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Contents

Abstract

The functional capacity can be affected with advancing age by changes in cardiovascular and muscular performance. The Baltimore Longitudinal Study of Aging is developing several research protocols on the general area of frailty and physical independence which are in part characterized by losses of motor units (MU).

Studies have shown that the MU number of upper and lower limb muscles and thenar muscles of the elderly was reduced in comparison to the younger age groups. The electrophysiological and contractile properties of human MUs will be studied within this research area. Moreover, the relationship between these properties will be investigated by measuring both EMG signals and force signals synchronously.

Equipment is available to measure the neuromuscular signals. The EMG signals are measured using the Advantage EMG system, whereas, the force signals are measured using the KIN-COM system. However, both systems use their own proprietary software to collect and process data and no automatic integration nor synchronization of measurements performed by both systems is possible. Moreover, thenar force signals recorded from a thumb-force-measurement system cannot yet be collected and processed. Therefore, a device has been developed to collect and process both types of neuromuscular signals in order to synchronously achieve the age-associated parameters of these signals.

The use of a separate, third, computer and a sophisticated data-acquisition board to which the different measurement systems are connected resulted in a device that is able to collect, process and analyze neuromuscular signals in a synchronous manner. A program has been written using the programmable software 'LabVIEW' to control this device in terms of collecting, processing and analyzing the recorded data. The complete developed measurement system is called the Synchronous Signal Detection System (SSDS).

A simple test has been performed to understand how the SSDS operates. The flexion and extension of the rectus femoris muscle has been recorded together with the surface EMG. The test showed good results in terms of the synchronous detection of both the signals and analysis of the signals. However, no clinical conclusion can be made out of these results because the SSDS still needs to be calibrated.

1. INTRODUCTION

Aging in human is generally associated with a substantial decline in neuromuscular performance (T.J. Doherty, 1993a). Characteristic of this decline is an age-related reduction in skeletal muscle mass, leading to decreased voluntary and electrically evoked contractile strength. It is suggested that these age- associated reductions in muscle mass are primarily a consequence of losses of alpha motor neurons in the spinal chord and secondary a consequence of denervation of their muscle fibers. The decline in muscle mass, which is characterized by skeletal muscle atrophy and weakness, is in part attributable to losses of motor units (MUs).

The MU is the basic functional component of the mammalian motor system. It is comprised of an α motor neuron with its cell body in the ventral horn of the spinal chord, its single motor axon, and the population of muscle fibers innervated by that axon. Using an electrophysiological technique, it was shown that the number of MUs in upper limb muscles (biceps brachii, brachialis) and thenar muscles of human subjects between 60 and 80 years of age were reduced compared to subjects between 20 and 40 years of age (T.J. Doherty, 1993a). Additionally, along with reduced MU number, studies have reported significant reductions in the electrically evoked and voluntary contractile force in the muscles of older subjects (T.J. Doherty, 1994). In general, electrophysiological studies have shown age-associated reductions in the maximum compound muscle action potential size (M-potential) coupled with increases in the mean motor unit action potential (MUAP) size. These findings suggested that there were, on average, fewer yet larger MUs in the muscles of elderly.

However, investigations of age-related changes in MU contractile and electrophysiological properties have been limited. Further study is required to provide a more thorough understanding of the underlying changes and adaptive capabilities of MUs in older adults. Additionally, it would be of great interest to relate the contractile properties of the MU to the electrophysiological properties of the MU and the whole muscle. Although, devices are available to examine contractile properties of human upper and lower limb muscles (e.g. biceps brachii, brachialis,

rectus femoris (quadriceps), semitendinosus (hamstring) and thenar muscles) and electrophysiological characteristics of the MUs, there is no device available for synchronized examination of these phenomena in order to study the relation between these age-related variables. Because of this disability, the purpose of this study is to develop such a device.

For this development the basic information on electromyography, electrophysiological and contractile properties is necessary (chapter 2). With this information the study on age-related decline of MU is understandable (chapter 3 & 4). The measurement devices that are already used for neuromuscular studies are the KIN-COM System to measure body forces, the Advantage EMG System to measure the electrophysiological properties of MUs and the Thumb-Force-Measurement System (TFM) to measure thenar muscle forces. These systems are used for the development of the device for synchronized detection and examination of neuromuscular signals (Synchronous Signal Detection System (SSDS))(chapter 5). On the basic of some experiments with this device (chapter 6) general conclusions and recommendations are finally presented (chapter 7 & 8).

2. ELECTROMYOGRAPHY

2.1. Introduction

To be able to understand the age-related decline of MUs some basic information on electromyography is required. This chapter will describe the basis of electromyography, and electrophysiological and contractile properties.

2.2. The Motor Unit

2.2.1. Basis of the Motor Unit

The structural unit of contraction is the muscle fiber. In human skeletal muscles, these fibers never contract as individuals. Instead, small groups of them contract at almost the same time. These groups of muscle fibers are supplied by the terminal branches of one nerve fiber or axon whose cell body is in the anterior horn of the spinal grey matter. This nerve cell, or α motor neuron, with its cell body, its single motor axon, and all the muscle fibers innervated by the terminal branches of the axon, together constitute a motor unit (MU). Each terminal branch supplies just one muscle fiber (Fig. 2.1).

Under normal conditions an impulse or action potential that exceeds a specific threshold, propagating down a motor neuron, reaches the MU endplate and activates all the branches of the motor neuron. These branches activate all the muscle fibers of the MU almost simultaneously. A wave of contraction spreads over the fiber resulting in a brief twitch contraction followed by a quick relaxation. The duration of this twitch contraction and relaxation varies from a few ms to as much as 0.2s depending on the type of muscle fiber involved (fast or slow). The muscle normally contracts on such nervous impulses at a frequency below the upper physiological limit of 50Hz. When the muscle fiber is activated by the motor endplate,(called)depolarized, the depolarization propagates in both directions along the fiber. This membrane depolarization, accompanied by a movement of ions along the membrane, generates an electrical field in the vicinity of the muscle

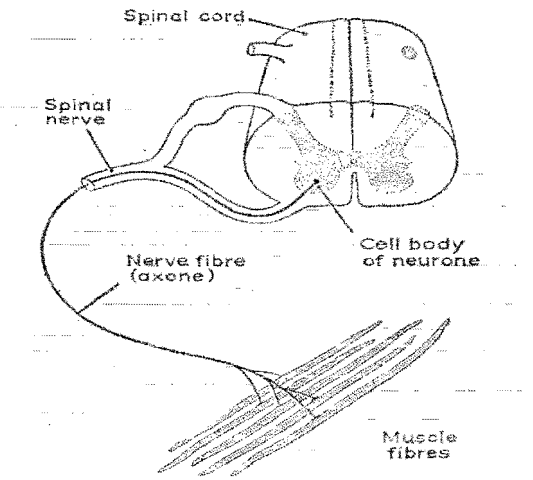

Figure 2.1: Scheme of a Motor Unit

fibers. A recording electrode can be used to detect the potential or voltage with respect to the ground, whose time excursion is know as action potential.

2.2.2. Motor Unit Characteristics

A MU will contract when the stimulus current is above its threshold and a MU potential will be detected. In electrochemical terms, threshold is the level of transmembrane potential at which a depolarization in the transmembrane potential will trigger an irreversible escalation in the proportion of open sodium channels. The threshold is normally between -55 and -60 mV in mammalian muscle (Brown, 1984). So, for a motor nerve fiber, threshold is the stimulus intensity at which the motor axon generates an "all-or-nothing" action potential in response to the stimulus.

Studies have shown that the normal upper limit of activation of MUs is about 50 times per second. These studies have also shown that this firing rate of MUs increases with stronger contractions. Fuglsang-Frederiksen et al. (1987), showed no relation between the maximum force and the motor unit firing intervals in patients. The probability of a MU firing after a previous firing has occurred, increases exponentially with respect to elapsed time.

Under normal conditions a slight voluntary contraction will activate the smaller

MUs first (smaller potentials) and an increasing force subsequently will recruit larger MUs. Moreover, the frequency of firing increases for all MUs with an increasing force (Dorfman et al., 1988; Jones et al., 1989; Thomas et al., 1987).

The stimulation threshold for motor fibers in the same nerve are lower for the fibers of a small diameter than for those of a larger diameter. The smaller nerve fibers supply the smaller MUs which appear to be the most easily recruited MUs in normal voluntary contraction. In general, the lower the input resistance of motor neurons, the higher the threshold for recruitment in response to peripheral and central inputs, the larger the twitch tension of the MU, and the less resistance the MU has to fatigue (Brown et al., 1988).

The force that MUs can generate vary widely. This is probably mainly because of the larger numbers of the muscle fibers in the higher tension MUs. The number of contractile elements is approximately related to the cross-sectional area of the muscle fiber which means that a larger cross-sectional area of the fiber has more contractile elements and therefore the generated force is higher. Moreover, the type of muscle fiber is also important because the force generated per unit cross-sectional area is higher in fast compared to slow muscle fibers. Because of the higher contraction and relaxation time of slow muscle fibers, no significant change in force output occurs in a train of twitches (tetanic contraction) for a given firing frequency, whereas in fast MUs, appricial force decrements may occur. Both the number of active MUs and the firing rate of the MUs correspond to the force produced by the muscle. To increase the force output, the firing rate of active MUs increases and increasingly larger MUs are recruited. Also the amplitude of the surface electromyographic signal (section 2.3) and the number of action potentials per unit time will increase (Brown et al., 1988; Dorfman et al., 1988; McGill et al., 1985). The contractile force is highly correlated to MU action potential shape, behavior properties, and correlated to effects of age, gender differences, and intermuscular variability (Dorfman et al., 1988).

