Study on the activation of the biceps brachii compartments in normal subjects

par
Nahal Nejat

Institut de génie biomédical
Faculté de médecine

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Présentée par :
Nahal Nejat

a été évalué par un jury composé des personnes suivantes :

Vincent Jacquemet, président-rapporteur
Pierre A. Mathieu, directeur de recherche
Michel Bertrand, co-directeur
Danu Gagnon, membre du jury
Abstract

The latest myoelectric prostheses have several degrees of freedom and therefore require a large number of myoelectric signals to fully exploit their capabilities. Muscle compartments, which are intra-muscular subdivisions innervated by an individual muscle nerve branch, can be exploited to provide additional independent muscle control sites to operate such prostheses. This research presents a work to investigate the activation of the 6 biceps brachii compartments in healthy subjects to see if they have the ability to activate those compartments voluntarily. Therefore, electromyographic (EMG) signals were recorded from an array of seven and ten pairs of equally spaced surface electrodes positioned across the short and long head of the biceps of ten healthy subjects. The EMG signals are collected in two positions: 1) with the subject seated, right elbow flexed \(~100\degree\), and 2) with the subject standing with the right arm extended horizontally in the coronal plane (90\degree shoulder abduction). In both positions, the hand is either fully supinated, neutral, or fully pronated. The average root mean square value of the EMG signals obtained from the pairs of electrodes positioned over the short head are compared with the average obtained for the other pairs placed over the biceps long head. Ultrasound imaging also used to visualize the long and short heads of the biceps in flexed and extended arm while the hand was in different postures. Depending on the task to be accomplished, activity was larger in one head or in the other. Being able to activate either head of the biceps, while not yet completely independently, suggests that the selective use of compartments could be a possible avenue for controlling upper limb myoelectric prostheses.

Keywords: Biceps brachii, Compartment, Electrode array, Surface EMG, Ultrasound.
Résumé

Les prothèses myoélectriques modernes peuvent être dotées de plusieurs degrés de liberté ce qui nécessite plusieurs signaux musculaires pour en exploiter pleinement les capacités.
Pour obtenir plus de signaux, il nous a semblé prometteur d'expérimenter si les 6 compartiments du biceps brachial pouvaient être mis sous tension de façon volontaire et obtenir ainsi 6 signaux de contrôle au lieu d'un seul comme actuellement. Des expériences ont donc été réalisées avec 10 sujets normaux. Des matrices d'électrodes ont été placées en surface au-dessus du chef court et long du biceps pour recueillir les signaux électromyographiques (EMG) générés par le muscle lors de contractions effectuées alors que les sujets étaient soit assis, le coude droit fléchi – 100 ° ou debout avec le bras droit tendu à l'horizontale dans le plan coronal (sur le côté). Dans ces deux positions, la main était soit en supination, soit en position neutre, soit en pronation.
L'amplitude des signaux captés au-dessus du chef court du muscle a été comparée à ceux obtenus à partir du chef long. Pour visualiser la forme du biceps sous les électrodes l'imagerie ultrasonore a été utilisée. En fonction de la tâche à accomplir, l'activité EMG a été plus importante soit dans un chef ou dans l'autre. Le fait de pouvoir activer préférentiellement l'un des 2 chefs du biceps, même si ce n'est pas encore de façon complètement indépendante, suggère que l'utilisation sélective des compartiments pourrait être une avenue possible pour faciliter le contrôle des prothèses myoélectriques du membre supérieur.

Mots-clés: Biceps brachial, compartiment, matrice d'électrodes, EMG de surface, écho.
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List of abbreviation

ANN: artificial neural network
BB: biceps brachii
BMI: body mass index
CSA: cross-sectional area
EMG: electromyography
MVC: maximum voluntary contraction
MRI: magnetic resonance imaging
MU: motor unit
LH: long head
RMS: root mean square
SH: short head
SENIAM: Surface EMG for Non-Invasive Assessment of Muscles
US: ultrasound
Dedicated to my supportive parents, Homa and Mehdi, and my soul mate, Arash.
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Chapter 1

Introduction

Upper limb plays very important role in performing the daily tasks and activities and as well in body appearance. Amputation can happen at any life stage due to a disease, dramatic accident or events such as war where mainly young people are involved. Hand loss is extremely overwhelming and can have a huge physical and emotional impact on amputees’ lives. Fortunately, a prosthesis can offers them the ability to produce some useful movements in their daily activities. While basic mechanical prostheses such as body operated hooks are still in usage, more socially acceptable prostheses replicating the human hand which are controlled by muscle activity are often preferred.

Following the surgery, the remnants muscles above the amputation level can still be contracted. A movement cannot be produced but an electromyographic (EMG) signal can still be recorded either in or above the muscle at the skin surface. Being voluntary produced, these signals can be used to activate a myoelectric prosthesis. The ability to produce certain useful movement is thus regained and contributes greatly to the independence of the amputee people. Since their introduction in the 1960s, the design of upper-limb myoelectric prostheses has improved significantly but until few years ago, only few degrees of freedom were available for prosthetic control. This condition is changing recently due to new prostheses such as the i-Limb developed by the Touch Bionics company and mainly by the very important projects of the U.S. Defense Advanced Research Projects Agency (DARPA). Their project Revolutionizing
*Prosthetics 2007* [1] was aimed at developing prostheses mimicking the natural movements of the upper limb. Since the operation of such modern prostheses requires many control sites. Another project *Revolutionizing Prosthetics 2009* was funded to develop a variety of methods by which people with amputation could control their prostheses as naturally as possible. Typically, 2 muscles are used for a given movement: for instance, one for closing the hand and another one for its opening. For additional actions or degrees of freedom (DOFs) more muscle pairs are required unless signal processing methods are utilized to produce more than one action per muscle’s signal (Tenore et al., 2008).

As the amputation level gets closer to the shoulder the number of muscular control sites gets smaller and new strategies have to be developed. Targeted muscle re-innervation (TMR) is an example of a quite remarkable one for those who have lost one or both of their arms. In this approach, the remains of the severed nerves which were activating the arm muscles are rerouted to innervate the thorax muscles such as the pectoralis which is made up of many segments. Following surgery and after proper time of recovery, it is possible for the person to flex his/her amputated elbow by issuing the same voluntary command used before amputation to perform the arm flexion. This action would happen through contraction of one segment of the pectoralis and it’s the EMG signal collected with a surface electrode from that part of pectoralis is used to produce a flexion at the elbow level of the prosthesis (Kuiken et al., 2007).
Fortunately, most amputations are less severe but the number of available control sites is often not large enough to take full advantage of modern prostheses. While sophisticated new signal processing techniques are being developed to increase the number of control signals, from a given set of EMG signals, exploitation of some muscles anatomy is another approach that could offer an additional solution. While performing cadaver dissections, Segal (1992) found within the short and long heads (SH and LH) of the biceps brachii (BB) the presence of up to 6 compartments each innervated by a nerve branch. Physiological evidence for functional partitions or divisions in the BB had already been provided: using intramuscular electrodes, Ter Haar Romeny et al. (1984) found that some motor units (MUs) of the LH of the BB were activated during flexion of the elbow while other MUs were only active when the hand was positioned in either supination or pronation. Brown et al. (1993) also showed the differential functionality between the two heads of the BB, by using two surface electrodes on top of each of them in motions involving the arm where the muscle distal insertions are found.

Under specific conditions, it may thus be possible to voluntarily contract each compartment of the BB either individually or as a group. This would increase the number of EMG signals that could be used to control a myoelectric prosthesis. In this work we investigated the activation of the BB compartments in healthy subjects to see if they have the ability to activate those compartments voluntarily. If the answer is positive, a door would be open to investigate if persons who sustained an amputation can also take advantage of muscular compartments.
In parallel with EMG recordings, ultrasound images of the upper arm where obtained. In dynamic situations where the hand position was progressively moved between pronation and supination, the contour of the BB muscle and the separation line between its SH and LH were carefully visually tracked. Then, in static hand position, the contour of the BB and of the SH and LH were traced and their corresponding cross section areas determined. That anatomical information assisted the interpretation of the EMG signal recorded over the BB.

In the next chapter an overview of the anatomy and physiology of muscle structure and contraction is presented. Then, EMG techniques and muscular ultrasound imaging interpretation is considered followed by a brief review on myoelectric prosthetic control.

In the third chapter, techniques of EMG recording and signal processing are presented as well as the main characteristics of the ultrasound equipment that we used.

Results are presented in the fourth chapter. It starts with an article which is published in the Journal of Medical and Biological Engineering (JMBE). The presented results were obtained with an array of 7 pairs of electrodes placed over the BB of four healthy subjects. This article is followed by a conference proceeding (ISSPA 2012) on results obtained from the same 4 subjects but with an expanded array of 10 electrodes. The chapter continues with new results obtained with 6 additional subjects with the 10 electrodes array. Finally, the results obtained with the ultrasound images are presented.
In the fifth chapter, a discussion of the obtained results is presented. This is followed by a
Conclusion and a view on where future works could be heading.

Chapter 2

2.1 Anatomy of muscle

The notions presented here are drawn mainly from "Vander’s Human Physiology the
mechanisms of body function" (Widmatier, Raff and Strang, 2011).

There are 3 types of muscles: smooth, cardiac and skeletal. Smooth muscles are found in
the internal organs and are activated by the autonomic system which is related to
vegetative states. Cardiac muscles are spontaneously active and their existence is the
origin of the blood pumping of the heart which is vital for any living organisms. As for
skeletal muscles, they are attached to the skeleton through tendons and they are under our
voluntary control through signals generated within the central nervous system (CNS).

As shown in Fig. 2.1, an individual skeletal muscle is composed of hundreds up to
thousands of muscle fibers bundled together making a fasciculus which is wrapped with
connective tissues. The diameter of human muscle fibers ranges from 10 to 100 μm and
they run the entire length of a muscle which could reach up to 20 cm. Each muscle fiber
contains many individual contractile subunits called myofibrils extending from one end
of the fiber to the other and fusing with the tendons at the end of the fiber. The myofibril
is made from a chain of sarcomeres (up of 10,000 or more) which are the functional units
of the muscle. They are composed of filaments of actin and myosin proteins with a spatial
arrangement permitting a sliding between the 2 filaments thus shortening them which results in a muscle contraction (bottom of Fig. 2.1). Muscles are surrounded by connective tissues which act as a protection and also provide passages for the blood vessels which nourish them and nerves for their activation.

Figure 2.1 Structure and organization of the skeletal muscle (Vander’s et al, 2011, p.252).
There are 3 general architectures for skeletal muscles (Fig2.2). In the longitudinal one, muscle fibers run parallel to the muscle’s force-generating axis, as in the BB; for unipennate architecture, muscle fibers run at a fixed angle relative to the muscle’s force-generating axis, as in the vastus lateralis muscle. In multipennate architecture, muscle fibers run at several angles relative to the muscle’s force-generating axis such as gluteus medius muscle (Liber and Friden, 2000). It is to be mentioned that fiber direction varies spatially within a muscle length and dynamically during a contraction (Staudenmann et al., 2010). Muscle fiber orientation also changes during isometric contractions of increasing force (Maganaris and Baltzopoulos, 1999).

![Image](image.png)

Figure 2.2 Three types of muscle structure. A: parallel in biceps brachii. B: Unipennate in the vastus lateralis muscle. C: Multipennate gluteus medius muscle. In this figure, Lm is the muscle length while Lf is the length of its fibers. $L_m = L_f$ in muscles only where fibers run parallel to its structure as in A. Otherwise $L_m \neq L_f$ as in B and C (Liber and Friden, 2000).
2.2 Upper limb

Extending from the shoulder down to the hand, the upper limb is divided between the arm which is the region between the hand and the elbow and the upper arm which is referring to the region between the elbow joint and the shoulder. Within the upper arm, lies the humerus bone while the radius and ulna are found in the arm (Fig. 2.3A). The presence of those 2 bones permits the rotation of the hand. In the arm, many small muscles are found since many finger movements should be executed while in the upper arm, to produce elbow extension and flexion and the hand rotation, only 5 larger muscles are present. In the upper arm, the position and function of those 5 muscles are mainly separated by the humerus bone: in the anterior group one find the biceps brachii, the brachialis and the coracobrachialis for the arm flexion while the triceps and the anconeus are found in the posterior group and produce an extension of the limb. Four of those muscles are illustrated in Fig2.3 B and C. It can be observed in C that the biceps brachii (BB) is made of two parts: a long head toward the outside of the limb and a short one toward its interior side. The two heads of the BB join in the distal part of the upper arm and attached through a tendon to the interior part of the radius. Since the ulna and radius bones can move relative to each other, the biceps can rotate the radius to produce the supination i.e. palm facing up. When contracted, the BB with its 2 neighbours produces a flexion at the elbow level. An opposite movement, i.e. an extension is produced when the triceps is activated.

Being only interested in the upper arm muscle in our project, no description of the muscles located below the elbow is made here.
Figure 2.3 A: Bones of the upper limb. B. Lateral view of the right upper arm illustrating 4 of its muscles. C: front view of the 4 muscles. While the anconeus is not shown in B and C, the deltoid D and part of the pectoralis major P can be seen in B (panels B and C modified from Thibodeau, Patton, 2007, p.376).

2.3 Physiology of muscle contraction

Following a command initiated in the brain, electrical signals propagate in the CNS and reach the peripheral nervous system to finally make contact with a given number of muscles to make them contract leading to the production of a movement. Information in the CNS is conveyed through action potential (AP) generated by various movements of Na⁺, K⁺, Cl⁻ and Ca²⁺ ions across the membrane of neurons. When such potentials reach muscle fibers at a neuromuscular junction usually positioned in the center of the fibers, they induce in each fiber the production of 2 muscular APs traveling in opposite direction from the neuromuscular junction up to the end of the fiber. As they travel along the fiber at ~4-5 m/s, these APs induce the release of calcium ions. The presence of those ions within the sarcomeres makes the heads of myosin to bind with actin (Fig. 2.4) to form
cross-bridges and cause the sliding of actin toward the myosin which shortens each sarcomere and results in the muscle contraction. In absence of APs, Ca\(^{++}\) ions are pumped back into its reservoir and the muscle relaxes.

