motor intention of a paraplegic patient installed in an exoskeleton, from the upper body movements only, instead of relying on the use of a remote or stereotypical gestures. A first work on the robust detection of gait initiation thanks to IMUs (worn on the back and shoulders) of Anticipatory Postural Adjustements and classification algorithms has recently been published [137]. We will apply this approach systematically in the future to also offer users a natural control of the gait termination and steering.

6.2.3.2 Supernumerary Robotic Limbs (SRL) for operators in industry

In the coming years, I would like to broaden the scope of my research to also consider the case of assistance to "experts" gesture, such as industrial operators, in particular by exploring the development of robotic supernumerary limbs [138]. This new field of research, mainly led by the team of Prof. H. Asada at MIT, proposes a framework that seems directly adapted to the implementation of some of the work that we have done for prosthetic control. Within the NIMA ("*Non Invasive Interface for Movement Augmentation*) funded by the EU (H2020 FET), we will study the possibility of transferring coordination-based control approaches such as the C.C.C to naturally pilot a worn third arm which could possibly increase the dexterity of its wearer, for particular three-hands tasks rather common in industrial and maintenance tasks.

6.2.4 ELS questions of wearable assistive robotics

While assistive technologies for impaired users are growing, the abandonment rate of those devices appears to remain rather constant, especially for upper-limb devices [9]. Understanding this phenomenon of abandonment or reject by users might be the key to a better understanding of the multi-factorial relationship between users and assistive technology, in particular in relation to technical aspects such as the complexity of use, the lack of technical training of users but also clinicians, or more fundamentally the definition of the specification and the identification of patient's need. In collaboration with the research collective "Corps & prothèses" that I co-founded, we will address some of these questions within the research project APADIP ("*Amélioration du parcours d'appropriation des dispositifs prothétiques : usages des personnes amputées appareillées, pratiques des soignants et savoirs expérientiels*") funded by the IRESP. Our goal will be to identify key factors of prosthesis abandonment and to propose guidelines and recommendation to users, clinicians but also designers.

As a consequence of the analysis conducted so far, I would also like to find ways to bring my research closer to users, through a "co-design" approach, possibly by recruiting patients as research partners to ensure the development of a useful, acceptable and efficient assistive robotics. A first attempt was made through the participation to the Cybathlon 2020 Global Edition during which we incrementally developed an advanced personalized prosthesis **for and with** our pilot for the competition, C. Huchet. We will try to enhance such kind of exchanges within the incoming years and research projects.

Finally, I would try to participate in global initiatives on the development of ethical and legislative frameworks for new technologies, such as invasive or implanted ones, dedicated to human body reparation or enhancement.

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