2.3. The Electromyographic Signal

2.3.1. Basis of the Electromyographic Signal

Electromyography (EMG) is the study and use of the EMG signal that originates in the membrane of muscle fibers as they contract. As shown in section 2.2.1 the membrane depolarization of a muscle fiber generates an electromagnetic field in the vicinity of the muscle fibers. The potential or voltage of this elec-

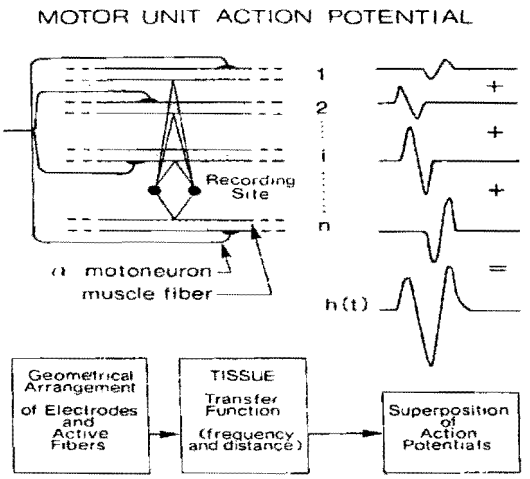

Figure 2.2: Schematic representation of the generation of the MU action potential

tromagnetic field can be detected using needle or surface electrodes. The signal that is measured, a superposition of the action potentials of the MUs that are innervated, is called the EMG signal (Fig. 2.2). Within this EMG signal a lot of physiological properties of the MU can be found.

2.3.2. Characteristics of the Electromyographic Signal

The EMG is affected by the anatomical and physiological properties of the muscle, the control scheme of the peripheral nervous system, as well as the characteristics of the instrumentation that is used to detect and observe it. Using EMG equipment (see section 5.3.1) to detect the action potential of MUs several physiological properties can be measured and determined:

1. maximum M-potential (sum of all MU action potentials of the muscle)
2. single MU action potential (section 2.2.1 and 4.2)
3. estimation of the number of MUs (section 4.2)
4. conduction velocity (section 3.2.2)
5. firing rates (Doherty et al., 1993a)

These factors are determined using stimulation electrodes or voluntary contraction to activate the MUs and the EMG signal is recorded with surface or needle electrodes. The surface EMG signal is an expression of anatomical, biochemical, physiological, and electrical factors. The MU action potentials originate from the membrane of the muscle fibers and propagate radially through the muscle, fascia, fat and skin tissue (which acts as a filter) to reach the electrode placed on the surface of the skin. The signal is affected by the distance it must travel between the source and the recording electrode as well as the geometric and electrical characteristics of the electrode.

Surface electrodes are placed relatively far from the MU territories and have large pick-up areas (i.e., the observed part of the muscle). This causes that not only MU action potentials originating from MUs at a short distance from the electrode are observed, as with needle electrodes, but also at larger distances. This implies that usually a signal is found that is composed of the superposition of several MU action potentials.

The application of surface EMG has the main disadvantage that patterns occur usually difficult to interpret with the naked eye. However, the use of surface EMG has some typical advantages:

1. Large parts of a muscle are examined. This means that the function of the total muscle is more or less taken into account.

2. Surface EMG implies non-invasive technique and is painless in contrast with the application of needle EMG. This must be regarded as a very important aspect. One cannot deny that in longitudinal studies the cooperation of many patients stands or falls with the fact if the tests are painless or not.

3. Routine surface EMG examinations can be performed by non-clinicians.

The surface EMG signal differs from the needle EMG signal. With the surface arrangements, the signal presents a superposition of the MU action potentials of all active MUs in the detectable vicinity of the intramuscular electrode. So the surface EMG signal does not always provide the single MU action potentials which are available via needle or intramuscular EMG (De Luca, 1994).

Using the needle electrodes to detect MU action potentials only a very limited part of the muscle is observed, the pick-up area is very small. In such an area only the activities of one or two muscle fibers of a single unit are registered. Using conventional needle electrodes ($\emptyset \simeq 100\mu$m) a pick-up area of several mm can be

examined. This means that with conventional needle electrodes only the activities of a few MUs can be studied. Placing the needle electrode in the right position in the muscle the activity of one single MU can be detected. Repositioning of the needle electrode can give a complete different signal coming from a different single MU. With this information all the active MUs during a specific contraction can be found.

3. Age-Related Changes in the Neuromuscular System

3.1. Introduction

Very few researchers have investigated single human MU electrophysiological and contractile properties in relation to aging. Electrophysiological measurements are influenced by multiple factors namely temperature, height, as well as age (Robinson, 1994). Over the past few years, techniques have become available to estimate the number of MUs in human muscles. From the very few human studies, age-related changes in the number and physiological and contractile properties of human MUs is described. This chapter will give a summary of several studies of age-related changes in human MUs.

3.2. Aging Effects on the Motor Unit

3.2.1. The Motor Neuron

Age is known to be associated with losses of motor neurons, alteration in neuron size (i.e. atrophy) and other structural alterations and a variable degree of functional and non-functional regeneration (i.e. sprouting). The decrease of neurons is not uniform among classes of neurons. With losses of motor neurons, the remaining MUs are enlarged as reflected by increased mean single MU action potential sizes (Brown, 1994; Doherty et al., 1994; Dyck, 1994).

Rates of motor neuron cell losses based on physiological studies are similar to those derived from anatomical studies of losses of cells (Brown et al., 1988). The magnitude of the losses varies widely with motor neuron cell or muscle studied and the methods used to derive the numbers of motor neurons. Besides aging, other factors can contribute to the losses of motor neurons, e.g. neural diseases. Losses in spinal motor neurons and MUs in lower limb muscles became apparent by 60 years of age (Booth et al., 1994; Doherty et al., 1993b). No evidence of

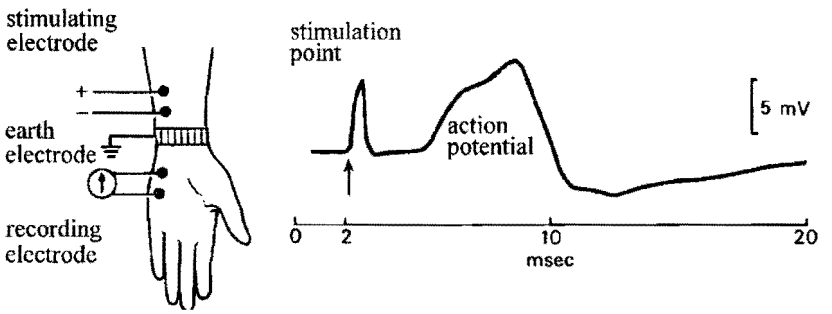

Figure 3.1: Motor Conduction Velocity measurement. Evoked potentials are obtained from abductor digiti minimi after stimulation of the ulnar nerve at the wrist. If the distance between the stimulation electrode and the recording electrode is devided by the latency the CV is calculated.

ventral horn cell body loss was detected until 60 years of age when their numbers began to decrease progressively. However, these findings were collected on different subjects and longitudinal data can show the variability in the numbers of motor neurons present in any group. These findings suggest age-associated losses of motor neurons and the subsequent degeneration of their axons.

3.2.2. The Conduction Velocity

The functioning of the peripheral motor system is often investigated by measuring the maximum motor Conduction Velocity (CV) of a given nerve. It is well known that aging is associated with reduced maximum motor CV in peripheral nerves supplying various muscles (Basmajian, 1978; Brown, 1994; Doherty et al., 1993b; Dyck, 1994). These reductions could be the result of selective losses of the largest and fastest conducting motor fibers or simply losses of the same fibers through natural random attrition or, as found by Doherty et al. (1994) and Brown (1994), a more or less uniform slowing of the motor axon CVs (Fig. 3.1) of all nerve fibers. The cause of reductions in the motor CVs of all nerve fibers with aging might reflect variety of changes in the underlying nerve fibers such as reductions in axonal diameter, and reductions in internode length. Motor nerve CVs generally drop about 0.2 m/s/yr (Robinson, 1994).

3.2.3. The Motor Unit Action Potential

The few studies investigating human muscles with EMG in older subjects, documented age-related changes in the MU action potential in terms of amplitudes and the duration of the MU action potential (Basmajian, 1978; Booth et al., 1994; Brown, 1984 & 1994; Doherty et al., 1993b; Dyck, 1994; Robinson, 1994). There is an increase in the MU action potential durations of about 0.05 ms/yr shown for the biceps brachii muscle (Robinson, 1994). Brown et al. (1988), studied the biceps and the brachialis muscles and showed that in subjects of 60 years of age or older that there was a significant increase in mean surface MU action potential size, but the range of values was wide at all ages. For the thenar muscles, the single MU action potential size were significant larger (39%) in older subjects (age 68 $\pm$ 3 yr) compared to the young (Doherty, 1994). They also showed that in older subjects there was besides a significant increase in the mean single MU action potential size, a shift in the distribution towards greater numbers of larger single MU action potentials.