![Sliding Filament Model](http://spot.pcc.edu/~lkidoguc/Topics/muscles.htm)

**Figure 2.4** Sliding filament models (From: http://spot.pcc.edu/~lkidoguc/Topics/muscles.htm).

### 2.3.1 Motor units

The number of muscles fibers activated by the arrival of the AP is dependent on the size of the motor unit (MU). A MU consists in a neuron motor (called a motoneuron), and all the fibers with which it make contact through a neuromuscular junction (Fig. 2.5). Small MUs innervates only few fibers while large MUs are made of up to more than thousands
of muscle fibers. Small MUs are used in precise muscle movements such as for the eyes muscles.

![Illustration of 2 motor units](http://www.baileybio.com/plogger/?level=picture&id=239)

**2.3.2 Force production**

The mechanical force produced as a response of a muscle to a single AP (or an external stimulus), is known as a twitch: a contraction of few grams lasting ~100 ms. When a second AP arrives before the muscle has relaxed, a summation of the twitches occurs. As the frequency of the APs is increased, the twitch summation reach a maximum force
called the tetanic force which is approximately 3 times larger than the twitch amplitude (Fig. 2.6).

![Isometric contraction produced by an impulse stimulus](image)

Figure 2.6 Isometric contraction produced by an impulse stimulus. As the frequency of stimulation is increased, the addition of the mechanical output reached a maximum called the tetanic force of a MU (Vander’s et al, 2011, p.266).

As shown in Fig 2.7(b), as the tetanic force of a MU is reached, the force level can still be increased by setting in action additional MUs which are of more powerful. Such orderly recruitment starting with small MUs and recruiting larger and larger ones as required is called the Henneman's principle.

Muscular force generation is associated to 3 different muscle fibers. Type I fibers are associated to small MUs where oxidative processes generate long twitches of small force but with a high endurance to fatigue. In type IIA the force production is an oxidative-glycolytic process and the production of their twitch amplitude is greater and faster than the first type, these MUs are of the medium size. For the type IIB fibers, a glycolytic
process is present. MUs are large and produce high force/power/speed production but their endurance to fatigue is limited. Figure 2.7 (a) illustrates the different MU types and their spatial disposition within a muscle. Their relative tetanic tension is shown in panel (b).

Figure 2.7(a) Diagram of a cross section through a muscle composed of the 3 types of motor units. (b) Tetanic muscle tension resulting from the successive recruitment of those 3 types (Vander’s et al, 2011, p.271).

Figure 2.8 Left: Isotonic contraction, muscle shorten and produced movement. Right: Isometric contraction muscle pulls force fully against the load but does not shorten (Thibodeau and Patton, 2007, p.414).
Muscle contraction can be further qualified as isometric and/or isotonic (Fig. 2.8). Isometric contraction is produced when the muscle develops a tension but does not shorten as in trying to keep a weight in a constant position without any movement. In isotonic contraction the length of the muscle changes while the load on the muscle remains constant.

2.4 Muscle compartments

While the information in the previous sections is generally well known, the presence of muscles compartments is a situation which has been less noticed. It has been suggested in the literature that some skeletal muscle are constituted from organized sub-units called neuromuscular compartments. Cohen (1953) was the first to show that stretching a small strip of cat rectus femoris muscle caused a reflex contraction of that strip but not in the other parts of the muscle. Later, many studies demonstrated neuromuscular compartment in various animal muscles such as: cat lateral gastrocnemius and plantaris muscles (English and Letbetter, 1982), cat biceps femoris and tensor fasciae latae (Chanaud et al., 1991), rabbit masseter muscle (Widmer et al., 2003), triceps brachii muscle of rat (Lucas-Osma and Collazos-Castro, 2009).

The presence of muscle compartments has also been found within many human skeletal muscles. This includes the tensor fascia latae (Paré et al., 1981), the gluteus maximus and medius (Manueddu et al., 1989), the pectoralis major (Paton and Brown, 1994), the trapezius (Holtermann et al., 2009), shoulder muscles (Brown et al., 2007, Wickham and Brown, 2012, Wickham and Brown, 1998). In the upper limb one finds the biceps brachii
(Segal, 1992), the triceps brachii (Lucas-Osma and Collazos-Castro, 2009), the flexor carpi radialis, the extensor carpi radialis longus (Segal et al 1991), the flexor digitorum profundus (van Duinen et al., 2010). As for the lower limb, partitions were found in the lateral and medial gastrocnemius, the soleus (Wakeling, 2009) and the hamstring (Lee et al., 2010).

Being interested in the control of myoelectric prostheses, our interest was attracted by the upper arm muscles compartments specially by the BB because Segal (1992) observed, from anatomical cadaver dissections, that the BB was composed of up to 6 compartments each innervated by a nerve branch (Fig. 2.9).

Figure 2.9 Top: Photographs of biceps brachii specimens (posterior view). Bottom drawings of the biceps muscle. A: posterior view showing 6 compartments with private nerve branches. B: Anterior view (Segal, 1992).
In addition to those anatomical findings, physiological observations also support the presence of functional partitions or divisions in the BB. Using intramuscular electrodes, ter Haar Romeny et al. (1984) found that some MUs of the long head of the BB are activated during flexion of the elbow while other MUs are only active when the hand was in either supination or pronation. More recently, Holtermann et al. (2005) applied a 13x12 electrodes matrix over the BB during isometric contraction of the elbow between 0 and 80% of maximum voluntary contraction (MVC). They observed that the MU recruitment was not scattered randomly across the electrodes matrix implying the presence of distinct functional regions in the BB. As for the lower limb, Wolf et al. (1993) used fine wires inserted in the 3 regions of the lateral gastrocnemius, they found significant differences in the 3 “partitions” of the muscle and about the 8 functional tasks accomplished by the subjects.

A review article on the compartmentalization of muscles was published in 1993 by English et al. From anatomical and physiological studies performed primarily on cats and rats but also in humans, they suggested that partitions may have functional or task-oriented roles, i.e. different portions of one muscle may be activated depending on a particular task. This is in line with that hypothesis that we will be trying to explore if and how the 6 compartments of the BB can be voluntarily put under contraction by healthy subjects and eventually by people with upper limb amputation.
2.5 Muscular activity measurement methods

To assess muscular activity, various methods can be used but the gold standard is electromyography (EMG) which is related to the electrical activity of the muscle. In some occasions, the mechanical activity associated with the contraction is detected either with a microphone or an accelerometer placed over the muscle. The signal obtained is known as the mechanomyogram (MMG). In our project, EMG signals were used.

As for muscles imaging magnetic resonance imaging (MRI) can be used for monitoring musculoskeletal structures as well for evaluation of their function. Determining the cross-section area or muscle volume by MRI is useful information to track changes associated to diseases, trauma, immobilization, rehabilitation treatments or exercise. Muscle activity or portion of muscles participating in a task can be studied with MRI images taken with specific analysis of T2 times. In addition to MRI, ultrasound (US) imaging is also used for displaying muscle contour changes associated to static positions or during limb movements. US imaging is non-invasive as MRI but provides real time images. In addition, it is a relatively low-cost technology offering great information for clinical and research goals. US and MR elastography, a processing technique to analyze the mechanical properties of small area within a muscle is gaining in popularity (Segal, 2007). These approaches could eventually be used to detect within a whole muscle where are located the contracted zones or fibers. In our study, US imaging was used to study muscle deformations and its displacements under the surface electrodes during isometric contractions while the hand is in different positions.
2.5.1 Electromyography (EMG)

2.5.1.1 Intracellular recording
Such recordings are done either with needles or fine wires inserted within the muscle. This is an invasive approach which is used only when activity of single MUs is of interest or when activity of muscles lying deep beneath the skin has to be recorded. Intramuscular EMG signals are in the millivolt (mV) range (Cram, 2011) and their spectrum ranges from 2-1000 Hz (Rash, 1999). Intramuscular recording could be painful and associated with the risk of infection. This type of EMG recording is usually performed by a specialist and attention has to be paid for not puncturing veins, arteries and specially nerves.

2.5.1.2 Surface recording
This is a non-invasive and painless technique where activity of the most superficial muscles contributes the most to the recorded signal. Surface electrodes are usually made of Ag/AgCl circular disks put over the skin. Two kinds of surface electrodes are generally used: dry electrode which has direct contact with the skin and gelled electrode where an electrolytic paste makes the bridge between the skin and the electrode surface and which help decrease the skin impedance (Day, 2002). According to European standard for Surface EMG for non-invasive assessment of muscles (SENIAM) a low impedance gives stable recordings and low electrode noise levels (Stegeman and Hermens, 2007). Surface recorded voltages are in the microvolt (μV) range since potentials and associated current densities in the volume conductor decrease as the recording site is set further away from the source (Cram, 2011). The spectrum of the surface signal ranges from 10-600 Hz (Rash, 1999). In our study, surface EMG was used.
Being of low amplitude, EMG signals are prone to contamination. Some of the noise sources arise from electrostatic field, electromagnetic field (power line), motion artifact at the electrode-skin contact (<10 Hz), heart activity, etc. Some of those contaminations can be minimized with some precautions such as proper skin cleaning (or sometimes some sanding). This could also be done technologically with appropriate filtering, shielding and by using differential recording or double differential recording to obtain a smaller pick-up area and better rejection of propagated signals than monopolar recording (Fig. 2.10). According to the European SENIAM project, electrodes are to be placed between the tendons and the end-plates innervation zones and parallel to the fibers' direction (Stegeman and Hermens, 2007).

![Figure 2.10 schematic of electrode configuration for EMG recording](http://www.powershow.com/view/2a5456-OGQ2M/Aucun_titre_de_diapositive_flash_ppt_presentation).
2.5.1.3 Signal processing
The mean value of a raw EMG signal is close to 0 with a near Gaussian amplitude distribution the width of which is dependent on the number of involved motor units action potentials (MUAPs), their amplitudes and firing rate (Staudenmann et al., 2010). Raw EMG and noise signals share similarities. While raw EMG provides information on muscle activity, some processing as rectification, root mean square, integrated EMG or moving average are used very frequently to facilitate its analysis (Rash, 1999).

To be able to compare EMG signals collected from different subjects or from task to task for a given person, normalization is needed in terms of time and amplitude of the contraction. The most common method is to ask each subject to produce a maximum voluntary contraction (MVC) two or three times and to take the average as a 100% MVC. In a given protocol, subjects are usually asked to produce various contractions at <100% MVC to prevent fatigue which would corrupt the expected signals.

Although, surface EMG is non-invasive and safe, an objective quantification of a given muscle may be difficult due to different factors such as crosstalk. This occurs when the energy from one muscle propagates in the limb volume conductor and reaches the muscle over which recording electrodes are placed. Dependent on the volume conductor characteristics, cross-talk can be more or less important (Staudenmann et al., 2010). Crosstalk can be minimized with smaller electrode diameter, by reducing spacing between electrodes and by mathematical differentiation (Winter et al., 1994).
EMG signal analysis is useful in clinical and biomedical fields as for example: identifying a neuropathy from a myopathy: an amplitude increase in MUAPs is an indication of a neuropathic situation (a motoneuron problem) while a decrease in duration of the MUAPs is a myopathic sign (a muscular problem). EMG is also useful to study neuromuscular and motor control disorders. Sometimes an estimate of the force generated by a muscle is associated to the amplitude of its EMG signal. Nowadays EMG signal analysis is used in biomechanics, clinical rehabilitation, ergonomic and kinesiology fields. On a practical point of view, EMG signals collected over muscles can be used, for persons who sustained an upper limb amputation s to operate a myoelectric prosthesis with which some daily life movements can be usefully accomplished.

2.5.1.4 Surface electrode arrays

Different aspects of muscles anatomy or physiology can be investigated with electrode arrays consisting in many electrodes grouped together in various ways. With a linear array placed along a muscle, EMG signals are detected at a number of points along the muscle and the propagation velocity of the APs can be measured. With such an array, location of the MUs innervation zone can be estimated as well as the decomposition of the surface EMG signal in its constituent MUAPs, volume conduction studies and clinical applications are also possible (Merletti et al., 2003).

The use of multiple surface electrodes was initiated with the study of Monster et al. in 1980. Since then, multiple surface electrode arrays have been used and in some occasions on the BB: 1×17 electrode array was placed along the longitudinal axis of the muscle by
Masuda and Sadoyama (1986) for studying signal propagation along muscle fibers; a 6×10 matrix of electrodes was used for recording signals of both the biceps and tibialis anterior by (Yamada et al., 1987); a 3×8 matrix for recording EMG signals around human arm muscle during isometric contraction was used by (Cote and Mathieu, 2000), Holtermann et al. (2005) applied a 13x12 electrodes matrix over the BB during isometric contraction of the elbow between 0 and 80% of MVC. Arrangement of 16 electrodes in four columns (first and fourth columns containing of 3 electrodes and the middle two containing of five electrodes) for recording the EMG signals investigating MUs properties in chronic stroke patients and healthy subjects was used by Kallenber and Hermens (2009).

In our work, to study the 6 compartments of the BB, we first used an array of 7 electrode pairs then moved to 10 electrode pairs for better spatial resolution.

2.5.2 Ultrasound technique

By exposing part of the body to an ultrasound wave (>20 kHz) and analyzing the reflections or echos generated at each anatomical structures where changes in the acoustical impedance of the tissues occur, an image of the scanned body part can be obtained. Also known as sonography, US imaging does not use ionizing radiation such as X-ray or computed tomography (CT) scan, is non-invasive, painless and safe. In addition, equipment is much cheaper than MRI and CT scan. US imaging can be used to show the structure of the soft tissues and movement of the body’s internal organs,
showing pulsating blood flow. It is largely used to follow the foetus development during pregnancy. This technique is also a valuable method for many neuromuscular studies.

Ultrasound transducer generally contains a row of up to few hundreds crystal or ceramic piezoelectric elements which convert electrical energy into sound waves, which pass through the body, the elements then convert the reflected sound waves from the body into signals processed by the ultrasound system to produce pictures of the internal organs.