3.2.4. The Number of Motor Units

Subjects over 60 years of age had less than half the number of MUs in the thenar muscles when compared to the younger subjects. Also in the biceps brachii and brachialis muscles and the extensor digitorum brevis (thenar) muscle, age-related reductions in the number of MUs have been shown besides a significant increase in mean surface MU action potential sizes (Brown et al., 1988; Doherty et al., 1993b). MU loss in the thenar muscles seems to begin between the ages of 50 and 60 years (Booth et al., 1994; Brown et al., 1988; Doherty et al., 1993a).

As a result of the loss MUs, it is thought that some of the muscle fibers from the lost MU become reinnervated by the other remaining MUs. The reasoning for this inference is based upon:

1. The enlargement of MU size with aging.
2. Muscle fibers within a given area of the muscle becoming more homogeneous in fiber type (i.e., fiber type grouping).
3. The endplates in aged muscles are more complex (Booth et al., 1994, Brown, 1994; Doherty et al., 1993b; Dyck, 1994; Fielding, 1994).

Suggested is that the underlying mechanism is not only failure of nerves to reinnervate muscle fibers in the cycle of denervation/reinnervation, but also motor

neurons are degenerating. If muscle fibers are lost prior to the degeneration of spinal motor neurons, then the primary lesion may originate in the muscle fiber and/or neuromuscular junction. However, an accelerated loss of total muscle area and a decrease in muscle fiber number begins about 50 years of age, losses of MUs are present in men and women by the seventh decade. The aforementioned electrophysiological studies provide evidence for reinnervation, fiber grouping, and increases in MU size.

3.2.5. The Contractile Properties

The age-related reductions in MU number are accompanied by significant reductions in both maximum twitch and maximum voluntary contractile forces of the following muscles: thenar, biceps brachii, brachialis, and extensor digitorum brevis (Booth et al., 1994; Brooks et al., 1994; Brown, 1994; Doherty, 1993a; Howard et al., 1988; McComas, 1994). Thus, losses of MUs are accompanied with increases in sizes of both surface and intramuscular recorded MU action potentials and with larger twitch tensions in the remaining MUs. Additionally, prolonged MU contraction times (CTs) along with reductions in the threshold MU firing rate have been shown in the first dorsal interosseous muscle (Doherty, 1993a; Doherty et al., 1993b; Fielding, 1994).

MUs that generate larger MU action potentials not only generate larger twitch tensions but are recruited at higher thresholds in voluntary contractions as compared with MUs generating smaller-sized potentials and lower tensions (Brown et al., 1988). The increased MU action potential and the increased twitch tension in aged MUs may provide evidence for reinnervation of muscle fibers which increases MU size. Additionally, MUs exhibit significant prolonged CTs and one-half relaxation times ($\frac{1}{2}$RTs, i.e. recovery time from peak muscle twitch force to a value of one-half of the peak.) which is associated with the reduction in strength (Brown, 1994; Doherty, 1993a; Dyck, 1994). Consistent with these differences are the results of a number of studies that have reported decreases in MU firing rate with aging (Brown, 1994; Doherty, 1993a; Howard et al., 1988; McComas, 1994). These results are in agreement with the reported increases in CTs and $\frac{1}{2}$RTs in the aforementioned studies. Whether these reductions in firing rates represent an adaptation to the slower contractile speeds of elderly MUs or simply a reduced capacity of the central nervous system to drive motor neurons at higher firing rates is unknown.

3.3. Conclusions

Aging in human is associated with reduction in muscle mass (atrophy) and the loss of functioning motor neurons resulting in changes in muscle strength, muscle twitch, and size of the compound MU action potential. There are greater numbers of muscle fibers per MU, resulting in larger amplitude potentials and twitch tensions. The underlying cause is thought to be an ongoing denervation/reinnervation process that contributes to increase in the number of muscle fibers per recruited MU through axonal sprouting.

4. Longitudinal Studies

4.1. Introduction

All body movements are produced by contractions of skeletal muscles. Consequently, any impairment in the functional properties of skeletal muscles results in some degree of immobility. A loss of mobility inhibits participation in physical activities, as well as successful performance of the necessary activities of daily living. Clarification of the mechanisms responsible for the neuromuscular changes would enhance our understanding of the degree to which they are preventable or treatable.

A consequence of skeletal muscle atrophy with aging is the reduction in muscle strength. Muscle strength appears to be relatively well maintained up through 50 years of age. Muscle atrophy, declining strength, and physical frailty are generally accepted as inevitable concomitants of aging, however, the causes are not completely known. Physical frailty describes the summation of the effects of muscle atrophy, decline in muscle strength and power, fatigue, and injury. The degree to which these changes are preventable and treatable is not clear. Several research protocols are being developed to focus on the general area of frailty and physical independence. A prominent institute that is concerned with such protocols is the National Institute on Aging (NIA) in Baltimore. Within this institute the Baltimore Longitudinal Study of Aging (BLSA) provides the information about these age-associated characteristics.

4.2. The Baltimore Longitudinal Study of Aging

4.2.1. Introduction

The BLSA has the opportunity to investigate the role of biological factors and the natural history of development of age-associated changes in functional abilities that contribute to frailty in a group of volunteers. A study has been designed to examine the role of the peripheral nerve on age-associated loss of muscle strength

and the contribution of strength loss to physical independence and other health factors. The specific goal of the BLSA study is to explore gender and racial effects on age differences in neural control of muscle function, and to explore whether potential differences in neuromuscular function are associated with differences in physical activity or functional capability.

4.2.2. Study Protocol

At the neuromuscular level, the loss of muscle strength, muscle mass and muscle efficiency may be associated with age-related changes in the muscle, in the nervous innervation of the muscle, or with circulatory factors that are involved with muscle homeostasis. Early studies found that age differences occur in the distribution of fiber type, muscle metabolism, and secondary, in messenger function (primarily calcium regulation) with decreases in force generation, slower contractions and increased fatigability (Booth et al., 1994;Dyck, 1994; Fielding, 1994). On the other hand lower extremity muscles tend to show much greater loss of strength than those in the upper extremities with increasing age. Also exercise appears to reverse or prevent some of the changes that can be observed in the elderly. In addition, while the decreases in muscle mass, strength, and power may be related to decreased activity levels throughout the life time, maintenance of physical activity does not appear to protect skeletal muscles completely from these age-related decrements. Even trained world class athletes show similar trends and time courses of decline in structural and functional properties (Brooks et al., 1994; Brown, 1994; Fielding, 1994).

The relationships between physiological factors and age-associated loss of muscle strength by age, gender, and race, will be investigated by motor nerve and muscle contraction measurements. There are a few areas in which the BLSA is particularly interested:

- The relationship between upper and/or lower limb muscle contractions (e.g. biceps brachii, brachialis, quadriceps and hamstring) and their electrophysiological properties with aging.
- The relationship between agonist vs. antagonist muscle contractions and their electrophysiological properties in upper and lower extremities (e.g. biceps brachii, brachialis, quadriceps and hamstring) with aging.
- The relationship between thenar contraction properties and their electrophysiological properties with aging.

Upper and Lower Extremities Contraction Properties vs. Electrophysiological Properties with Aging

There is a particular interest in the upper and lower extremities contraction properties vs. their electrophysiological properties with aging. As stated before there is a dramatic change in the neuromuscular system at the age of 50. Upper and lower limb muscles are pre-eminently muscles to detect these changes because their decline with aging is much greater than the age-associated decline of other muscles, like abdominal and dorsal muscles. Longitudinal studies have been and are still performed to relate the contraction properties to the electrophysiological properties. In these studies voluntary contractions of interesting muscle groups are measured and detected using a strength measurement system, the KIN-COM System (section 5.3.2). Subjects between the age of 20 to 80 years are tested by relating their contractile properties to the electrophysiological properties which are measured and detected using an EMG detecting system, the Advantage EMG System (section 5.3.1). However, both systems use their own proprietary software to collect and process data. To obtain a better understanding in the relationship between the contractile and electrophysiological properties an integrated system with synchronized data collection is necessary.

Agonist vs. Antagonist Contraction and Electrophysiological Properties with Aging

A new area of interest concerning age-related decline of muscle control and strength is the relationship of agonist vs. antagonist muscle contraction properties and the electrophysiological properties. Muscle coactivation, the low-level activity of the antagonist muscle during the activity of the agonist has been studied by Solomonow and D'Ambriosa (1991). Most of the purposes of muscular coactivation, regulation of joint motion and control of joint stability, are well known, but the respective mechanisms that control motor unit recruitment in each muscle are still unknown. A deeper understanding of the control strategies when muscles work as agonist/antagonist unit could provide very useful applications in the fields of exercise physiology, physical therapy and physiatrics. Longitudinal studies can be performed to measure and detect contractile properties of for example the rectus femoris (quadriceps) vs. the semitendinosus (hamstring) during a isometric contraction in relation to their electrophysiological properties using the KIN-COM and Advantage EMG Systems. However, there is no system available for synchronized collection of data of muscle coactivation and their physiological

properties. These longitudinal studies require again an integrated system with synchronized data collection.

Thenar Contraction Properties vs. Electrophysiological Properties with Aging

Doherty et al. (1993), examined the decline of contractile and electrophysiological properties of thenar muscles with aging using the Multiple Point Stimulation method. This new method is described in section 5.3.1 and it uses electrodes to stimulate thenar MUs for studying the electrophysiological properties and estimating the numbers of thenar MUs and characterizes the extent to which thenar MUs are lost with aging.

The estimation of the number of MUs present in the muscle can be made by division of the maximum M-potential amplitude (i.e. the sum of all MU potentials generated by those motor axons excited by the stimulus) and the mean MU potential amplitude:

$$Motor\ Unit\ Estimation = \frac{Maximum\ M-potential\ Amplitude}{Mean\ Single\ MU\ potential\ Amplitude}$$

The mean single MU potential amplitude is obtained by collecting a sample of several single MU potentials and average the amplitudes of the single MU potentials. The single MU potentials are collected using the Multiple Point Stimulation technique (MPS). Multiple sites along the median nerve are stimulated to find different single MUs. Several assumptions underlying the MPS method combined with twitch tension measurements, include:

1. The ability to stimulate percutaneously one single MU, in an "all-or-nothing" manner, and to record the surface-detected single MU action potential from the muscle.

2. The sample of the first motor axons excited above threshold and the MUs they innervate, are representative of the relative numbers of single MU action potentials of different sizes within the muscle group studied.

3. Collecting 10 to 20 single MU action potentials is a sufficient large sample to accurately represent the whole population.

Doherty (1993a) provided evidence that these assumptions are correct.

Together with the stimulation of the different MU the abduction and/or flexion force produced by the different thenar MUs are measured using a thenar force measurement system developed by Ellen Olmer (Olmer, 1995) (section 5.3.3). With this system the amplitude and direction of the resultant force vector, consisting of abduction and flexion forces of thenar muscles, can be determined. However, no data-acquisition system was available for the detection of thenar muscle forces and an integrated system with synchronized data collection of the force and EMG signals is required.

4.2.3. Study Integration

The aforementioned proposed studies each require an integrated data-acquisition system with synchronized data collection of age-related characteristics. For each single characteristic measurement devices are already available. However, these measurements are not representative for the relationships of the age-related phenomena in real time. Moreover, the studies mentioned in section 4.2.2 all have the same goal, i.e. to achieve the relationship of contractile and electrophysiological properties with aging in real time. It may be clear that if such combined measurements are to be performed systematically, a system that is able to integrate acquisition of both types of signals is highly desirable. Therefore, the purpose of this study is to develop a system to measure these variables synchronous for the different proposed studies.

5. Development of SSDS

5.1. Introduction

Investigations of age-related changes in MU contractile and electrophysiological properties have been limited. Further study is required to provide a more thorough understanding of the underlying changes and adaptive capabilities of MUs in older adults. Additionally, it would be of great interest to relate the contractile properties of the MU to the electrophysiological properties of the MU and the whole muscle. Although, devices are available to examine contractile properties of human upper and lower limb muscles (biceps brachii, brachialis, quadriceps, hamstring and thenar muscles) and electrophysiological characteristics of the MUs (section 5.3), there is no device available to examine these phenomena synchronous in order to study the relation between these age-related variables. Therefore, the purpose of this study is to develop a device to be able to study the relationships between the interesting, synchronous obtained aforementioned age-associated variables.

To develop such a device some available measurement systems of contractile properties and electrophysiological characteristics of the MUs will be used. At first, some information on the different available measurement systems will be given. These systems will be connected to a separate data-acquisition system and a program will support this system to obtain the age-related neuromuscular signals with their characteristics. The system will be called Synchronous Signal Detection System (SSDS) and its applications will be discussed in section 5.3.7..

5.2. Purposes and Requirements of the SSDS

As described in section 4.2.1 through 4.2.3 there is a need for a system that can detect the aforementioned age-related variables of the different proposed studies in a synchronous manner. Therefore, a system should be developed that can serve the needs of the proposed studies. This data-acquisition system that will be able

to collect and process the signals of the various types of equipment (KIN-COM and Advantage EMG) should meet with the following requirements:

- The neuromuscular signals recorded have to be time-locked to guarantee that the force signals measured are indeed recorded at the same instance as the EMG signals are.
- The data-acquisition process should be fast enough to enable correct registration of the signals, i.e. data should be collected at a frequency high enough to include all relevant components of the signals.
- It should provide possibilities to amplify and filter recorded signals, because the recorded signals are often raw input signals.
- The data should be stored into files in an accessible way for further analysis.
- Derive age-related variables from the obtained signals, e.g. Peak-to-Peak amplitude, Negative Peak amplitude, Negative Peak Duration, Maximum Force, Average Force, Contraction Time and one-half Relaxation Time.
- Meet with the options of sophisticated neuromuscular measurement systems, such as system settings or data analysis options, to obtain a complete system.
- Present data readily to analyze.
- Data obtained should be comparable and realistic.
- Easy to use
- Low costs
- Good reliability
- Easy and fast calibration

5.3. The Development of SSDS

The proposed studies of the BLSA need force and EMG measurement systems. The force measurement systems are used to collect data of muscle contractions of the upper and lower limb muscles (the KIN-COM) and of thenar muscles (the Thumb-Force-Measurement system). The EMG measurement system (Advantage EMG) is used to collect data of muscle innervations of the upper and lower limb muscles and thenar muscles and is used to stimulate the thenar muscles. There are a few solutions to serve the needs of the different longitudinal studies in terms of modifying the software and/or hardware of the existing measurement systems. However, changing the hardware of the measurement systems might affect the safety aspects of the systems and changing the hardware and software, if at all possible, takes too long a time to accomplish this goal. Moreover, an integrated data-acquisition system still needs to be developed for the thenar neuromuscular signals. Therefore, the best solution would be to use a separate, third, computer to connect the different single outputs of the measurement systems with this computer. Use of this third computer would have the advantage that there is no need to reveal and change the inside of the Advantage EMG and KIN-COM hardware and software and that there is much more freedom for designing and adapting data-acquisition and analysis software according to the needs of the experimenters within the longitudinal studies.

Such a separate system would require, besides the already available force and EMG measurement systems, the use of a "standard" PC, e.g. a 486DX2 66MHz with 8 MB RAM, and a reasonably sized hard disk (500MB), and an ADC board with suitable development software, e.g. the AT-MIO-16 board with 12 bit resolution, 16 channel ADC with maximum 100kHz sampling frequency and options for programmable gain and sampling rates. To control the board, the computer language 'LabVIEW' can be used for easily developing data-acquisition and analysis schemes for data processing. Finally, a filtering and amplifying system is necessary to calibrate the different signals coming from the measurement systems. So, the complete integrated system will consist of the following components:

- A PC 486DX2 66MHz, 8MB RAM, 500MB hard disk.
- A 12 bit, 16 channel, AT-MIO-16 ADC Board
- The Advantage EMG System.
- The KIN-COM System.

- The Thumb-Force-Measurement System
- The Computer Language 'LabVIEW'
- A filtering and amplifying system

In the next sections the different components, as they are used in the study protocols, will be discussed.

5.3.1. The Advantage EMG System

The Advantage EMG System (Fig. 5.3), which is manufactured by the Clark Davis Medical Systems Inc. in London Ontario Canada, is a system which is used to detect and record electrophysiological signals such as single MU action potentials, M-potentials and MU number estimation. The Advantage can detect EMG signals of voluntary contractions or stimulated contractions using two different types of detecting electrodes:

1. needle or intra-muscular electrodes
2. surface or extra-muscular electrodes

This EMG system is specially designed to improve the accuracy of MU number estimation and is convenient to operate in a clinical environment. Its technical specifications are to be found in appendix A. Technical innovations incorporated into the Advantage EMG system enhance the EMG testing process (Advantage EMG system Operating Manual, Clark Davis Medical Systems Inc.):

- High graphic processing speed guarantees true real time waveform display, eliminating the need for an external analog monitor.
- Fast data-acquisition allows sampling rates up to 350 kHz.
- Continuous background signal monitoring and continuous screen readout of amplifier, stimulator, and list parameters are displayed on the same screen.

Motor Unit Decomposition

For the study 'Upper and Lower Extremities Contraction Properties vs. Electrophysiological Properties with Aging', a computerized decomposition method is used for obtaining single MU action potentials and MU number estimation. Because it is almost impossible for the subject to activate one single MU, several MUs are recorded in stead of one MU. Then the recorded interference pattern will be decomposed to get the single MU action potentials.

Motor Unit Decomposition is a technique which uses voluntary contraction to determine the sizes and shapes of surface detected MU potentials. The decomposition method will be used for the proximal muscles including the vastus medialis and biceps brachii. In this technique, voluntary MU recruitment is analyzed by the method based on spike-triggered averaging, with a needle electrode inserted in the muscle and used to identify corresponding surface MU action potentials.

First the maximum voluntary contraction (MVC) is determined using the KIN-COM system (section 5.3.2). The MVC refers to the condition in which a person or subject attempts to recruit as many muscle fibers as possible to develop maximum force, that is, maximum contraction. Then the maximum M-potential is determined by percutaneous stimulation of the nerve and detecting the signal with surface electrodes. This is necessary for the MU estimation. For this estimation, the peak-to-peak amplitude of the electrical response (M-potential) to muscle activation using surface electromyogram is examined and divided by the average peak-to-peak amplitude of the MU action potential analyzed.