The US wave is propagating in soft tissues at an average speed of 1540 m/s. Two materials with the same acoustic impedance will not give an echo at their boundaries while a weak or a strong one will be produced depending on the importance of the difference in the two acoustic impedances. On an US image a large echo is seen as white and weaker ones in gray levels (Aldrich, 2007). At each reflection the beam is losing energy which limits the US depth penetration. A higher frequency being more attenuated than a lower one (Maria Pia Zamorani 2007), its penetration depth will be smaller than a beam of lower frequency. Thus, the choice of a probe depends on how deep the organ of interest is lying within the body. Probes working in the frequency band 7-15 MHz are appropriate for quite superficial hand muscles while to investigate deep and large muscle found in the thighs or buttocks, a probe of 3.5-10 MHz is used (Maria Pia Zamorani 2007). When an air gap is present between the probe and the skin, a large reflection occurs and practically no energy is left to penetrate the tissues. To prevent this, an ultrasound gel is applied over the interested area of the body.
Figure 2.11 Ultrasound image of the biceps brachii and surrounding tissues (left arm measured at two thirds from the shoulder). The right panel shows the different structures schematically (Pillen, 2011).

Muscles have low echo intensity and they have a relatively black appearance in US images (Fig. 2.11). As for the perimysial connective tissue, group muscle fibers in fascicles, is moderately echogenic and appears as speckles in the transverse plane. In the longitudinal plane (Fig. 2.12), the fibers orientation is detectable and can be seen as parallel, pennated or with a triangular structure (Pillen, 2011).

Figure 2.12 Macro architecture display the way muscle fibers are organized: at the left they are in parallel (biceps), in the middle they are pinnated (tibialis anterior) or, at the right, arranged in a triangular fashion for the latissimus dorsi (Pillen, 2011).
With a resolution of ~100 μm, the tiniest muscle structure that can be pictured is either a large fiber or a group of small ones (Maria Pia Zamorani 2007). With US, many studies have been done on the: muscle thickness, pennation angle (the angle between deep aponeurosis or bone and the muscle fascicle), fiber length in: tibialis anterior, BB, brachialis, transversus abdominis, obliquus internus abdominis and obliquus externus abdominis during isometric contractions (Hodges et al., 2003). Studies have also been conducted on cross sectional area (CSA) in the vastus lateralis muscle in leg muscle (Reeves et al., 2004). In diseases such as muscular atrophy, echo intensity is increased and echo patterns are modified (Maria Pia Zamorani 2007).

On US equipment, muscle thickness and area can be measured using calipers which are software operated. Muscle cross-sectional area (CSA) can be used for an estimation of the muscle volume (Sanada et al., 2006) or to estimate a muscle force-generating capacity (Clague et al., 1995). CSA measurement can be simply done for small muscles for which the whole muscle contour can be seen on the screen. This is not possible for large muscles, such as the rectus femoris, because the probe size is limited to a width of 4-5 cm (Maria Pia Zamorani 2007).

### 2.6 Prosthetic control

Upper limb amputation is an enormous loss which causes physical and emotional disturbances. Such impairment could lead those persons to isolate themselves from
public eyes and society. Amputation can result from an accident, a war situation or simply related to a disease such as diabetes, cancers or serious infections. Trauma-related amputations are decreasing compared to disease-related ones: in the United States, the annual occurrence rate of trauma-related amputations dropped from 11.37 to 5.86 between 1988 and 1996 but they still make up the majority of upper limb amputations (Dillingham et al., 2002). People affected by traumatic amputations are often young and can have a great contribution to society. Therefore, it is important to give them access to prostheses with which most of their daily living activities can be restored.

A prosthesis used to replace a missing body part can be only cosmetic i.e. with no moving parts or functional with the production of some movements (Schultz and Kuiken, 2011). Functional prostheses can be powered by body movements, by myoelectric signals or a mix of those approaches as illustrated in Fig 2.13). Body powered prostheses are attached to the body by a harness and the shoulder opposite to the amputation is moved resulting in a pull on a cable which produce a movement such as an elbow flexion or opening a hook to grasp something.

Following an amputation, muscles left in the stump can still be voluntarily activated even if no movement can be produced due to the absence of the severed part. The surface EMG signals of those muscles can be used to operate a myoelectric prosthesis within which electric motors, electronic circuits and batteries are found. Recording EMG signals from two independent muscles or by distinguishing between weak and strong
contractions of one muscle make this kind of control possible. Myoelectric control and body powered operation are combined in hybrid prosthesis (Schultz and Kuiken, 2011).

Figure 2.13 Block diagram illustrating different prosthetic hands.

Human upper limb is a complex element with its 22 degrees of freedom (DoFs) through the selective activation of 38 muscles (Zecca et al., 2002). The main goal of an upper limb prosthesis it to mimic as many as possible movements needed by the persons who sustained an amputation amputee person in his/her daily life activities.

In 1948, using a two-state amplitude modulation circuit, Ritter was the first who used myoelectric signals for prosthetic control. After semiconductor technology and miniaturization development, in 1960s and 1970s using myoelectric signals found its way to clinical application as a control signal for myoelectric prosthesis and commercialize by different companies such as Otto Bock, Hugh Steeper, Motion Control Inc., Liberty Mutual, Variety Ability System, and Fidelity Electronics. As the amputation level
increases, the available muscle control sources decreases. This limitation was somewhat overcome with three-state amplitude-modulated circuits making possible control of two functions by a single muscle source. This method was used by some of the above mentioned companies (Fig. 2.14) (Parker et al., 2006).

Figure 2.14 Left: two-state amplitude modulation. Right: three-state amplitude modulation for control of myoelectric hand. S1 & S2 are switching thresholds for flexor and extensor activity respectively (from Parker et al., 2006).

Typically, to activate a movement with a prosthesis, such as closing and opening the hand, an electrode pair is placed on a muscle such as the BB and another pair on an antagonist muscle i.e. the triceps. More pairs are required to produce additional movements with the prosthesis (Finley and Wirta, 1967, Lyman et al., 1976, Doerschuk et al., 1983, Englehart et al., 2001).

Using various signal processing strategies such as EMG features extraction in time and frequency domains, EMG pattern classification, artificial neural network (ANN), fuzzy logic and neural fuzzy logic make it possible to produce a variety of movements with fewer than 2 muscle sites per DoF (Zecca et al., 2002).
With a total amputation of the upper limb, no more arm muscles are left for control purposes but there are still ways to overcome such a situation. One approach, called Targeted Muscle Re-innervation (TMR), consists in a surgery where the arm nerves are re-routed to muscles of the thorax (Fig. 2.15). After recovery, healing and training period of 3-6 months, thorax muscles can be voluntarily made to contract by thinking about moving the arm as before the amputation and a sophisticated prosthesis produce the planned movements (Miller et al., 2005).

![Targeted muscle re-innervation on shoulder disarticulation patient](http://www.engadget.com/2007/11/13/targeted-muscle-reinnervation-enables-your-brain-to-control-pros/)

In recent time, by companies such as i-limb but mainly through the American Defense Advanced Research Project Agency (DARPA) funding, dexterous prosthetic upper limbs capable of many DoFs have been developed. However improvement on how to reduce...
the cost of those devices and how a person who sustained an amputation can take benefit of them is lagging.

In an interesting review article on the partitioning hypothesis, English et al (1993) put forward a number of goals to be met in the future. One of these was to investigate whether the anatomical partitions of human muscles were also functional partitions. In line with this goal and in addition to all the signal processing strategies being in development to operate those modern prostheses, we are presenting our work done on the exploration of the possibility to voluntarily activate distinct portions of the BB for the purpose of facilitating the control of modern myoelectric prosthesis by amputees.
Chapter 3

Methods and techniques

Considering that the biceps brachii (BB) is constituted of 6 compartments each innervated with a nerve branch, we are investigating if those compartments could be voluntarily set into action. Accordingly the EMG activity of the contracted BB was recorded while the hand, the arm and the upper arm were in different positions.

At the beginning of our experiments healthy subjects were tested with an array of seven pair electrodes, placed over the BB muscle. To accommodate subjects with large BB muscle and to get a better spatial resolution for the BB muscle compartments, an array of 10 electrode pair was used thereafter. The experimental protocol was executed in the EMG lab at the Biomedical Engineering Institute. Immediately after the EMG acquisition, ultrasound imaging was performed on each subject at Ste. Justine Hospital which is within walking distance from the EMG lab.

3.1 Subjects

Ten healthy subjects (5 males and 5 females) were enrolled in the protocol. Each of them met the following criteria:

1. Right handed
2. Aged between 20-35 years
3. Without any known neuromuscular problems

The University’s ethics committee approved the protocol (Annex A) in accordance with the Helsinki Declaration of 1975, as revised in 2004 and all the participants signed an
informed letter of consent. The protocol was well described to each participant and they were aware of their right to quit the experiment anytime without any prejudice. Information on each subject is provided in Table 3.1.

Table 3.1 Subjects specifications (BMI: Body Mass Index).

<table>
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<th>Subject ID</th>
<th>Gender</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI</th>
<th>Age</th>
<th>Arm circumference (cm)</th>
<th>Biceps length (cm)</th>
<th>Biceps width (cm)</th>
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<td>26.5</td>
<td>16.5</td>
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<td>M</td>
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<td>52</td>
<td>24.4</td>
<td>32</td>
<td>27</td>
<td>16.5</td>
<td>9</td>
</tr>
<tr>
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<td>F</td>
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<td>24</td>
<td>31</td>
<td>26.5</td>
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<td>9</td>
</tr>
<tr>
<td>4</td>
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<td>24.5</td>
<td>27</td>
<td>30</td>
<td>19</td>
<td>11</td>
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<tr>
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<td>M</td>
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<td>68</td>
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<td>11</td>
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<td>176</td>
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<td><strong>65,125</strong></td>
<td><strong>24</strong></td>
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<td><strong>28,5</strong></td>
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<td><strong>10,71</strong></td>
</tr>
</tbody>
</table>

For each subject, the biceps length and its width where evaluated by palpation while performing a 100° elbow flexion during which the borders of the muscle were marked with an ink pen. The mid-portion of the muscle (estimated zone of the neuromuscular
junctons) was found by dividing the length of the BB by two and that position was marked on the skin with an horizontal line which was intersected by a vertical line positioned at mid-point between the medial and lateral borders of the BB and considered as the separation line between the short head (SH) and the long head (LH) of the BB. Those reference marks were used to guide the electrode array placement.

3.2 Electrodes array

Gold disc surface electrodes of 6 mm in diameter (Grass technologies, model FE6GH) were used. Initially, an array of 7 pairs of such electrode where manually aligned on a trans lucid sticky medical tape (Medipore, Transpore) at a vertical and horizontal distance of 15 mm center-to-center as shown at the left of Fig. 3.1. Later on, a 10 pairs electrode array, with the same inter-electrode distance was used as illustrated at the right of Fig. 3.1, surface electrodes were placed over to BB to record EMG signals then a 10 pairs array was used.

Each electrode array was positioned across the individual BBs with the lower row of the electrode pair’s positioned 10 mm above the horizontal line drown over the estimate zone of neuromuscular junctions. With the 7 electrode pairs array, pair #4 was placed over the vertical line indicating the separation between the SH and LH. So, electrode pairs #1-3 were considered to be over the SH while pairs #5-7 to cover the LH of the BB. With the 10 pair electrodes array, electrode pairs #5 and #6 were placed at equidistance on each side of the mid-point. As shown on Fig 3.1, five pairs of electrodes were thus covering the SH of the BB and the five others the LH. With both electrode arrays, a
reference electrode was put on the left clavicle bone. Following a session, the conductive paste was removed and each electrode washed. Electrode alignment was restored when needed. After every 2 sessions, the electrodes were mounted on new bands of adhesive tape which was used as a support for the array.

![Electrode arrangements](image)

Figure 3.1 Electrode arrangements. Left: with 7 pair electrodes. Right: with 10 pair electrodes. Estimated orientation of the short and long head (SH & LH) of the BB has been showed above each electrode pair.

### 3.3 Experimental protocol

#### 3.3.1 EMG

Before the experiment, the subject was asked to shave the right arm hairs over the biceps if necessary. In the lab, the skin over the BB was slightly abraded with a sand paper and cleaned with an alcohol swap to reduce its impedance. Conductive electrode gel was applied on each electrode pairs before positioning them over the muscle.

For the establishment of a pertinent protocol, preliminary experiments took place in which the arm, the forearm, and the hand were placed in various positions while various
isometric and isotonic contractions were produced. The distributions of EMG potentials over the BB were analyzed with the use of polar diagrams as seen at the right of Fig. 3.2.

![Diagram of electrode positions and polar diagram](image)

**Figure 3.2** Left: 10 electrode pairs positioned across the right BB with. Right: polar diagram displaying the amplitude of the EMG signal recorded under each pair of electrodes. Each number represents root mean square (RMS) value of the mean of 3 trials in μV of the signal collected with each electrode pair.

Among the numerous different positions experimented with the upper limb, two of them appeared to produce the most distinct EMG potential distributions recorded over the LH vs. the SH. In the first condition, the subject was seated with the right arm close to the trunk and the elbow flexed at ~100° (Fig. 3.3 Seated position). In the second condition (Fig. 3.3 Standing positions) the subject was in a standing position with the right shoulder 90° abducted, the arm positioned horizontally in the coronal plane (out to the side) either with 0 kg or with 1kg load suspended at the wrist level. In each condition shown in the lower panel of Fig. 3.3, EMG was acquired while the subject hand was either in the neutral position, fully pronated or fully supinated (Fig. 3.4). To prevent fatigue in each of

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1 In the standing position, it was found easier to have the subject maintain isotonic conditions holding a weight as opposed to maintain a constant strain gauge reading. For control purposes, we compared constant weight vs. “constant” strain gage reading for a subject and the two sets of data were judged to be equivalent for the intended purpose here.
those positions, contraction of only 5 s in duration and at 20% MVC (maximum voluntary contraction) were produced.

![Seated position and Standing positions](image)

Figure 3.3 Upper row: experimental test conditions in seated and standing positions. Lower row: the 3 hand postures used in each condition.