The EMG measurements are recorded during an isometric contraction and the KIN-COM system will be used to control the constancy of force output. An isometric contraction is one where the muscle does not shorten or lengthen. Such a contraction can be either maximum or submaximum. The force is controlled by the subject, and is to be maintained within a 5% tolerance area of the target value. A concentric needle electrode (DMF 25 TECA) is placed into the body of the muscle and is used to detect the electrical potentials generated by those voluntary recruited MUs lying within the vicinity of the needle electrode. The surface electrode which also measures the MU action potentials is placed over the motor point and the ground electrode is placed near the recording electrode. The subject, sitting, will extend his/her leg for 30 seconds while the needle electrode and a surface electrode record the MU action potential of several MUs. The recording interference pattern is then decomposed by the computer program to identify specific MUs and their firing pattern. The expectations are that it is possible to decompose 5 to 10 MUs up to 10 to 30% of the MVC. If too many

MUs are recruited, it will be impossible to decompose the signal. The needle will be placed into several points of the muscle body to find up to 20 distinct MUs.

The Advantage EMG system has only two recording channels, which means that only two different electrodes can be used. As explained above, for the study 'Upper and Lower Extremities Contraction Properties vs. Electrophysiological Properties with Aging' the needle and surface electrodes are being used. However, for the study 'Agonist vs. Antagonist Contraction and Electrophysiological Properties with Aging' only two surface electrodes are being used, one for the agonist recordings and one for the antagonist recordings. So, for the latter study no decomposition programming can be used, because of the necessity of the needle electrode for this task.

Multiple Point Stimulation

For the study 'Thenar Contraction Properties vs. Electrophysiological Properties with Aging' a new technique is used to determine the mean single MU action potential amplitude in order to get the MU estimation. This method is called Multiple Point Stimulation (MPS) and it uses electrodes to stimulate thenar MUs by stimulating multiple sites along the median nerve.

Self-adhesive surface recording electrodes are cut into strips of 1.2 mm $\times$ 3.0 mm and used to detect thenar single MU action potentials. The "active" electrode is placed over the innervation zone with an inactive electrode on the muscle tendon. This zone is detected by stimulating the nerve to the muscle with electrical current, and moving the electrode around until a maximum recording is obtained. The ground is a metal plate fixed to the back of the hand.

A bipolar electrode (5 mm in diameter spaced 1.8 mm apart) stimulates the median nerve with low current and with the cathode distal. First, a maximum M-potential is elicited by gradually increasing the electric current (manually) during stimulation of the median nerve at the wrist, at 1 Hz. This will continue until the current is 20 % greater than the current which gives the maximum size and will then be reduced manually until it is just subthreshold.

To locate sites where a single motor axon can be excited, 0.05 to 1.0 ms duration pulses at intensities from 0 to 50 mA are applied at a frequency of 1 Hz to the median nerve. The stimulus intensity is increased to the level at which the first reproducible, "all-or-nothing" single MU action potential is detected. If it is impossible to detect a single, repeatable and clear "all-or-nothing" single MU action potential, free of alternation, the bipolar electrode will be moved.

The stimulation electrode is subsequently moved to points along the course of the median nerve between the thenar motor point and the distal forearm and between the elbow and the axilla, to detect single MU action potentials. In the latter sites, it is very important to avoid stimulation of the ulnar nerve as it supplies the finger and the hand muscles, which influences the single MU action potentials (Doherty, 1993a). Those single MU action potentials make no contribution to the maximum M-potential and should therefore be excluded in the sample of the single MU action potentials from which the thenar MU estimate is derived. At least 20 single MU action potentials of the thenar muscles will be identified for the estimation.

5.3.2. The KIN-COM System

The KIN-COM System (KIN-COM 125E Plus, Chattecx Corporation)(Fig. 5.3) is designed to provide the user with both assessment of muscle strength, as well as the tools of exercise training.

The KIN-COM (Operator's Manual, KIN-COM 125E Plus) provides:

- Comprehensive muscle testing capabilities in the concentric and eccentric spectrum.
- Multiple patient training capabilities: isokinetic, passive isometric, isotonic, and a protocol mode.
- Operating through screen touch technology.
- Visual feedback for both clinician and patient.

When working with subjects, in either a training or evaluation function, the operator monitors and controls the range of movement of the activity that is performed, the muscle tension the subject is to generate, and the speed of the movement.

The load cell measures the direction and the amount of force that is applied by the subject. The load cell can accurately measure from one Newton to 2000 Newton of force.

For the decomposition setup (study protocol 'Upper and Lower Extremities Contraction Properties vs. Electrophysiological Properties with Aging' and study protocol 'Agonist vs. Antagonist Contraction and Electrophysiological Properties with Aging', the EMG measurements are recorded 30 seconds during an isometric

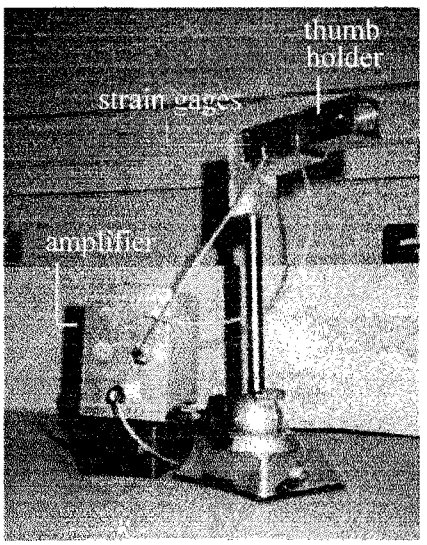

Figure 5.1: The Thumb-Force Measurement System.

contraction. The KIN-COM system measures the MVC, does not show the force vs. time, but digitally records the amount of force in real time. The system cannot measure the twitch tension of MUs because of the sensitivity that is required to detect forces of several milli Newtons.

For this study, it is desirable to use a system that can calculate and set the base line (for example 10% of the MVC), and the range within which the force has to be maintained. When the force falls outside this range, a buzzer or light will warn the operator and the subject. Also the force signal vs. time should be shown on one screen so the subject will know what time is left in order to maintain the isometric contraction.

5.3.3. The Thumb-Force-Measurement System

The TFM system (Fig. 5.1) is designed for the study 'Thenar Contraction Properties vs. Electrophysiological Properties with Aging' to measure the force and force direction of abduction and/or flexion produced by thenar muscles when human thenar single MUs are electrically stimulated by surface electrodes using the MPS method (section 5.3.1).

Median nerve stimulation can lead to abduction, adduction and flexion of the

thumb. It has been demonstrated by other researchers (Doherty, 1993a; Thomas et al., 1990a; Westling et al., 1990) that single MUs within the same muscle group, generate force in widely different directions. Thus regardless of the strain gages that are used to determine the thenar forces and their directions, the forces should be measured two-dimensional, otherwise the forces for many units must be reduced when measurements are made only in one direction.

Strain gages are devices used for the electrical measurement of mechanical quantities. They are used for the measurement of strain, tensile and compressive strain caused by forces, pressure, heat, structural changes of the material and so on. These parameters will change the resistance of the strain gages which will lead to a different output voltage.

An aluminum bar $1\frac{1}{4}$" square and $5\frac{1}{16}$" in length was formed to hold the thumb in position. When the median nerve is stimulated causing movement of the thumb, it will stress proportionally two sets of strain gages which are mounted on a milled surface which is designed to maximize the stress moment created by the thumb pressure moment. A round cup (59/64" diameter) was drilled at one end in which the thumb will be fixed.

Because of the small forces generated by thenar MU after stimulation (0-50mN), a small output voltage will be the result. Therefore, the output signal requires amplification before it is applied to a readout instrument. The chosen amplifier is the 2B31J Strain Gage conditioner with the AC1213 Edge Connector of Analog Devices (for more information: Olmer, 1995).

5.3.4. The ADC Board and the Connections

The main measurement systems for the proposed studies are discussed above. To get an integrated measurement system for synchronized recording of the different signals a data-acquisition (DAQ) board is necessary to which all the different signal outputs of the measurement systems are connected as analog inputs. There are 6 different analog inputs coming from the different measurement systems, i.e.:

- Two analog input channels coming from the two analog outputs of the Advantage EMG system. Because there are two input channels for the recording of EMG signals, there are also two analog outputs.
- Two analog input channels coming from the KIN-COM system, i.e. one input for positive and one input for negative forces.

- Two analog input channels coming from the TFM system, i.e. one input for the flexion forces (e.g. forces in the x-direction) and one input for the abduction forces (e.g. forces in the y-direction).

The signal outputs of the different measurement systems are connected to an AT-MIO-16 DAQ board. The AT-MIO-16 is a high performance, software-configurable 12-bit DAQ board for laboratory, test and measurement, and data acquisition and control applications. The board performs high-accuracy measurements with high-speed settling to 12 bits, noise as low as 0.1 LSBrms, and a typical DNL of ± 0.5 LSB (AT-MIO-16 User Manual, National Instruments Corporation). Because of its FIFOs and dual-channel DMA, the AT-MIO-16 can achieve high performance, even when used in environments that may have long interrupt latencies such as Windows (see appendix B for technical specifications).

A common problem with DAQ boards is that it cannot easily synchronize several measurement functions to a common trigger or timing event. The AT-MIO-16 has the Real-Time System Integration (RTSI) bus to solve this problem. The RTSI bus consists of a custom RTSI bus interface chip and a ribbon cable to route timing and trigger signals between several functions on one or DAQ in the PC.