In the seated condition, the contraction force was measured with a strain gauge (PAXLSG, Red Lion Controls). Its output was stored with the EMG data and also presented to the subject as a feedback signal used to maintain a constant force level. The subject’s task was to perform an isometric contraction at a constant level of 20% MVC while performing each hand posture. In order to identify this level of contraction for each subjects in different test conditions, they asked to pull on the strain gauge through the wrist band with maximum power three times. The average of the performed three times of maximum power was considered as the 100% MVC for each subjects in each conditions. Then 20% MVC has been calculated and corresponded digit has been given to each subject to maintain on that level in each test condition with performing different hand postures. Each 5 s EMG data record was obtained during a constant contraction level (20% MVC).
3.3.2 Ultrasound imaging

Following the EMG acquisition, ultrasound images and video clips were taken from each subject’s right upper arm at 1 cm above the midsection of the BB where a mark had been put before, during the EMG signals acquisition. US acquisitions were done in the seated and standing condition:

subject’s tasks in seated condition:

1) with the right limb supported with the armchair rest and elbow flexed at ~100°
   keep the hand in pronation, neutral or supination without any charge at the hand level while ultrasound images and video clips were collected during 5 s.
2) do the same as above but with the support just at the elbow point while holding a 500 gr load in the hand.

subject’s tasks in standing condition:

1) with the right arm extended to the side as for EMG acquisition, put the hand in pronation, neutral or supination (no load) while ultrasound images were taken.
2) do the same while holding a 500 g load in the hand.

3.4 Data acquisition

3.4.1 EMG

In all the 3 conditions illustrated in the upper panel of Fig. 3.3, EMG signals were acquired during a period of 5 s while the hand was either in the neutral, pronated or supinated position and a constant force was produced. As illustrated in Fig, 3.4, the
differential signal collected from each electrode pair was amplified by a factor of 2000 (15A54 Quad amplifier, model 15LT physiodata Grass amplifier) and band-pass filtered between 10 and 1000 Hz. Data was digitized at 2 kHz (NI USB-6225, National Instrument) and saved in Matlab format for further processing through a custom LabView program (National Instrument Inc.). At the end of each 5 s acquisition, the data were visually inspected and the trial was repeated if an artifact or abnormal activity was detected.

![EMG data acquisition chain](image)

Figure 3.4 EMG data acquisition chain.

### 3.4.2 Ultrasound imaging

An ACUSON S2000 ultrasound system from Siemens was used. Interested in the BB which is located not far from the skin, a linear and high density transducer 18L6 HD was used. That probe (6 to 18 MHz) has a large field of view and the automatic system set up available for the musculoskeletal system was used (depth: 4cm, 12 MHz, 0 dB, Map E).

A load of 500 g instead of 1 kg as for the EMG acquisitions was used because a 1 kg load induced such a muscle deformation that part of the BB muscle was out of the ultrasound field of view. Images were taken with the hand in pronation, neutral and supination. The probe was placed perpendicular to the muscle fibers direction. Video clips of 5 s were obtained while the hand position was moved at a constant speed from
pronation to supination and vice versa. All the images and video clips have been taken both in seated and standing positions.

3.5 Signal processing

3.5.1 EMG
At the beginning and at the end of each experiment while in the seated position, the subjects were asked to relax while a recording was made of the instrument background noise and the involuntary muscle activity. The RMS values of the background recordings were always less than 7 μV. At the end of the experiment, similar results were obtained, indicating stable recording conditions. Our results include this background noise. A Matlab detrend operation was initially applied on the raw EMG data. Then, the RMS value of each recorded EMG was computed and the mean value of the 3 trials (4 trials for S5-S10) in each position was obtained. Statistical differences between the SH and LH averaged signals was evaluated with a simple Student t-test (p<0.05). Correlation coefficients matrices (10x10 with the 10 electrode pairs array) were computed for each 5 s record. Thus for each tested position, an average correlation coefficient matrix was then interpolated on a 101x101 grid to obtain smoother iso-correlation levels.

3.5.2 Ultrasound imaging
Following careful observation of each ultrasound images, the BB muscle contour was identified as well as the humerus, veins, arteries and connective tissues. CSAs of the SH and LH of the BB were calculated with an image measurement tool available on the US
equipment. In order to find the line of separation for the SH and LH of the BB in different conditions tested with 3 hand postures ultrasound video clips of the hand movement from pronation to supination and the one with the inverse movement were watched carefully for each subject. Then estimated location of the LH and SH were determined by visually tracking the muscle deformation in those video clips and the localized area implemented in each corresponded ultrasound images. Afterwards contour for that predicted area was drawn on each image for different hand postures. Finally, the cross section area of the drawn contours was calculated automatically with the caliper tool available on the ultrasound machine.
Chapter 4

4. Results

This section is made of 4 different contributions. First an article published in the Journal of Medical and Biological Engineering (JMBE) is related to the result obtained with an array of seven electrode pairs. Prior to this article, preliminary results with this array had been presented at a national conference (Annex B). The second part is a conference paper presented at the 11th international of Information Science, Signal Processing and their Applications (ISSPA, 2012) 4 subjects where tested with an array of 10 electrode pairs In the third part, we present an extension of the ISSPA conference results where 6 new subjects were enrolled in the protocol with the 10 electrode pairs array to form a group of 10. Finally, to help explain the EMG signal distribution recorded over the biceps of those 10 subjects, ultrasound images obtained at the electrodes level were used to document the modifications of the biceps contour as hand position was changed from pronation to supination.
4.1 JMBE Article

Investigation on Muscle Compartments in the Biceps Brachii*

Nahal Nejat¹, Pierre André Mathieu¹,* , Michel Bertrand²

¹Institute of Biomedical Engineering, Université de Montréal, Canada
²Institute of Biomedical Engineering, École Polytechnique de Montréal, Canada

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ABSTRACT

The latest myoelectric prostheses have several degrees of freedom and therefore require a large number of myoelectric signals to fully exploit their capabilities. Muscle compartments, which are intra-muscular subdivisions innervated by an individual muscle nerve branch, can be exploited to provide additional independent muscle control sites to operate such prostheses. To explore whether muscle compartments can be voluntarily controlled, electromyographic (EMG) signals are recorded from an array of seven pairs of equally spaced surface electrodes positioned across the biceps brachii of four healthy subjects. The EMG signals are collected in two positions: 1) with the subject seated, right elbow flexed ~100°, and 2) with the subject standing with the right arm extended horizontally in the coronal plane (out to the side). In both positions, the hand is either fully supinated, neutral, or fully pronated. The average root mean square value of the EMG signals obtained from three pairs of electrodes positioned over the biceps short head are compared with the average obtained for the three pairs placed over the biceps long head. Out of the nine hand position/load pairs examined, two pairs are found to elicit larger EMG activity in the long head or in the short head. The potential to preferentially activate either the short or the long head of the biceps suggests that the selective activation of muscle compartments is a promising strategy for facilitating the control of myoelectric prostheses capable of generating many types of movement.

Keywords: Biceps brachii, Compartments, Surface electromyography, Ultrasound.
4.1.1. Introduction

Prostheses allow amputees to produce useful movements despite the loss of limbs. Although body-operated hooks are still in use, more socially acceptable myoelectric prostheses are often preferred. Upper limb prostheses have recently acquired the ability to make many types of movement due to the recent efforts from the U.S. Defense Advanced Research Projects Agency (DARPA). Although the protection worn by modern soldiers has reduced the mortality rate, the number of war amputees has increased [1]. As voluntary recruitment attracts mainly young people, veterans are now younger than those of previous wars and, with a longer life expectancy, their rehabilitation becomes more important. To address this problem, DARPA promoted a research project (Revolutionizing Prosthetics 2007) to develop sophisticated prostheses that closely mimic the natural movements of the upper limbs [2-4]. Such developments benefit all amputees.

The operation of such modern prostheses requires a large number of control sites. Thus, DARPA funded another project (Revolutionizing Prosthetics 2009) to develop a variety of approaches for naturally controlling prostheses. Following an amputation, muscles left in the stump can still be voluntarily activated even if no movement can be produced. Usually, two muscle sites are used to activate a prosthesis, such as for closing and opening the hand, with more pairs required for additional movements. Using signal processing techniques, it is possible to produce a variety of movements with fewer than two muscle sites per degree of freedom (DOF) [5].
As the amputation level becomes more proximal, the number of potential control sites decreases. Targeted muscle re-innervation has been proposed for addressing the rehabilitation needs of those who have lost one or both of their arms [6]. In this approach, what remains of severed nerves is transplanted to the muscles of the thorax such as the pectoralis, which is made up of many segments. Following surgery, one segment of the pectoralis is contracted and its EMG signal, detected by a surface electrode, is used to flex the elbow of the prosthesis. The number of movements (or DOFs) that an amputee can control depends on the number of successfully rerouted nerve segments.

After amputation, the number of available control sites is often insufficient to take full advantage of modern prostheses. To address this problem, various signal processing techniques have been developed [7, 8]. Based on anatomical considerations, one additional possible approach could consist in exploiting the presence within a muscle of compartments each innervated by a nerve branch. Under certain conditions, it may be possible to voluntarily contract those compartments either individually or as a group, and to use the obtained EMG signals to control prosthesis.

First demonstrated mainly in various muscles of the cat [9, 10], muscle compartments have also been found in humans. From the dissection of cadavers, Segal et al. [11] studied the flexor carpi radialis (FCR), the extensor carpi radialis longus (ECRL), and the lateral gastrocnemius (LG). Based on both architectural considerations and innervation patterns, they found three partitions in the FCR and two in the ECLR. For the LG, although three partitions are anatomically well defined, their innervation is not clearly
separated. Segal [12] studied the biceps brachii (BB) of human cadavers and based on both architectural and innervation criteria found that the muscle has up to six compartments.

Previous physiological observations had already provided evidence for functional partitions or divisions in the BB. Using intramuscular electrodes, Ter Haar Romeny et al. [13] found that some motor units (MUs) of the long head (LH) of the BB were activated during flexion of the elbow while other MUs were only active when the hand was positioned in either supination or pronation. Holtermann et al. [14] applied a 13×12-electrode matrix over the BB during isometric contraction of the elbow between 0 and 80% of the maximum voluntary contraction (MVC). They observed that the recruitment of MUs was not scattered randomly across the electrode matrix, implying the presence of distinct regions in the BB. Wolf et al. [15] inserted fine wires in the three regions of the LG and found significant differences in the three partitions of the muscle and across the eight functional tasks accomplished by the subjects.

In a review article on the partitioning hypothesis, English et al. [16] put forward a number of goals to be met in the future. One of these was to investigate whether the anatomical partitions of human muscles were also functional partitions. The present study thus explores the potential to voluntarily activate distinct portions of the BB for facilitating the control of modern myoelectric prostheses.
4.1.2. Methods

4.1.2.1 Subjects

The protocol was tested on four normal right-handed subjects (three females, one male) aged between 26 and 32 years with no known muscular problems within six months prior to the experiment. Their mean body mass index was 23.9±0.89. The university’s ethics committee approved the protocol in accordance with the Helsinki Declaration of 1975, as revised in 2004, and the participants signed an informed letter of consent.

4.1.2.2 Equipment and methods

Initially, the arm, forearm, and hand were placed in various positions and the corresponding EMG potential distributions were recorded over the BB from seven recording sites (Fig. 4.1.1(a)). The distributions of EMG potentials were examined and compared using polar diagrams, such as that illustrated in Fig. 4.1.1(b). The configurations of the hand and arm illustrated in Fig. 4.1.1(c-d) where used in this study, as they appeared to reveal the most distinct root mean square RMS EMG potential distributions. In the first configuration, with the hand in the neutral, pronated, or supinated position, the subject is seated (Fig. 4.1.1(d), left) with the right arm close to the trunk and the elbow flexed at around 100°. In the second configuration, the subject is standing with the right shoulder abducted (Fig. 4.1.1(d), right). In that position, the arm is held horizontally in the coronal plane (out to the side) without load (0 kg) or with a 1-kg load attached at wrist level, and with the hand either in the neutral, pronated, or supinated position. In the seated position, the contraction force was measured with a strain gauge unit (PAXLSG, Red Lion Controls, Canada), the output of which was displayed to the
subject, and recorded on the data acquisition computer (Fig. 4.1.1(e)). The subject’s task was to maintain a constant contraction at a specified level.

Figure 4.1.1 Illustration of the position of electrodes #1-7 over the biceps with SH (S) and LH (L). (b) Example of polar diagram used to illustrate the RMS potential distribution. For each electrode, the RMS EMG is displayed in µV at the tip of a ray whose length is proportional to its value. (c) Three hand positions investigated in the study. (d) Two arm positions investigated in the study. (e) Details of seated position where the elbow is nominally flexed at around 100° and a specified contraction level maintained during 5 seconds. The force sensed by a strain gauge unit is displayed in front of the subject as a feedback signal and digitized with the EMG signals.

Before the electrodes were applied, the skin over the right BB was slightly abraded and cleaned with alcohol. Seven pairs of 6-mm-diameter gold disc electrodes (F-E6GH, Grass Technologies, U.S.A) were positioned 10 mm above the mid-portion of the BB with a center-to-center electrode distance of 15 mm along the muscle fiber and each pair
distributed 15 mm apart over the BB. As shown in Fig. 1(a), the 4th pair was near the center of the BB, approximately separating the short head (SH) on the left and the long head (LH) on the right.

Isotonic and isometric contractions were used for all five-second-long trials. In the seated position, the isotonic condition was set by the subject, whose task was to pull on a strain gauge via a cable attached to a wristband while maintaining a constant contraction at a specified level. The cable and strain gauge stiffness in conjunction with the fixed subject position set the isometric conditions. The MVC values were obtained with the hand in the neutral, pronated, and supinated positions, respectively. The associated three force levels represented 100% MVC for each hand position. All subsequent recordings in the seated position were acquired at 20% MVC, which appeared large enough to obtain a good signal-to-noise ratio without fatiguing the subject. In the standing position, the constant weight provided the isotonic condition while maintaining the arm extended in the horizontal plane provided the isometric aspect. The data were visually inspected; when an artifact or abnormal activity was detected, the trial was repeated. Three 5-second artifact-free and visually stable recordings were thus acquired in the seated and standing positions for the three hand postures, respectively. At the end of each acquisition, the subjects were permitted to rest.

Differential signals collected at the electrode sites were amplified by a factor of 2000 using a physiodata amplifier (15LT, Grass Technologies, U.S.A) and band-pass filtered (10-1000 Hz, second-order) before being digitized at 2 kHz (NI USB-6225, National
Instruments, U.S.A.) and stored in a Matlab file using the LabVIEW program (National Instruments, U.S.A.). For each acquired signal, the RMS value was calculated. For each experimental condition, the mean RMS value of the three trials was obtained. These mean values were used to produce diagrams such as that in Fig. 4.1.1(b), where the arm boundary is represented by a circle from which emerge radiating spokes, the length of which is proportional to the mean RMS potential (μV) of the three signals collected over the corresponding recording site. For the four subjects’ arms, as illustrated in Fig. 4.1.1(d), electrode sites #1-3 spanned the SH of biceps and electrode sites #5-7 were situated over the LH, as shown in Fig. 1.1.1(a). It was assume that electrode site #4 captured signals from both heads.

At the beginning and at the end of each experiment in the seated position, the subjects were asked to relax while a recording was made of the instrument background noise and the involuntary muscle activity. The RMS values of the background recordings were always less than 7 μV. At the end of the experiment, a similar recording was made and similar results were obtained, indicating stable recording conditions. The results presented here include this background noise. Statistical analysis was performed with the t-test (p<0.05). For the seated and standing positions, experiments where repeated twice by each subject on two different days to verify the reproducibility of their activation patterns.

To help interpret the EMG potential distributions over the biceps, ultrasound images where acquired from the studied region using an 18L6 high-density linear probe (Acuson
S2000, Siemens, Germany). The arm positions were the same as those during EMG acquisition in the seated protocol; however, no contraction load was used. The ultrasound scans were taken in a plane perpendicular to the fiber direction and parallel to the subject’s transverse plane; the probe was positioned over the BB at the same level as that for the electrodes. Images were acquired while the hand was in the neutral, pronated, and supinated positions, respectively.

4.1.3. Results

Amplitudes of EMG signals obtained from one subject on two occasions are presented in Fig. 4.1.2. In the seated position (Fig. 4.1.2(a), upper row), the activity of the SH increased as the hand position changed from pronation to supination. When the experiment was repeated (Fig. 4.1.2(a), lower row), similar results were obtained. In the standing position with no weight at the wrist, activity over the LH was generally greater than that over the SH (Fig. 4.1.2(b), upper row). The activity of the SH increased across hand positions but to a lesser extent than in the seated position. When the experiment was repeated in the standing position (Fig. 4.1.2(b), lower row) the activity over the LH was again observed to be greater than that over the SH across all hand positions from pronation to supination but to a lesser extent than in the first experiment (Fig. 4.1.2(b), upper row). Activity in the SH also increased with the hand movement from pronation to supination in the second experiment. Similar results were obtained for the other subjects.

These general trends, but with individual variations, were also observed when results of the four subjects were compared in the seated and standing positions with a load of 1 kg (Fig. 4.1.3). In general, across all the positions tested, higher activity was detected in the
SH (electrode #1-3) in the seated position (Fig. 4.1.3(a)) than in the standing one (Fig. 4.1.3(b)). For the seated position, the highest activity was detected over the SH 8 times out of 12 (three hand positions x four subjects). For the standing position, the highest activity was detected over the LH 9 times out of 12.

Figure 4.1.2 Graphical representation of the distributions of EMG activity over the BB for one subject on two different days (S3* and S3). Results obtained with the subject (a) in the seated position at 20% MVC and (b) in the standing position without external load (0 kg). Numerical values of averaged RMS data (over three repetitions) at each electrode site are shown in μV.

For a quantitative description of the differences between the SH and the LH, the mean value of the signals over the SH (electrode pairs #1-3) was calculated and compared to that of signals over the LH (electrode pairs #5-7). As can be observed, for the seated position (Fig. 4.1.4(a)), the SH was more active (10/12 situations) than the LH, but this difference was only statistically significant in the supinated position for S3.
Figure 4.1.3 EMG activity for the four subjects. (a) Seated position and (b) standing position with 1-kg external load. Only maximal and minimal values in μV are shown for each case. Out of the 12 graphs, the maximum value was found lying over the SH 8 times for the seated position and over the LH 9 times for the standing position.

For subjects S1 and S3, a significant increase in the SH activity was observed between the pronation and supination positions (double stars). For the standing position with 0 kg (Fig. 4.1.4(b)), the dominant activity for all the subjects was always in the LH. The differences were statistically significant in both the pronation and neutral hand positions for S1 and S2. Statistically significant differences were observed in pronation for S3 and in supination for S4. In Fig. 4.1.4(c), with a 1-kg load suspended at wrist level, the
dominant activity was within the LH for all positions for S1 and S2, whereas for only the pronation and neutral positions for S4.

Figure 4.1.4 Bar graphs showing the mean RMS values in $\mu$V obtained from signals #1, #2, and #3 over the SH and from signals #5, #6 and #7 over the LH of the biceps. Mean RMS values are shown as pair of bars (white for S head and black for L head) with ± standard deviation. Results obtained (a) in the sitting position and (b) standing position without external load (0 kg). (c) Results obtained in the standing position with a 1kg load. Tests for significant statistical difference between values were performed (t-tests with $p<0.05$). * indicates significantly different values for SH vs. LH in (a), (b), and (c) and ** is used for comparison of SH results for different hand positions in (a). When 0 and 1 kg conditions are compared, *** indicates a significant difference either for the LH or the SH.

Significant differences were obtained in these two positions for S1 and S4, and in the pronation position for S2. Adding a 1-kg weight at the wrist resulted in a significant
increase in LH activity (triple stars) in each hand position for S1 but only in the neutral and supination positions for S4 and in the neutral and pronation positions for S3. Adding weight also increased the SH activity. This was statistically significant (triple stars) with the hand in the neutral and supination positions for S2 and in the pronated and neutral positions for S3 but not for S1 and S4.

Cross-correlation coefficient matrices (36 in total) between the seven channels for the three hand positions for the seated and standing positions were computed for all four subjects. Table 4.1.1 shows three of those matrices obtained for subject S3.

Table 4.1.1 Sample of matrices of correlation coefficient (r) obtained from the seven recording sites in the three hand positions for subject S3 in the standing position with 1-kg load. Bold values in the boxes are associated with the yellow and orange/cold color areas in the lower panel of Fig. 4.1.5 for S3. The matrices are symmetric so only halves of the terms and the diagonals are shown.

<table>
<thead>
<tr>
<th>PRONATION</th>
<th>NEUTRAL</th>
<th>SUPINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>#2</td>
<td>#3</td>
</tr>
<tr>
<td>1.00</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>0.60</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>0.65</td>
<td>0.60</td>
<td>1.00</td>
</tr>
<tr>
<td>0.76</td>
<td>0.77</td>
<td>1.00</td>
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In order to facilitate comparisons for such a large set of matrices, a graphical color-coded representation was used (Fig. 4.1.5). The matrices are shown as correlation maps that are
symmetric with respect to the unit amplitude autocorrelation diagonal; only their lower halves are shown. In the upper panel of Fig. 4.1.5, each cross-correlation value in a given matrix is represented by small yellow, orange/gold, violet, and blue rectangles, with yellow ones representing the highest correlation range (0.9, 1) and blue ones the lowest (<0.5). As expected, moving away from the diagonal, which implies comparing electrode pairs that are more distant from each other, correlation coefficients get smaller. However, particular correlation patterns can be identified. For example, with subject S2 in the seated position, electrode signals from pairs #4, #5, and #6 (yellow) form a highly correlated triplet; however this correlation breaks down in the 0-kg standing position, in particular in pronation and supination positions. To get a global picture of the cross-correlation behaviour among subjects and positions, a graphical representation that reveals the shapes of the correlation maps was used. The lower panel of Fig. 4.1.5 displays interpolated correlation maps onto which iso-correlation levels are drawn using the same color code as that in the upper panel. The width of the yellow band is indicative of the redundancy between EMG data from adjacent electrodes. A wide yellow band thus indicates that the EMG signals from neighbouring electrodes are correlated and therefore are produced by a common source, a phenomenon sometimes labeled as cross-talk. A good example of this is shown for subject S1 in situations (b) and (c) of Fig. 4.1.5 with the hand pronated.
Figure 4.1.5 Map of the correlation coefficients $r$ for the seven differential signals of each subject. As illustrated by the four color patches between the maps, yellow corresponds to $r \geq 0.9$, orange/gold corresponds to the range $0.8 \leq r < 0.9$, violet corresponds to the range $0.5 \leq r < 0.8$, and blue corresponds to $r < 0.5$. See text for further explanation.

Conversely, a narrow yellow band means that adjacent electrodes capture more distinct signals and thus may be better candidates for myoelectric control of prosthesis with several DOFs. For subject S3 when standing with a load of 1 kg and the hand pronated,
the high correlation region forms one of the narrowest bands of all. It bulges near electrode #7, indicating that EMG of electrode #7 resembles that of electrode #6; this is quantitatively translated in Table 4.1.1 into a coefficient of correlation of 0.94 between electrodes #6 and #7 in pronation. Finally, correlation maps may display what appears as local maxima; these result from a recording site having a higher correlation with a distal site than with an adjacent one. For example, electrode pairs #1 and #3 have low correlation and pairs #1 and #4 have high correlation for subject S4 in standing position and no load. This is confirmed in the upper panel for these particular electrode sets. Sometimes, the correlation map may appear highly fragmented, as for S4 in the standing position (b) and (c).

It is not unusual to observe cross-talk when closely positioned electrodes are used. From a myoelectric prosthesis control point of view, such cross-talk is at first seemingly undesirable since it effectively reduces the number of independent control sites available with a given electrode configuration. In the protocol used here however, it is interesting to note that for a given contraction task, changing the hand position can reduce correlation between adjacent electrodes and thus increase the potential for an independent myoelectric control source. In Fig. 4.1.5, subject S4 holding a 1-kg load is a good example of this effect: as the hand is moved from supination to pronation the area of high correlation (> 0.8) get smaller. In addition to functional changes with hand position, anatomical changes also contribute to the complex modifications in the correlation maps. Figure 4.1.6(a) shows a sample of the ultrasound images collected over the biceps. With the neutral position as a reference, the dotted lines are positioned on the top of the humerus and on the top of the BB.
Figure 4.1.6 Sonograms showing a cross-section of the right arm for subject S3 in a seated position with the hand placed in the three positions studied without load. (a) Horizontal dotted lines delimit the top of both the biceps and the humerus (H) in the neutral position and white dots are positioned over the cephalic vein near the top right side and the basilic vein near bottom left of each figure. (b) Images in (a) with the contour of the biceps muscle highlighted with white dotted lines. The area occupied by the muscle is given in arbitrary units.

White dots were used to help locate the cephalic and basilica veins, respectively, found at the upper right and lower left portions of the three images. In Fig. 4.1.6 (a), the top of the BB is the same in each position whereas the humerus position is lower in the pronation and supination positions with respect to the neutral position. In Fig. 4.1.6 (b), where the contour of the muscle is outlined with a dotted white line, the shape of the muscle is
modified depending on hand position. With the help of image processing software (SliceOmatic, Tomovision Inc., Montreal), the outline of the muscle was manually defined (as illustrated in Fig. 4.1.6 (b)) and the program calculated the enclosed surface area expressed in pixel units. Relative to the neutral position, the area was 2.2% smaller in pronation and 11.6% larger in supination. For all subjects, the area occupied by the muscle was smaller in pronation and larger in supination as compared to the neutral position (Fig. 4.1.7).

![Graph showing area (pixel units) for subjects S1 to S4]

Figure 4.1.7 Cross-section area of the BB of the four subjects as obtained from ultrasound images when the hand was pronated (P), in neutral position (N), and supinated (S).

### 4.1.4. Discussion

The presence of anatomical partitions within human and animals muscles has been reported in several anatomical studies [9, 11, 12]. The physiological significance of these divisions has also been investigated [13, 14]. A general partitioning theory was proposed by English et al. [16] based on an extensive set of studies reporting such anatomical and physiological findings. The present study conducted experiments to investigate whether BB divisions could be voluntarily activated to facilitate the operation of multiple-DOF
myoelectric prostheses. With the hand pronated, in the neutral position, or supinated, data from four normal subjects, either seated with the elbow flexed at ~100° or standing with the arm maintained horizontally in the coronal plane, was collected.

In the seated position, the small differences in the activity patterns between the two experiments can be linked to the small difference in the electrode array positioning. Although this source of error is also present in the standing position, it was difficult in that position to exactly duplicate the same arm position during the second acquisition made few days later. In the standing position, differences between the two acquisitions can thus be expected larger than when the subject is seated and there are fewer DOFs. In the supination position, a significant increase in the SH EMG activity was seen for S4 and S2 whereas for the two other subjects, the p values were near the minimum significance level (0.070 and 0.054, respectively).

In the seated position, the SH of the BB became more active with the hand supinated than when pronated. The same observation was made in the standing position with no load and became even more apparent when the 1-kg load was applied, which approximately replicates the arm tension exerted in the study for the seated position (20% MVC). In contrast, no clear difference was observed for the LH as hand position changed in both the seated and standing positions. However, in the standing position, the LH was typically more active than the SH for all hand positions and subjects. A possible explanation for this could be that the activity of the LH in the standing position participates with the deltid during shoulder abduction.
These results are similar to those of Brown et al. [17], who reported that more activity is found in the SH of the biceps during a rapid supination movement of the hand with surface electrodes, as well as to those of Romeny et al. [13], who found more activity in the medial (electrodes #4 and #5 here) than in the lateral portion (electrodes #6 and #7 here) of the LH during supination with wire electrodes. The data acquired in the present study were from normal subjects because they are considered to be the best candidates for demonstrating whether anatomical biceps partitions can be voluntarily activated. Upper limb amputees will be studied in the future in conditions adapted to their level of amputation to evaluate what kind of control they can exert on their BB.

Based on the correlation maps of Fig. 4.1.5, it appears that when producing a given BB contraction, the position of the activated muscle fibers within the muscle is subject-dependent, as reported previously for similar conditions [18]. While, the maps of S1, S2, and S3 share some similarities, those of S4 are quite different. One parameter that could partly explain this difference is the subject arm circumference. The seven columns of the electrodes were equally spaced by 15 mm while the arm circumference for each subject was 253 (S1), 275 (S2), 270 (S3), and 300 mm for S4. The analysis of the ultrasound images obtained for the three hand positions indicated that when the hand is moved from one position to another, the structures under the skin are subject to complex motions that include deformation, rotation, and translation. Such displacements of the EMG sources relative to the position of the recording electrodes are sufficient to modify the EMG parameters. Among the subjects, differences in these displacements could contribute to the differences observed in the correlation maps.
Other sources of data variability may be related to the position of the electrodes along the biceps and to inter-subject anatomical differences, in particular the relative size of their biceps LH relative to the SH. The length of the biceps of each subject was measured when the elbow was flexed at \( \sim 100^\circ \), with the center of the lower row of the differential electrodes positioned 10 mm above the middle of the biceps. By palpation, the boundaries of the muscle in the horizontal plane were delimited by its mid-point over which electrode pair \#4 was placed. At that location, it is difficult to distinguish the precise location of separation between the 2 heads of the BB, so it is uncertain whether the electrodes were placed over the same anatomical muscle configuration for each subject. Another source of variability is hand position. Subjects were asked to put their hands in the desired positions but no precise measures of these positions were made in the experiments. Consequently, the extent of actual hand supination or pronation could have exceeded or fallen short of the desired position. As the number of subjects was relatively small, the results presented here can only be considered exploratory at least from the point of view of developing a paradigm for robust myoelectric control with several DOFs.