The DAQ board is set to the differential mode (DIFF Configuration) with differential connections. Differential connections are those in which each AT-MIO-16 analog input signal has its own reference signal or signal return path. Each input signal is tied to the positive input of the instrumentation amplifier. The reference signal, or return, is tied to the negative input of the instrumentation amplifier. When the AT-MIO-16 is configured for DIFF input, each signal uses two of the multiplexer inputs, one for the signal and one for its reference signal. Therefore, only eight analog input channels are available when using the DIFF configuration. In this situation, channels 0 through 7 of the connector pin assignments (Fig. 5.2) are tied to the positive input of the instrumentation amplifier and channels 8 through 15 are tied to the negative input of the instrumentation amplifier.

The different analog inputs of the measurement systems are connected to the AT-MIO-16 I/O Connector Pin Assignment in the following way (Fig. 5.2):

- The ground signals of the KIN-COM, Advantage EMG and the TFM system are connected to channel AIGND, i.e. pins 1 and 2.

- The positive force signal coming from the backside of the KIN-COM PC is connected to channel ACH0, i.e. pin 3, whereas the negative force signal is

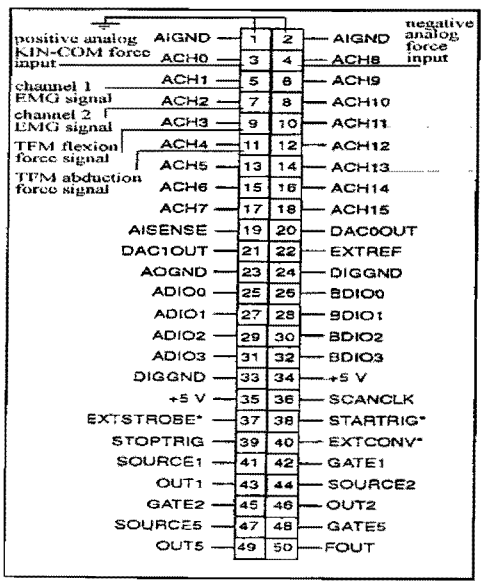

Figure 5.2: AT-MIO-16 I/O Connector Pin Assignments.

connected to channel ACH8, i.e. pin 4.

- The EMG signal coming from channel 1 on the Advantage EMG is connected to channel ACH1 of the DAQ board, i.e. pin 5, and the EMG signal coming from channel 2 on the Advantage EMG is connected to channel ACH2 of the DAQ board, i.e. pin 7.

- The flexion force signal coming from the TFM is connected to channel ACH3, i.e. pin 9, and the abduction force signal coming from the TFM is connected to channel ACH4, i.e. pin 11.

The DAQ board with its connections will be inserted into a PC from within which the DAQ board will be controlled. However, to get reliable signals the different signals need to be amplified and filtered for which an amplifying and filtering system has been used.

5.3.5. Amplifying and Filtering System

The output signals of the two channel inputs of the Advantage EMG system are adapted from within the system, which means that the signal outputs are fairly reliable for the real signal as they are presented on the display screen of the Advantage EMG system. Some minor modifications can be done using the programmable software to control the DAQ board.

However, the signals coming from the other two measurement systems, the KIN-COM and TFM system, are raw output signals of the systems. These signals need to be amplified and filtered to get signals which are reliable for the parameters that they present. Therefore, an amplifying and filtering system has been used to modify these raw signals. Because there was no sophisticated amplifier and filter available at the time, an ordinary home-made system has been used to modify the signals (Fig. 5.3). With this system the raw signals became rather reliable, but a straight forward calibration of the signals was not possible. A pre-amplifier (Type820) was set to 0.5 mV/mm and 0.02V/mm for the raw output signals of the KIN-COM and TFM system respectively with preamplified multipliers of 0.01 and 0.1. The filter was set to a High Frequency Response of 30Hz for the raw signal outputs of both the KIN-COM and TFM system. These settings showed fairly good results to test the complete system (section 6.2).

5.3.6. The Main Computer

The main computer will be used to control the complete system with its different measurement devices. A PC 486DX2 with 66MHz CPU speed and 8MB RAM and 500MB hard disk (Fig. 5.3) should be satisfying for this job. To this computer the different measurement devices, i.e. the Advantage EMG, the KIN-COM and the TFM, are connected by implementing the AT-MIO-16 DAQ board inside this computer. From within this computer the different study protocols will be started and with the use of the computer language 'LabVIEW' the data-acquisition and analysis will be controlled. 'LabVIEW' is the programmable software used to control the DAQ board and therefore the complete system. Because of the different studies to be performed a complete program has been written in 'LabVIEW' to operate on the integrated data-acquisition system (section 5.3.7). The complete integrated data-acquisition system as presented in this study with its different components is called the Synchronous Signal Detection System or SSDS (Fig. 5.3) and will be used in future studies for the detection of neuromuscular signals within the Baltimore Longitudinal Study of Aging of the National Institute on

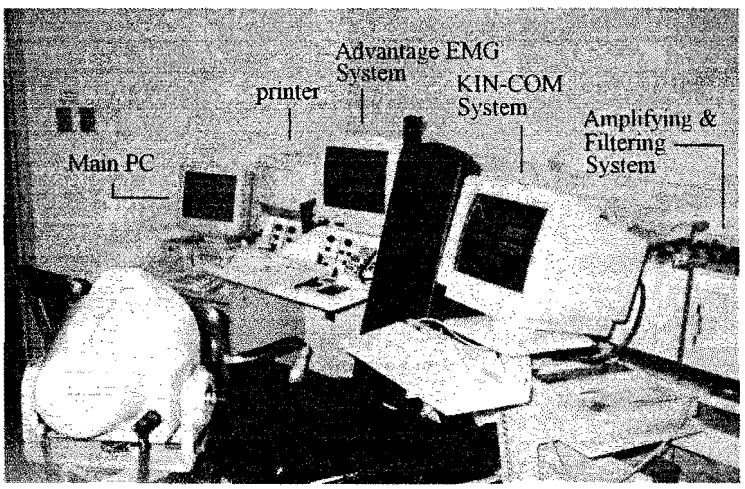

Figure 5.3: The SSDS with its different components: main PC, printer, Advantage EMG system, KIN-COM system, TFM system (not on picture) and the amplifying and filtering system.

Aging.

5.3.7. The Programming for the SSDS

As stated before, the programmable software package 'LabVIEW' has been used to control and operate the SSDS. The different study protocols are implemented within this programming. It consists of a Main Menu in which different options are available for performing different studies and neuromuscular signal analysis (Fig. 5.4). Each option represents a study protocol within which data will be recorded and analyzed. The next part will briefly discus the principal options.

KIN–COM Force Measurements

This option contains the study protocols of 'upper and lower extremities contraction properties vs. electrophysiological properties' and 'the agonist vs. antagonist contraction and electrophysiological properties' (Fig. 5.5).

The program starts with some general questions that have to be specified about the system settings of the measurement devices and the subject that is to

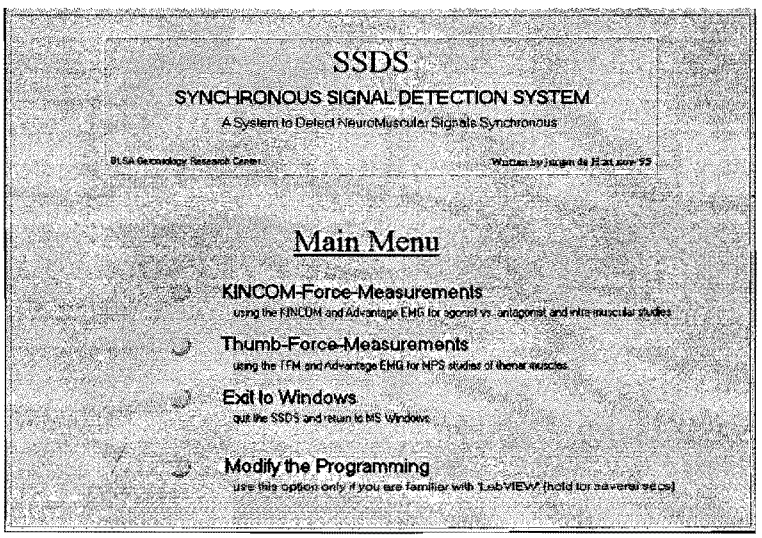

Figure 5.4: Main Menu of the SSDS with its different options.

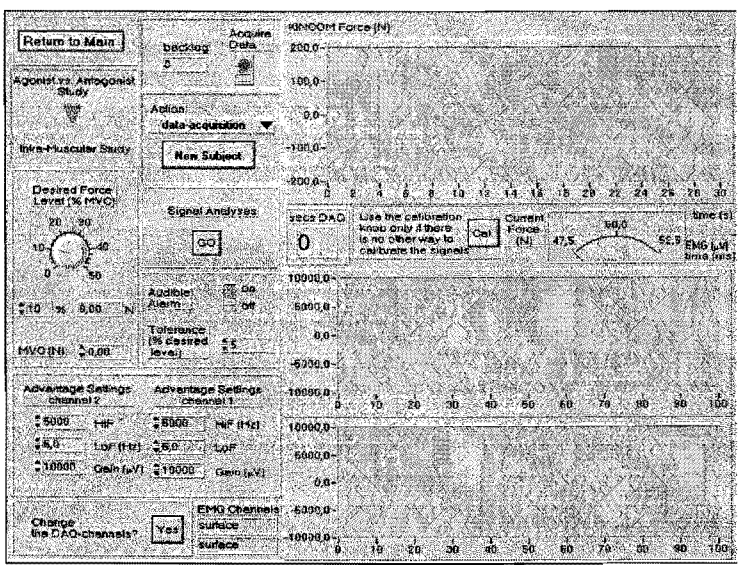

Figure 5.5: The KINCOM-Force Measurements menu.

be tested. The operator or clinician can choose between an intra-muscular study for the study protocol 'upper and lower extremities contraction properties vs. electrophysiological properties' or an agonist vs. antagonist study for the study protocol 'agonist vs. antagonist contraction and electrophysiological properties' by using the switch in the upper left corner (Fig. 5.5). The next task for the operator is to set the desired force level as a percentage of the MVC together with the tolerance level as a percentage of the desired force level. An audible alarm can be set to indicate that the subject exceeds the tolerance level. After all the different measurement devices are set, the operator can start acquiring data by pressing the 'Acquire Data' button. The recorded force will be seen in the KIN-COM Force Graph which is is a history waveform chart that records the last 30s of a contraction and stores the data in a 2-D array which will be used for further analyzes.