### 4.1.5. Conclusion

EMG signals were recorded from an array of seven pairs of equally spaced surface electrodes positioned across the BB of four healthy subjects to explore whether muscle compartments can be voluntarily controlled. This study confirms the potential of using a partitioning model to enlarge the framework for the myoelectric control of prostheses.
The results suggest that supination is the most appropriate position for increasing the EMG activity in the SH and that a standing position with an abducted shoulder should be chosen to preferentially activate the LH. It may thus be possible to use each head of the BB as a unique control site. The results suggest that the compartmental structure of the BB can be used to simplify the control of modern myoelectric prostheses. Further investigations are required to demonstrate whether and how individual compartments can be voluntarily activated. In this search, ultrasound imaging was a valuable tool for determining how variations in the muscle cross section under the recording electrodes in the various limb positions can help explain the observed EMG changes.

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REFERENCES


4.2 ISSPA 2012 conference paper*

DIFFERENTIAL ACTIVATION OF THE BICEPS BRACHII HEADS
IN NORMAL SUBJECTS

Nahal Nejat¹, Pierre André Mathieu¹,* Michel Bertrand²

¹Institute of Biomedical Engineering, Université de Montréal, Canada
²Institute of Biomedical Engineering, École Polytechnique de Montréal, Canada

ABSTRACT

To facilitate the use of upper limb myoelectric prostheses, we investigated if and how muscle compartments, i.e. intra-muscular subdivisions each innervated by a nerve branch, could be voluntarily contracted. Five pairs of electrodes were positioned across the short head of the biceps brachii and 5 others across its long head. Electromyographic signals from 4 able subjects were collected. They produced voluntary isometric and isotonic contractions with the arm kept in different positions while the hand was either fully supinated, neutral or fully pronated. Root mean square value of the signals, from the 5 electrode pairs across the long and short heads were averaged. Depending on the task, activity was found larger in one head or in the other. Being able to activate either head of the biceps, while not yet completely independently, suggests that the selective use of compartments could be a possible avenue for controlling myoelectric prostheses.

Keywords: Biceps brachii; Compartment; Electrode array; Surface EMG.

4.2.1 Introduction

Our upper limb being very important in our daily life activities, it is a dramatic loss when an amputation occurs. Fortunately, remnants muscles above the amputation level can still be contracted and generate the electromyographic (EMG) signals which can be used to activate a myoelectric prosthesis. The ability to produce some useful movement is thus regained and contributes greatly to the independence of the amputee person.
Since the introduction of upper-limb myoelectric prostheses in the 1960s, their design has improved significantly. Recently, through the founding of the American Defense Advanced Research Project Agency (DARPA), one of the most advanced hand prosthesis with 22 degrees of freedom (DOF) was developed [1]. Usually, for each DOF such as closing and opening of the hand, 2 antagonist muscle sites are used to activate the prosthesis. With an appropriate signal processing strategy it is however possible to use only one muscle site but for an amputee person, the mental load of such an approach is higher than with a pair of antagonist muscles [2].

When one or both arms have to be amputated, no limb muscles are left to activate a myoelectric prosthesis. In such cases, through a complex surgery, the nerves who were supplying the arm muscles are rerouted to innervate thorax muscles which, after training, can be voluntarily made to contract [3]. Most amputations are less severe but the number of available control sites is not always large enough to take full advantage of prostheses.

In parallel with new signal processing techniques that are being developed to address this problem, it could also be worthwhile to investigate the possibility to activate muscles’ compartments i.e. anatomical sections within a muscle, which are individually innervated by a nerve branch. Such compartments have been found in use in some animals, such as the cat’s sartorius and lateral gastrocnemius [4]. In humans, the capability of independently control of different subdivisions of the trapezius has been investigated with biofeedback guidance [5]. From cadavers’ dissection, Segal [6] found in the biceps brachii (BB) up to 6 compartments individually innervated. Prior to this finding with intramuscular electrodes, ter Haar Romeny et al. [7], found in the BB that some motor units of the long head were
activated during flexion of the elbow while others were only active when the hand was either supinated or pronated. When Holtermann et al. [8] applied a 13x12 electrodes matrix over the BB during isometric contraction of the elbow by increasing strength, they observed that the recruited motor units were not scattered randomly across the electrodes matrix suggesting the presence of distinct regions in the BB.

Considering that the BB could be constituted of up to 6 compartments, we are investigating if and how these could be voluntarily set in action in groups or individually. So with the arm, upper arm and the hand in different positions, we recorded EMG activity over the BB while it was contracted.

4.2.2 Methods

4.2.2.1 Subjects
Four normal right-handed subjects were tested (3 females, 1 male). Aged between 26 and 32 years, without any known muscular problems and their mean body mass index was 23.9±0.89. The protocol was approved by an ethics committee in accordance with the Helsinki Declaration of 1975 (revised in 2004) and the subjects signed the informed consent letter.

4.2.2.2 Data acquisition
Ten pairs of electrodes (Fig. 4.2.1A) were positioned across the estimated fiber direction. The lower electrode row was positioned (after the skin had been slightly sanded and cleaned with alcohol) 10 mm above the mid-portion of the BB (estimated zone of the
neuromuscular junctions). The medial and lateral borders of the BB muscle were identified by palpation and the mid-point between those two positions, marked with a pen, was considered to separate the S from the L head. Electrode pairs #5 and #6 were placed at equidistance on each side of that point. As shown on Fig. 4.2.1B, 5 pairs of electrodes were thus covering the S head of the BB and the 5 other ones over its L head. Out of many trials with different positions of the arm, forearm and hand, the three conditions revealing the largest differences between potential distributions over the L vs. the S heads were retained. In the first condition, the subject was seated with the right arm close to the trunk and the elbow flexed at ~100° (Fig. 4.2.1.C) and constant isotonic and isometric contractions of 5 s were produced at 20% maximal voluntary contraction (MVC). In the other two positions,(middle and right of Fig. 4.2.1C), the subject was standing and right shoulder was 90° abducted, the arm was held horizontally in the coronal plane (out to the side) without load (0 kg) or with 1kg load attached at the wrist level². In the 3 conditions, EMG was acquired while the hand was either in the neutral position, pronated or supinated. At the end of each 5 s acquisition, the data were visually inspected and the trial was repeated if an artifact was present or if an abnormal activity was suspected. In each tested positions, 3 records of 5 s were processed.

² In the standing position, it was found easier to have the subject maintain isotonic conditions holding a weight as opposed to maintain a constant strain gauge reading. For control purposes, we compared constant weight vs. “constant” strain gage reading for a subject and the two sets of data were judged to be equivalent for the intended purpose here.
Figure 4.2.1 A: Layout of the electrode array made of 10 pairs of 6 mm gold electrodes (Grass F-E6GH). B: Illustration of the position of electrode pair #1 to #5 over the short head (S) and pairs #6 to #10 over the long head (L) of the biceps. C: three body positions were experimented: seated position with 20% MVC at the left, standing with no load (middle) and with 1kg load (right). D: 3 hand postures tested: pronation (pro), neutral (neu), supination (sup).

4.2.2.3 Signal processing

Differential signals collected at the electrode sites were amplified by a factor of 2000 and band-pass filtered (10-1000 Hz, second-order) with a Grass system (model 15LT physiodata amplifier). Sampling rate was 2 kHz and LabView software was used for the data online acquisition. Data were saved as Matlab file (Mathworks, USA) for further processing. In the seated position, a strain gauge unit displaying the force amplitude provided a visual feedback to the subject so he could maintain it at the prescribed level. The strain gage signal was also digitized and saved with the EMG. In the standing position, the
constant load (0 or 1 kg) set the isotonic condition; maintaining the arm extended in the horizontal plane was considered as adequate for an isometric test.

4.2.2.4 Analysis

After applying a Matlab detrend operation, the root mean square (RMS) value of each recorded EMG was computed and the mean value of the 3 trials in each position was obtained. Looking for significant differences between the S and L heads, thus obtained values for the five electrodes over each head were averaged and a simple Student t-test (p<0.05) was used determine if those two means were significantly different. Correlation coefficients matrices (of size 10x10) were computed for each 5 s records. Thus for each position, an average correlation coefficient matrix was then interpolated on a 101x101 grid to give a correlation map on which smoother iso-levels were drawn. At the beginning and at the end of each experiment in the seated position, the subjects were asked to relax while a recording was made of the instrument background noise and the involuntary muscle activity. The RMS values of the background recordings were always less than 7 μV. At the end of the experiment, a similar recording was made and similar results were obtained, indicating stable recording conditions. Our results include this background noise.

4.2.3. Result

Fig. 4.2.2 illustrates the results obtained for one subject. In the seated condition it can be seen for #1 to #5 electrode pairs over the S head, that the activity is smaller in pronation and higher in supination. Over the L head (#6 to #10 electrode pairs) activity does not vary much with the hand position as compared with the S head. As for the 0 kg standing condition, the activity over the long head is larger than over the short one in the 3 hand
postures and the activity in both heads increases with the 1 kg load. Quite similar results were obtained for the other 3 subjects.

This is detailed in Fig. 4.2.3 for the four subjects, the three body positions and the three hand postures studied. In that figure, the averaged RMS value for the set of electrodes over the S head (electrodes #1 to #5) is compared to that over the L head (electrodes #6 to #10). In the seated situation, activity over the S head is always larger than over the L head particularly when the hand is supinated. In the S head, the increase of activity between pronation and supination is statistically significant ($p < 0.05$) for each subject. In the 2 standing positions more activity is always found in the L head particularly when the hand is pronated. Not displayed on Fig. 4.2.3, the addition of 1 kg induced an increase activity in the BB more often significant (10 times) for the L head than for the S head (5 times) which indicates the contribution of the L head in those positions.
Figure 4.2.2 EMG RMS values (μV) averaged for the 3 trials over the 10 electrode pairs for subject S2 in the 3 body positions while the hand was either in pronation, neutral or in supination. White background is associated to electrode #1 to #5 placed over the S head while the colored one is for the 5 other electrode pairs over the L head.

In summary, it has been observed that the largest activity in the S head occurs in the seated condition with the arm flexed and hand supinated while for the long head it occurs in standing position with the arm extended and hand pronated. To see what underlies these findings, Fig 4.2.4 presents individual EMG channels activity, where the channel displaying the maximum value for a given body and hand position is numbered. Among the 4 subjects in the seated position, maximum activity over the S head varied from electrode pairs #2 and #5. In the 2 standing positions variation is narrower i.e. between #7 and #9.
Figure 4.2.3 Mean RMS values (μV) of all 4 subjects (S1-S4) obtained over the short head (white bars) and the long head (orange bars) of the biceps for 3 repeated trials when the hand was in pronation (1), neutral (2) and in supination (3). * identifies significantly different values between short and long head while ** is used for comparison of short head or long head results with the hand in different postures (p<0.05).

To analyze relationships between the various EMG signals, correlation coefficients matrices were computed for the 4 subjects and the 3 positions retained in Fig 4.2.3 and 4.
Figure 4.2.4 Mean RMS EMG potential distributions (μV) of all four subjects in 3 positions where maximum activity was in the S head (left column) and in the L head (middle and right column). In each distribution, the electrode pair with the largest activity was identified. White background is associated to electrodes over the S head and the colored one to the electrodes over the L head.

Given the symmetry along the diagonal, only half of the maps are presented in Fig. 4.2.5 where the same four color-coded iso-correlation levels were used. Yellow/gold regions are
those of high correlation coefficients; blue/purple are those of low correlation. Expected region of high correlation coefficients are found on and in the vicinity of the diagonal, i.e. the auto-correlation coefficient which by definition is unity.

Figure 4.2.5 Color map of the correlation coefficients r for the 10 differential signals for the 4 subjects and three positions used for Figs. 3 and 4. The ratio of the blue area to the total area in each half matrix is shown in %.

The width of the yellow diagonal band indicates how adjacent EMG channels are dependent from each other or, in other words, share a signal that originates from the same source. Conversely the area covered by the blue/purple pixels would be indicative of the degree of channel independence, a valuable parameter for multiple DOF myoelectric
control. To provide an index of channel independence, we computed the relative area (%) occupied by correlation coefficients $r < 0.5$ (blue region on each map) relative to the entire area. The larger the blue area, the more EMG channels could be available for independent control.

### 4.2.4 Discussion

Exploring if and how different parts of the biceps brachii, that could be associated to the muscle’s compartments, can be voluntarily contracted, two situations have been identified in which larger EMG activity can be found either over the short or the long head.

In the seated position, the present results indicate that activity in the S head is greater than in the L head with the flexed arm in supinated hand posture (Fig. 3). This confirms our previous observations made with only 7 pairs of electrode positioned across the BB [9]. This is also in accordance with Brown et al. [10] who found, with subjects having their elbow flexed at 120° and hand in supination, more activity in the S head of the BB than in its L head.

In the standing positions, more activity was found in the L head than in the S one. While this occurred for all hand postures, the difference was largest in pronation. This result is in line with those reported by Sakurai et al. [11] for the larger involvement of the L head in relation to movements associated with the shoulder$^3$.

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$^3$ With a neutral forearm rotation, these authors [11] investigated the activity of the BB in relation with the shoulder during 24 different arm positions and founded more activity in the L head in 20 of their 24 isometric contractions
Looking within the L head, we observed in seated position with the hand in supination position, a larger activity under electrode pairs #6 to #8 for S1, and #6- #7 for S2 and S3, a location that can be considered as the medial part of this head. Similar findings have been reported by ter Haar Romeny et al. [7] with intramuscular electrodes: more motor units activity were detected in medial portion of the L head of BB than in its lateral part (our electrodes #9 and #10) with subjects having their elbow flexed and the hand supinated.

The differences observed among the subjects could be due to several factors. First, at the electrodes level the arm circumference varied between 253 and 300 mm. With a fixed transverse distance of 15 mm between each pair of electrodes, differences relative to the underlying structures of the biceps cannot be avoided. Second, inter-subject differences in the relative size of the long vs short head are suspected from preliminary analysis of ultrasound images of the biceps. Third, the medial and lateral limits of the muscle were determined by palpation and since it is not easy to locate precisely the separation between the 2 heads at that level, we are not sure that the electrodes were placed over the same muscle anatomical configuration for each subject. Finally, while the subjects were asked to put their hands in a given position, no measurement was made except visual supervision. Therefore, the hand postures could have been somewhat different contributing to the observed inter-subject differences.

With the closely positioned electrode pairs we used, crosstalk is inevitable as displayed by the high correlation areas ($r>0.9$) shown in Fig. 5. However, except for two positions for S1
and one for S2, areas of low correlation (r<0.5) were still found to represent more than 20% of the total area but with different shape, size and location. This suggests that for accomplishing the same task, individuals have a personal pattern for the recruitment of motor units within the S and L heads. Further acquisitions could help to confirm those observations.

4.2.5 Conclusion

Current results suggest that supination with flexed arm is the most appropriate position for increasing the EMG activity in the short head and to preferentially activate the long head, the standing position with the 90° abducted shoulder must be chosen. Therefore, possibility of using each head of the biceps as a unique control site becomes more evident. In addition, the presence of relatively large zones of low correlation for at least 3 of the subjects is encouraging in view of our longer-term goal which is to exploit the compartmental structure of the biceps brachii to facilitate the control of myoelectric prostheses capable of producing many hand movements. In the future, we will expand our data set with a larger population of subjects (~15) so as to get more robust statistics on which multivariate analysis would be applied. To localize individual compartments within each head of the biceps, which is somewhat impaired by known electrode crosstalk, we propose to pursue the analysis of the correlation maps and examine the use of tools such as principal components analysis.

Acknowledgments

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References


4.3 Results with the 10 subjects

To the previous 4 subjects tested with the 10 electrode pairs array, 6 new subjects were added and the results obtained by that enlarged group are presented here. As previously, the averaged RMS EMG value over the SH and LH where initially analyzed.

In the seated or standing condition, activity in the SH increased in all subjects as the hand posture changed from pronation to supination; in 5 occasions (S1 to S4 and S7). In the seated position (but only for S4 in the standing 1 kg condition), a statistically increase was found between pronation and supination (*** in Fig. 4.3.1). When comparing SH vs. LH in the seated position and the 3 hand postures, a larger activity was mainly found in the SH (7 out of 10 subjects: S1 to S6 and S9). For the 3 hand postures, a smaller activity in the SH was only found for S7 and S10 while this occurred only in the pronation and neutral postures for S8. In the standing position with no load and with 1kg load in all the hand postures, the activity over the LH was always larger than in the SH. This situation was statistically significant in 50 out of 60 times. From pronation to supination, the LH activity had a tendency to decrease (significant diminution in only in 2 conditions). Activity of both SH and LH increased with the addition of the 1 kg load.
Figure 4.3.1 Mean RMS values (μV) of additional subjects (S5-S10) obtained over the short head (white bars) and the long head (orange bars) of the biceps for 4 repeated trials when the hand was in pronation (1), neutral (2) and in supination (3). * identifies significantly different values between short and long head while ** is used for comparison of short head or long head results with the hand in different postures (p< 0.05).
Activity recorded by each of the 10 electrode pairs is displayed in Fig. 4.3.2 along with the pair number where the signal was maximal. The only illustrated results are those with the hand supinated for the sitting condition and pronated for the standing positions as EMG activity was the highest. As expected from Fig. 4.3.1 results, in the seated position, maximal activity was found over the SH with maximal value ranging between electrode #2 and #6 with a mean value of 4.3 (±1.3) while in the standing condition, maximal activity over the LH was seen over electrode #7 to #10 with a mean value of 8.3 (±1.2) both for 0 and 1 kg.

Cross correlation coefficient matrices between each of the 10 EMG signals were obtained for all subjects in the seated (20% MVC) and standing (0 and 1 kg load) for the 3 hand postures. The 90 interpolated matrices with four iso-correlated levels are illustrated in Fig. 4.3.3 where only half of the maps are presented due to the symmetry along the diagonal. High correlation coefficients areas are shown in yellow/gold whereas low correlation ones are in blue/purple. Anticipated region of high correlation coefficients can be observed on and in the vicinity of the diagonal, i.e. the auto-correlation coefficient which by definition is unity.

The width of the yellow region points out how adjacent EMG channels are dependent on each other or share a common signal source. Conversely the area covered by the blue/purple pixels is indicative of the degree of channel independence, a valuable parameter for multiple DOF myoelectric control.
Figure 4.3.2  Mean RMS EMG potential distributions (µV) of each subject in 3 positions. In each distribution, the number of electrode pair with the largest activity is shown. White background is associated to electrodes over the SH and the colored one to the electrodes over the LH. For S10, the large activity at electrode pair #1 was due to the presence of the noise.
Figure 4.3.3 Color map of the interpolated, correlation coefficients $r$ for the 10 differential signals for the 10 subjects in three conditions tested with three hand postures for each condition. The ratio of the blue area to the total area in each half matrix is shown in %. For each subject, the mean value of their sum for the 9 positions is shown at the right and it was used to rank the presentation from the smallest blue areas (top) to the largest ones (bottom) where the % values represent the mean values obtained for the 10 subjects in a given position.
To provide an index of channel independence, the area occupied by correlation coefficients $r<0.5$ (blue region on each map) has been computed relative to the entire area$^4$. The larger the blue area, the more EMG channels could be available for independent control. These percentages have been written on top of each corresponded figures. The mean value of their sum is presented at the right of the figure for each subject and has been used to rank the subjects. The mean value of the sum of the % in a given position is given at the bottom of the figure. So among the subjects, it would appear that S1 and S9 would have limited ability to contract independently parts of their biceps muscles. At the opposite, S8, S6 and S5 display a great potential to generate many different activity patterns. Others subjects are falling between those two classes. As for the sitting position with the hand supinated, it provides, for the ensemble of subjects, the best opportunity for independent activation of the biceps compartments while the less appropriate one would be the standing position with 1 kg and the hand pronated.

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4 The presence of few negative correlation coefficient values in S7, absolute values used to generate the correlation maps, may introduce a small level of error in the present data.
4.4 Ultrasound results

An example of the images of a subject is presented in Fig. 4.4.1. Following the identification of the border of the BB muscle as well as its SH and LH, the corresponding contour has been manually drawn on the image.

Figure 4.4.1 Contour modifications of the LH and SH from ultrasound images as the hand position is changed (pro: pronation, neu: neutral and sup: supination). Yellow lines outline the contour of the LH and SH of the biceps. Curve length of the LH on top of the muscles showed in beige (between *) as well as the curve length of SH showed in blue (between •).
Following this procedure, the ultrasound machine software displays area and various descriptive measurements. As can be seen in Fig. 4.4.1 for subject #5, the shape of the LH and SH are quite modified as the hand position is changes between pronation and supination. Such behavior was shared by the other subjects as can be observed in Fig. 4.4.2. On those US images, flatness at the top of some muscles results from the required pressure to be exerted on the ultrasound probe to get all (or most) of the muscle surface within the field of view. The curve length extending between the * symbols across the LH and between ● across the SH are presented in Table 4.4.1. From subject to subject, it can be seen that either an increase or a decrease is observed as the hand position is changed and in all hand postures, this measure was larger for the LH than for the SH in 7 out of ten subjects.

Additional information on what is happening under the electrodes placed over the skin is illustrated in Fig. 4.4.3 for 2 subjects. With the information on the area occupied by each head as the hand is moved from pronation to supination, one can notice an increase in the total muscle area as well as an appreciable muscle mass displacement relative to the humerus. Similar changes occurred with the other subjects.
Figure 4.4.2 For the 10 subjects, shape of the BB muscle (LH in beige, SH in blue) in seated position with no external load and in the 3 hand positions tested. The curved blue line is the top portion of the humerus (H). * Indicate a subject for whom the BB was larger than the ultrasound probe field of view. In such cases the right portion of the SH is an estimate of the reality.
Table 4.4.1 From US image measurements, curve length of the SH and LH with hand in pronation (P), neutral (N) and supination (S) for all the subjects.

<table>
<thead>
<tr>
<th>subject</th>
<th>Curve length, LH of the BB from US (mm)</th>
<th>Curve length, SH of the BB from US (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>N</td>
</tr>
<tr>
<td>S1</td>
<td>40,5</td>
<td>36,9</td>
</tr>
<tr>
<td>S2</td>
<td>33,9</td>
<td>34,4</td>
</tr>
<tr>
<td>S3</td>
<td>32,1</td>
<td>27</td>
</tr>
<tr>
<td>S4</td>
<td>22,9</td>
<td>27,2</td>
</tr>
<tr>
<td>S5</td>
<td>24</td>
<td>17,5</td>
</tr>
<tr>
<td>S6</td>
<td>39</td>
<td>28,5</td>
</tr>
<tr>
<td>S7</td>
<td>32,4</td>
<td>33</td>
</tr>
<tr>
<td>S8</td>
<td>40,3</td>
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</tr>
<tr>
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<td>31,9</td>
</tr>
<tr>
<td>S10</td>
<td>47,3</td>
<td>39,9</td>
</tr>
</tbody>
</table>

Figure 4.4.3 Deformation of the LH (beige areas) and SH (blue areas of the BB for subjects S3 and S4 in seated and standing condition without load and with 500 g load. Within the LH and SH, small values in each head represent the area of the head (cm²) and the larger values under each illustration is their sum as the total area of the BB. The humerus (H) positions relative to the muscle deformations can also be observed.
A summary on the muscle area changes occurring across the hand positions is presented for each subject in the upper panel of Fig. 4.4.4. To get a better view on the variations in the muscle area as hand position was modified, the change $\Delta A$ was defined as:

$$\Delta A (\%) = \frac{\text{Area in pronation or supination} - \text{Area in neutral}}{\text{Area in neutral}} \times 100$$

Figure 4.4.4 Upper panel: Effects of the hand posture (p: pronation, n: neutral, s: supination) on the area of the BB in the seated position without load (left) and with a 500 g load (right) for the 10 subjects. Lower panel: Percentage change of the BB area from pronation to neutral (blue bars) and supination relative to the neutral position used as the reference (red bars). Subjects ordered by the small area of the BB in neutral position to the larger area.
The $\Delta A$ of each subject is shown at the left of the bottom panel of Fig. 4.4.4. In supination (green bars), the BB area was always larger than in pronation while in pronation the BB area was smaller (blue bars) than in neutral position for 8 subjects. Somewhat similar results were obtained when a 500 g load was added when the subjects were seated (upper right panel of Fig 4.4.4). As for the area changes with a 500 g load (right portion of the lower panel of Fig 4.4.4), the BB area was larger in supination than in pronation for all subjects. This area in supination was larger than in neutral position for 9 subjects and smaller in pronation also for 9 subjects.

The area occupied by the BB muscle in the two seated and two standing conditions are illustrated in the Fig. 4.4.5 for all subjects with different hand postures. Effect of adding load was not the same for all of the subjects; almost half of the subjects (5) showed increased in area of the BB muscle in both seated and standing condition with different hand postures, while for the other half no increase or a decrease in the terms of total area occupied by the BB muscle was detected. This unexpected result could be associated with a 2D view of a deformable 3D muscle tissue: the expected increase in the muscle volume could have occurred away from the level where the US probe was positioned. Another explanation could be that the brachialis muscle was used to compensate for the additional load.
Figure 4.4.5 Area of the BB of the 10 subjects in seated position (upper panel) and standing position (lower panel). Condition of without load and with 500 g external load where tested in 3 hand postures (pro: pronation, neu: neutral and sup: supination).
Chapter 5

Discussion

Existence of anatomical partitions in human and animals muscles has been reported in anatomical studies such as those of (English and Letbetter, 1982, Segal et al., 1991, Segal, 1992) as well as in physiological experiments by (ter Haar Romeny et al., 1984, Holtermann et al., 2005). Integrating the findings of many of articles on the subject, English et al. (1993) gave a sound foundation to the presence of muscle compartments and proposed a general partitioning theory. Therefore, in the context of facilitating the myoelectric control of upper limb prosthesis we investigated if and how the voluntarily activation of the BB compartments could be first done with normal subjects before experimenting with persons who sustained an amputation.

Two experimental conditions were tested: 1) the subject was seated with the elbow flexed at ~100° and maintained an isometric contraction at 20% of his maximal voluntary contraction and, 2) the subject was standing while maintained the right arm horizontally on the side of the trunk with 0 or 1 kg load suspended at the wrist level. EMG signals were collected while the hand was either in neutral position, in pronation or supination in each of those 2 conditions.

In the seated position, the EMG signals recorded over the SH were generally of greater amplitude than over the LH. In all subjects, activity in the SH increased while the hand
position was changed from pronation to supination. With the hand supinated, maximal activity was found between electrode #2 and #6 positioned mainly over the SH. This is in accord with the results of Brown et al. (1993) with subjects having their elbow flexed at 120° and hand supinated.

During isometric elbow flexion, the dependency of the surface recorded EMG activity with the hand position has also been reported (Jamison and Caldwell, 1993, Holtermann et al., 2008, Harwood et al., 2010). Such a dependency on the motor unit activity when intramuscular electrodes were used was also reported (ter Haar Romeny et al., 1984, Van Zuyl en et al., 1988). With the hand supinated, we found more activity under electrode pairs #6 to #8 that can be associated to the activity within the medial part of the LH than in electrode pairs #9 and #10 positioned over the lateral part of the LH. Similar findings relative to the medial and lateral part of the LH where reported by ter Haar Romeny et al.(1984) with subjects having their elbow flexed and the hand supinated.