The EMG signals will be recorded by surface electrodes for the agonist vs. antagonist study and by surface and needle electrodes for the intra-muscular study (section 5.3.1). For the intra-muscular study the recordings of the surface electrodes (which are connected to channel 1 on the Advantage EMG) will be seen in the upper graph of the two EMG signal graphs and the recordings of the needle electrode (which is connected to channel 2 on the Advantage EMG) will be seen in the lower graph of the two EMG signal graphs. Both graphs are history waveform graphs and data of the last 30s will be stored and can be used for further analyzes.

Because of limitations of the system the operator will not be able to perform a decomposition analysis to detect the single MUs. The Advantage EMG system uses a sampling frequency of 20kHz to record the EMG signals, whereas, the SSDS uses a sampling frequency of 5kHz to record data. The sampling frequency can be modified with the programmable language, however, limitations of the RAM memory and CPU speed of the Main PC will result in a maximum sampling frequency of 5kHz. To analyze the EMG data a feed-back to the Advantage EMG system would be a solution. However, the data files coming from the SSDS must be converted into files that are accessible for the decomposition programming.

When the operators does an agonist vs. antagonist study the upper graph will plot the recordings of the surface electrodes which are detecting the EMG signals of the agonist muscle and are connected to channel 1 on the Advantage EMG, whereas, the lower graph will plot the recordings of the surface electrodes which are detecting the EMG signals of the antagonist muscle and are connected to channel 2 on the Advantage EMG. After the SSDS stops acquiring the data coming from the different input channels on the DAQ board by pressing the

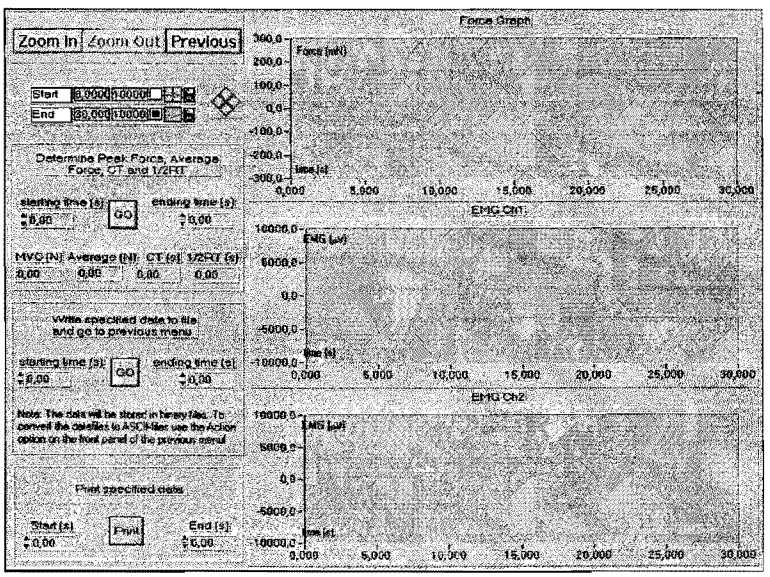

Figure 5.6: The Signal Analysis menu of the KINCOM-Force Measurements option.

'Acquire Data' button again, the recorded signals can be analyzed using the 'Signal Analysis' button (Fig. 5.6).

The 'Signal Analysis' menu contains the data of the last 30s of the force and EMG measurement devices. The upper graph displays the force recording during the test, whereas, the middle and lower graph display the EMG signal recorded by channel 1 and channel 2 respectively. The 'Signal Analysis' menu has the option to zoom in to view up to 50 ms. With this option the operator can get a better understanding in how the EMG signals behave when the muscle contracts. Especially for the agonist vs. antagonist study a better understanding can be obtained when the characteristics of the EMG signals are clear for up to 50 ms. An other option is to analyze typical force characteristics by determine the Peak Force, Average Force, CT and 1/2RT from the force graph for a specified area of the contraction time (Fig. 5.7).

The 'Determine Peak Force, Average Force, CT and 1/2RT' option contains a graph which displays the signal for the specified time interval entered in the previous menu (Fig. 5.6) and sets the cursors of the 'starting', 'ending' and 'maximum' contraction time automatically. If the cursors represent the wanted time periods

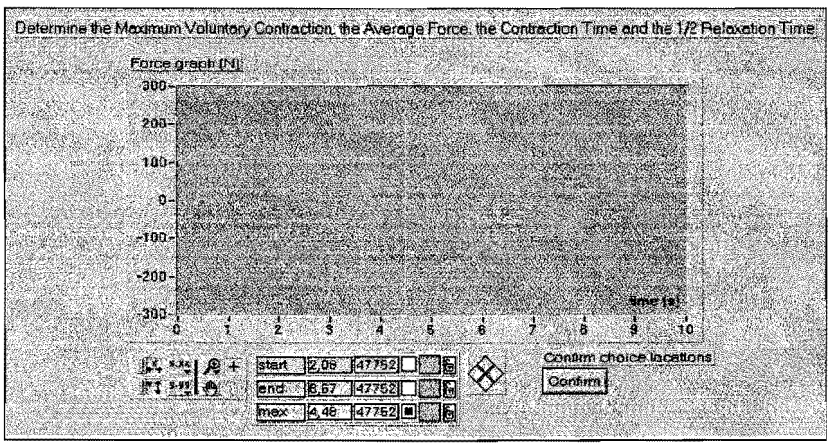

Figure 5.7: The "Determine the Peak Force, Average Force, CT and 1/2RT" menu.

the operator has to press the 'confirm' button and the force characteristics will be presented in the 'Signal Analysis' menu. For analysis of the EMG signals other software is suggested and therefore the data of a specified time interval will be saved in binary files which can be converted to ASCII files in the 'KIN-COM Force Measurements' menu (Fig. 5.5) by using the 'Action' option with the 'file management' button. Also a log-file will be created for every test that is performed which contains all the relevant information of the test.

Thumb-Force Measurements

This option contains the study protocol of 'Thenar Contraction Properties vs. Electrophysiological Properties with Aging' (Fig. 5.8).

The program starts with some general questions that have to be specified about the system settings of the measurement devices and the subject that is to be tested. The setup for performing the study is basically the same as for the 'KIN–COM Force Measurements'. In this study the thenar MUs will be stimulated using stimulating electrodes. This stimulation will result in a twitch contraction of thenar muscles for a time interval of several ms. The resultant twitch force will have a defined direction because of the mixture of flexion and abduction forces. These different forces will be displayed in the two graphs in the lower right corner.

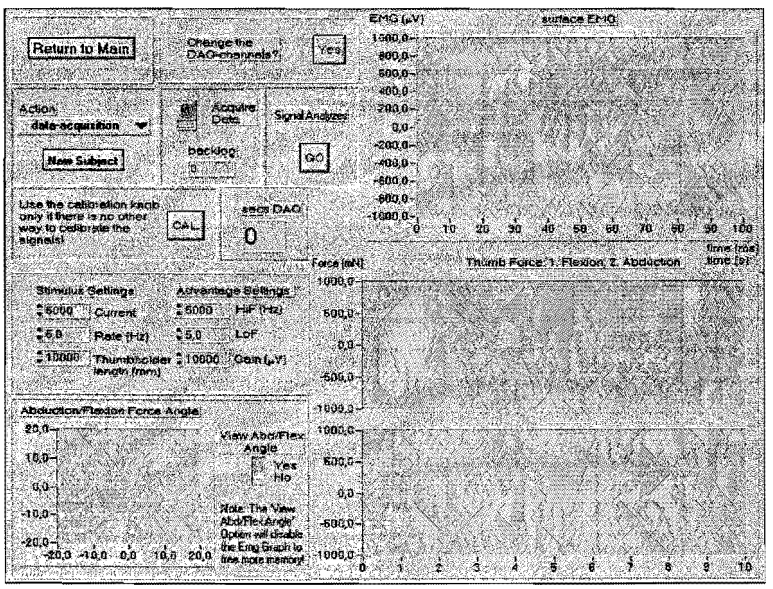

Figure 5.8: The Thumb-Force Measurements menu

These graphs are history waveform charts and the last 5s of the recorded data will be stored. The EMG signals will be detected by using surface electrodes and will be displayed in the surface EMG graph in the upper right corner which is a history waveform graph that also stores the last 5s of the recorded data for further analysis.