In the standing position with and without load and regardless of the hand posture, a higher activity was always found in the LH than in the SH. That difference was statistically significant in 50 out of 60 times. Having more activity in the LH than in the SH while performing 90° shoulder abduction i.e. the standing condition is consistent with the results of Sakurai et al.(1998) who investigated the activity of the BB in relation with the shoulder during 24 different arm positions and observed more activity in the LH in 20 of their isometric contractions accomplished in 24 different arm positions.
Our correlation maps indicated that the position of the activated muscle fibers within the BB muscle to accomplish a given task is subject-dependent as reported for similar isometric conditions (Cote and Mathieu, 2000). Based on the blue areas which are associated with the number of independent EMG channels a subject achieved, it appeared that S1 and S9 had practically no sites were the signal was independent of the others recording positions whatever the hand or body positions. The situation was quite different for S8, S6 and S5 where the availability of independent recording sites was much larger. It would seem however that the sitting position, with few changes with the hand position, appears as the best one.

Intermediary results were obtained with the other 5 subjects.

To explain the observed EMG differences among our subjects, several factors could be mentioned. While the center-to-center distance between electrodes was always 15 mm in the electrode array, the arm circumference of the subjects at the recording level ranged from 250 to 310 mm (Table 5.1). Therefore, the same structures of the biceps were not always positioned under the same surface electrode pairs (right portion of Table 5.1). This is supported by the ultrasound images from which the curve length extending over the muscle upper surface was measured (Table 4.4.1). In some cases, the width of the biceps being smaller than the length of the electrode array, some electrode pairs at both ends of the array were not directly positioned over the BB as illustrated in right side of the Table 4.4.1. Prior to the positioning of half of the electrode array on the SH and the other electrodes over the LH, the midline separating those 2 heads was only identified by palpation which could have introduced errors in its identification and thus some offset toward the right or
the left may have also contributed to some of the differences observed on the correlation maps among the subjects. Finally, other factors are linked to the protocol: subjects were asked to put their hands in pronation, neutral or supination but no measurement was made except visual supervision as for the amplitude of the arm extension in the standing position.

Table 5.1 Anatomical information on each subject (ordered by increasing width of the biceps muscle). With this ranking, 3 estimated positioning of the electrode pairs relative to the width of the biceps are proposed at the right. At the top, the 4 grayed arrays identify 4 electrode pairs which were probably not positioned over the biceps of S3, S2, S7 and S5. Only for the 3 subjects at the bottom did the electrode array entirely covering the muscle width.

<table>
<thead>
<tr>
<th>subject</th>
<th>Arm circumference (mm)</th>
<th>BB width measured from top of the skin (mm)</th>
<th>BB area Neutral (cm²)</th>
<th>Electrode array coverage by the width of BB</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>265</td>
<td>90</td>
<td>6,89</td>
<td><img src="image1.png" alt="Image" /></td>
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Conclusion

From EMG recording and US images obtained from 10 healthy subjects it was found that supination with flexed arm is the most appropriate position to elicit more EMG activity in the short head while the long head is more active in the standing position with the 90° abducted shoulder. Therefore, possibility of using each head of the biceps as a unique control site becomes more evident. In addition, the presence of relatively large zones of low correlation among some subjects is encouraging in view of our longer-term goal which is to exploit the compartmental structure of the biceps brachii to facilitate the control of myoelectric prostheses capable of producing many hand movements.

As a concluding remark, significant contribution of our work during this project has consisted in set up a structured database of EMG signals and ultrasound images.

Future works

In order to pursue the localization of the individual compartments of the biceps in future, in addition to the correlation maps, other signal analysis could be easily applied for that purpose given the availability of a structured database. One could think of principal components and factors analysis by which the 10 EMG signals are converted in a set of linearly uncorrelated sources which could be associated to the muscle’s compartments. In addition to such approaches, it is planned to use a direct and inverse model to study the potential distributions collected over the biceps. With the model, dipole locations within the
muscle explaining the amplitude of the experimental signals will be proposed and their positions used to assess which compartments could have been active during a given contraction. As for anatomical information on the muscle, 2D ultrasound images are very valuable in terms of tracking the biceps deformation. On the other hand as part of the muscle mass may move out of the probe’s view in 2D US imaging, the use of 3D ultrasound could be an improvement to help explain the muscle morphological changes observed with hand movement. Such modality is commercially available for the equipment we used. As for the need to collect new data, it would be with below elbow amputee people to explore their capabilities to produce different signals form their biceps.
Bibliography


WAKELING, J. M. 2009. The recruitment of different compartments within a muscle depends on the mechanics of the movement. Biology letters, 5, 30-34.


Annex A: Ethical approval document
Objet: Certificat d'éthique - "An investigation on how to activate the upper limb muscles' compartments in normal subjects"

Monsieur Pierre A. Mathieu, Madame Nahal Nejat

Le Comité d'éthique de la recherche de la Faculté de médecine (CÉRFM) a étudié le projet de recherche susmentionné et a délivré le certificat d'éthique demandé suite à la satisfaction des exigences précédemment émises. Vous trouverez ci-joint une copie numérisée de votre certificat, copie également envoyée au Bureau Recherche-Développement-Valorisation.

Notez qu'il y apparaît une mention relative à un suivi annuel et que le certificat comporte une date de fin de validité. En effet, afin de répondre aux exigences éthiques en vigueur au Canada et à l'Université de Montréal, nous devons exercer un suivi annuel auprès des chercheurs et étudiants-chercheurs.

De manière à rendre ce processus le plus simple possible et afin d'en tirer pour tous le plus grand profit, nous avons élaboré un court questionnaire qui vous permettra à la fois de satisfaire aux exigences du suivi et de nous faire part de vos commentaires et de vos besoins en matière d'éthique en cours de recherche. Ce questionnaire de suivi devra être rempli annuellement jusqu'à la fin du projet et pourra nous être retourné par courriel. La validité de l'approbation éthique est conditionnelle à ce suivi. Sur réception du dernier rapport de suivi en fin de projet, votre dossier sera clos.

Il est entendu que cela ne modifie en rien l'obligation pour le chercheur, tel qu'indiqué sur le certificat d'éthique, de signaler au CÉRFM tout incident grave dès qu'il survient ou de lui faire part de tout changement anticipé au protocole de recherche.

Nous vous prions d'agréer, Madame, Monsieur, l'expression de nos sentiments les meilleurs,

Isabelle Ganache, présidente
Comité d'éthique de la recherche de la Faculté de médecine

Université de Montréal

/gp

cc. Gestion des certificats, BRDV
    Louise Bélanger (MD - Physiologie)
pj. Certificat #11-028-CERFM-D
CERTIFICAT D’ÉTHIQUE

Le Comité d'éthique de la recherche de la Faculté de médecine (CÉRM), selon les procédures en vigueur, en vertu des documents qui lui ont été fournis, a examiné le projet de recherche suivant et conclu qu’il respecte les règles d'éthique énoncées dans la Politique sur la recherche avec des êtres humains de l'Université de Montréal.

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<td>Pierre A. Mathieu (015532) - Professeur titulaire</td>
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<td>Nahid Nejat (NEJN21538103) - Étudiante à la maîtrise</td>
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Financement

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MODALITÉS D’APPLICATION

Tout changement anticipé au protocole de recherche doit être communiqué au CÉRM qui en évaluera l’impact au chapitre de l’éthique.

Toute interruption prématurée du projet ou tout incident grave doit être immédiatement signalé au CÉRM.

Selon les règles universitaires en vigueur, un suivi annuel est minimalement exigé pour maintenir la validité de la présente approbation éthique, et ce, jusqu'à la fin du projet. Le questionnaire de suivi est disponible sur la page web du CÉRM.

Isabelle Gagnon, présidente
Comité d'éthique de la recherche de la Faculté de médecine (CÉRM)
Université de Montréal

5 mai 2011 Date de délivrance 1er juin 2012 Date de fin de validité
Annex B: CMBEC34 conference paper

Proc. CMBEC34, nejat- 69741.pdf (FICCDAT CDROM)
3 pages, Toronto June 2011
SURFACE EMG AND MYOELECTRIC PROSTHESIS CONTROL

Nahal Nejat, Pierre.A. Mathieu

Institut de génie biomédical, Université de Montréal

Abstract— An electromyogram (EMG) signal is the signature of a muscle contraction by which our limbs can be moved. When part of a limb is lost, muscles used to move it can still be contracted. An amputee person can then use those muscular signals to activate a myoelectric prosthesis and produce some movements again. Newest myoelectric prostheses are capable of many degrees of freedom (DOF) and therefore many signals are required to fully benefit from their capabilities. In search of many muscle control sites to operate such prosthesis, muscle compartments, which are intra-muscular subdivisions innervated by individual muscle nerve branch, can be exploited. In order to explore if the compartments of those muscles could be voluntary controlled, we placed an array of 7 pairs of equally spaced surface electrodes across the biceps brachii (BB) of healthy subjects. EMG signals where collected while subject’s hand was in different positions. Our preliminary results indicate that depending on hand positions, parts of the biceps muscle are more active than others. Such knowledge could be useful for the control of a modern myoelectric prosthesis.

Index Terms: Biceps brachii; Compartment; Electrode array; Surface EMG

I. INTRODUCTION

Upper and lower limb amputees can be associated to diseases, accidents and in recent years due to wars in Iraq and Afghanistan as bullet proof vests save lives but not limbs. Limb loss is a tragic event that has effect on entire life. Specially for young amputee persons, there is a need for a several DOF prosthetic device they could use in their daily life activities. With a myoelectric prosthesis, electromyographic (EMG) signals recorded over the muscles of the amputee stump are used to produce movements by activating an electric motor linked to the mechanical levers or cables.

Myoelectric control was introduced in the 1940s and considerable progress was made in the 1960s. Founded by the American Defense Advanced Research Project Agency (DARPA), one of the most advanced hand prosthesis with 22 DOF has recently been developed [1]. The problem that has now to be solved is how to activate it.

In large muscles, compartments innervated by an individual muscle nerve branch can exist [2]. Selective activation of such intra-muscular subdivisions has been observed in some animal muscles (e.g. cat sartorius and lateral gastrocnemius) during locomotion [3]. In humans, the ability of independently control of different subdivisions of the trapezius has been investigated with biofeedback guidance [4]. In the BB, neuromuscular compartments each innervated by a nerve branch have been found through dissection of a cadavers [5].

The project is aimed at determining if each of those compartments can be under our voluntary control. To do so, an array of equally spaced surface electrodes is placed across the BB, which is contracted while the hand is placed in different positions. Initially, normal subjects will be tested and the acquired knowledge will then be used to see if amputee persons can also activate those compartments with the objective of fitting them with a prosthesis which is best adapted to his/her abilities.

II. METHODS

A. Subject

Data gathered from four subjects; two males and two females for preliminary experiment.
B. Experimentation

After preparation of the skin with abrasive paper and cleaning with alcoholic pad, conductive gel put on the electrodes and an array of 7 pairs of gold coated electrodes (6 mm diameter) equally spaced 1.5 cm form both horizontal and vertical distance, is fixed around the arm above the middle of BB and below the estimated zone of the neuromuscular junctions. Exploratory experiments carried out to get the optimum electrode placement around the arm in order to detect muscle compartment activation while the hand is in different positions. With this information, data acquired from the healthy subjects while their hands are in the following positions: Neutral, Half-Supination, Supination, Half-Pronation, Pronation, Supination with wrist Flexion (S-F) and Pronation with wrist Flexion (P-F).

C. Instrumentation

An EMG amplifiers system (Grass, model 15LT) with a band pass of 3 Hz to 1 kHz is used and connected to an A/D converter (National instrument, NI USB-6225). The sampling rate is 2 kHz and the digitized signal is store on a computer for off-line processing with Matlab. LabView software is used to control the data acquisition. To monitor the level of isometric contractions at 10 % and 20% MVC (maximum voluntary contraction) during the 5 s of each acquisition, a strain gauge is used and its output is displayed on a monitor as a feedback signal to the subject and digitized in parallel with the EMG signals. For those acquisitions, the arm is close to the trunk and flexed at 110° with a hand cuff at wrist, linked to the strain gauge placed near the hand.

D. Analysis

Mean RMS values of EMG signals for each 7 channels were calculated from the 3 repetitions of best recording trials in each hand positions. Slow drift in the signal due to instability of the half-cell potential of the electrodes was removed when present.

III. RESULT

Fig.1 illustrated the results obtained from 3 subjects for 3 hand positions. As it can be seen, for each subject, some parts of the biceps muscle are more active than others and that distribution is changes as the hand position is changed. Differences are also noted among the subjects. It can be observed that the signal at electrode #2 displays important changes between the different positions. Activity of the segment of the biceps under electrode #4 increases as the wrist position is moved from neutral to Supination and

Fig.1. Illustration of the EMG signals distribution (mean RMS values in μV) over the biceps brachii (electrode 1 to 7) vs. different hand positions. P:Pronation, N;Neutral, S; Supination. Subject#1: 10% MVC, subject #2, #3: 20%MVC.

reduced when wrist is put in Pronation. The pattern of the activity of the BB were found to be similar for all the other positions tested but not displayed here i.e.; Neutral, Half-Pronation and Half-Supination. In general more activity is observed on the medial side of the BB in Supination compared to the lateral side which indicate that short head of
the BB was more activated than the long head in the supination position.

Patterns of BB’s activity for Supination and Supination with wrist Flexion (S-F) were found to be the same. This was also observed for Pronation and Pronation with wrist Flexion (P-F).

IV. Discussion/Conclusion

The main objective of this study is to see if the anatomical compartments of upper arm biceps (and eventually the triceps) can be used to control a prosthetic hand capable of many DOF. From our preliminary results on the biceps, there is indication that some zones are more active depending on the hand position. Romeny et al [6] found that during elbow flexion, motor units in the lateral portion of the long head of the biceps are preferentially activated, whereas in forearm Supination, motor units in its medial portion are more activated. Our results show the same finding if we just look at the electrodes #4, 5 we see more activity in medial portion of the long head of the BB.

According to our results, more activity was found in the medial portion of BB which could be related to the short head of the BB and lateral portion of the BB had less contribution for keeping the arm at Supination position. This finding is in accordance with Brown et al. [7] experiment in which it was found that short head of BB has more contribution than long head in Supination motion when the elbow is in 120° of flexion.

In future work, the triceps could be investigated and we will try to locate the zones of tension within a contracted muscle with ultrasound imaging.

V. Acknowledgements

The authors gratefully acknowledge Ms. V. Desjardins for technical assistance. Research supported by NSERC grant #156144-2010.

References