Because of the two different force directions (flexion and abduction) it might be convenient to view the abduction vs. flexion force graph by switching the 'View Abd/Flex Force Graph' knob to 'Yes'. Because of the RAM memory limitation on the Main PC, the surface EMG graph will be disabled to free more memory.

The recorded data can be analyzed in the 'Signal Analysis' menu (Fig. 5.9).This menu displays: 1 the resultant twitch force graph of the thenar muscle in the upper graph; 2 the recorded surface EMG signal in the middle graph; and 3 the abduction and flexion force of the thenar muscle in the lower graph. Because the contraction time is in the order of several ms (50 to 100ms) the operator can zoom in for a specified time interval to have a better look at the relevant force and EMG signals.

Again, some typical force signal characteristics can be determined for the spec-

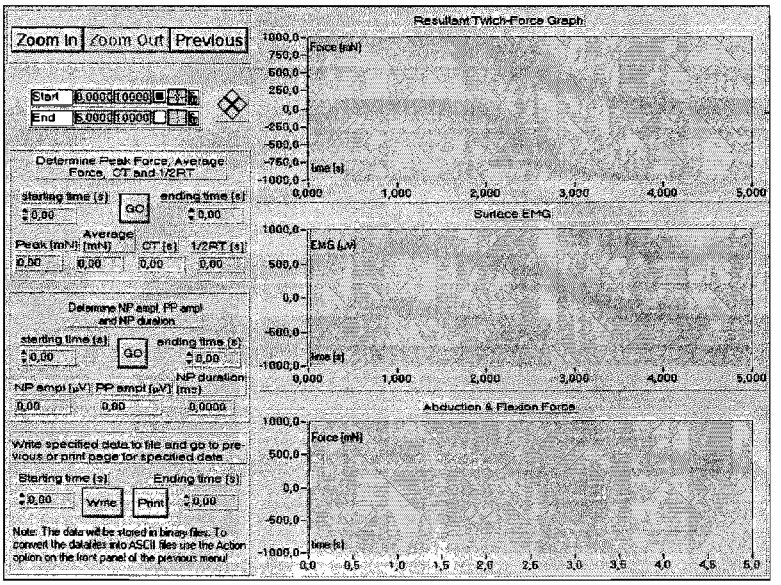

Figure 5.9: The Signal Analysis menu of the Thumb-Force Measurements option.

ified time interval by using the 'Determine Peak Force, Average Force, CT and 1/2RT' option. Moreover, because single MUs can be detected using the Multiple Point Stimulation technique to stimulate thenar MUs, some typical EMG signal characteristics can be determined for this time interval by using the 'Determine NP ampl, PP ampl and NP duration' option (Fig. 5.10).

The 'Determine NP ampl, PP ampl and NP duration' option contains a graph which displays the signal for the specified time interval entered in the previous menu (Fig. 5.9). Some EMG signal characteristics of the thenar MUs can be determined now, e.g. the negative peak amplitude, the negative peak duration and the peak to peak amplitude and therefore, the program will set cursors to interesting time points automatically, i.e. the ending time (back to base line), the time at which the EMG signal crosses the base line, the time at which the signal is a maximum and the time at which the signal is a minimum. If the cursors represent the wanted time periods the operator can press the confirm button and the EMG characteristics will be presented in the 'Signal Analysis' menu.

For future analysis, the different data can be written to binary or ASCII files for a specified time interval by using the 'write' option in the 'Signal Analysis'

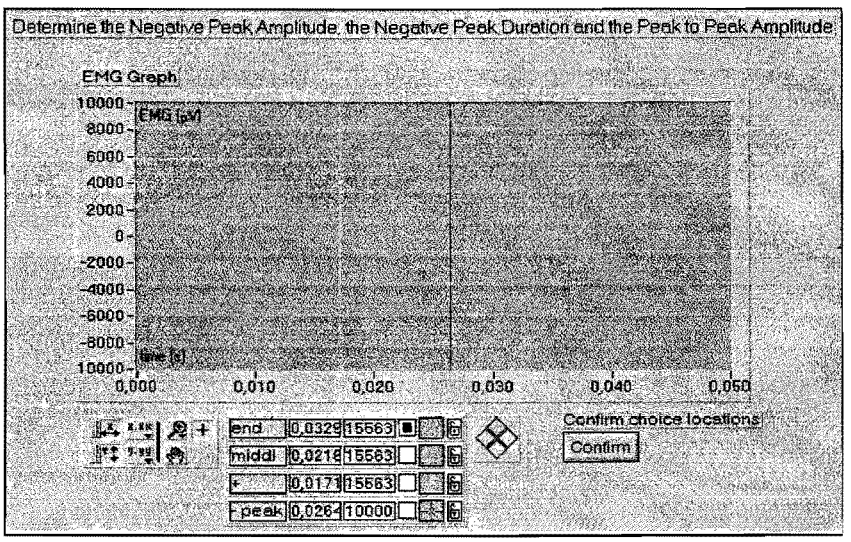

Figure 5.10: The 'Determine the Negative Peak Amplitude, the Negative Peak Duration and the Peak-to-Peak Amplitude' option.

menu. Also a log-file will be created for every test that is performed which contains all the relevant information of the test.

Modify the Programming

Although the SSDS has already the application to perform the different study protocols, the process of the development of the system is still in an early stage. A lot of modifications may have to be made in terms of changing the setup of the system for more or different studies to be performed or changes in the interests in other neuromuscular characteristics may occur. As a consequence, expanding of the programmable software might be unavoidable. Therefore, at this stage the SSDS programming has the option to be able to be modified by pressing the 'Modify the Programming' button (Fig. 5.4). This option will set the SSDS program in an editor mode from which further programming is possible.

6. EXPERIMENTS

6.1. Introduction

The development of the SSDS has been discussed in the previous chapter. The next task is to test the system. However, because of the limited time only a few tests have been done to look at the data recording and processing, and to look at the analysis of the recorded data. Validation of the system in terms of verifying the reliability of the recorded signals and possible calibration still need to be done. Therefore, the next section will only show some typical results obtained operating on the SSDS using the 'KIN-COM Force Measurements' option on the 'Main Menu'.

6.2. KIN-COM Force Measurements

A test has been performed to look at the data recording and processing of typical force and EMG signals. A subject was attached to the KIN-COM system whose extension and flexion of the right leg from a 78° bent knee starting position was being recorded for several seconds. The subject was also connected to the Advantage EMG system with surface and needle electrodes attached to the rectus femoris of the right leg. The data that have been acquired of this test using the SSDS are displayed on the main menu of the 'KIN-COM Force Measurements' menu (Fig. 6.1).

The upper graph displays the force signal coming from the KIN-COM system after amplifying and filtering. The extension starts after 65s and reaches its maximum at 69s, whereas the flexion of the leg starts at 78s and reaches its maximum at 83s. The horizontal line at 100N shows the 'Desired Force Level' as a percentage of the MVC with a bandwidth of 5% as the tolerance level. The vertical line is the time cursor which moves along the graph as data is acquired.

The two graphs below display the needle EMG and the surface EMG recordings respectively. This is a synchronized display of the two different electrodes. Note

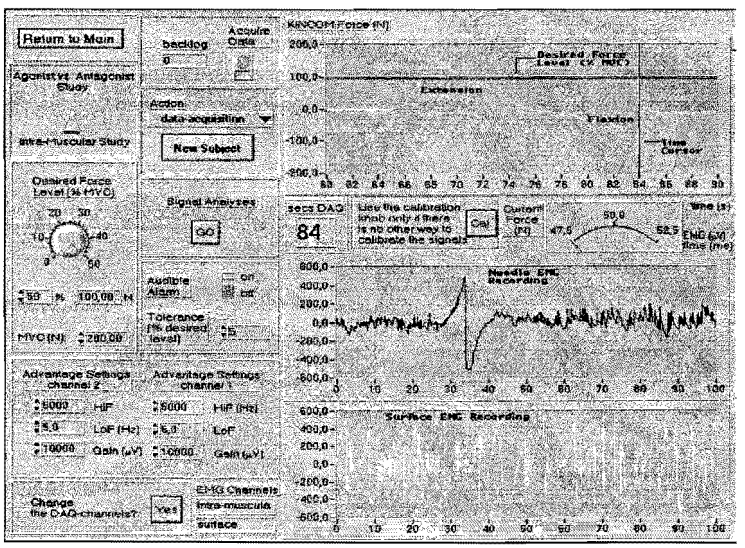

Figure 6.1: Data acquired with the SSDS during a test (see text for explanation). Note the different time scales of the Force and EMG graphs.

that in the needle EMG graph less activities can be observed than in the surface EMG graph as a result of the smaller pick-up area of the needle electrode (section 2.3.2).

The important advantage of the SSDS is that the different recorded signals can be viewed for the same specified time interval to get a better understanding of the relationship between the neuromuscular signals. Using the 'Signal Analysis' option will display the force and EMG signals (Fig. 6.2).

The three graphs initially show the last 30s of the force signal and the two EMG signals. Using the 'Zoom In' option to look at the time interval of 64s to 79s (new scale: 10s to 25s) the upper graph will show this part of the force signal (Fig. 6.2). The programming automatically will display the same time interval for the two EMG signals in the middle and lower graph. As can be seen in Figure 6.2 the needle EMG recording (middle graph) and surface EMG recording (lower graph) show some activities from time point of 11s (i.e. 65s on the original scale before the 'Zoom In' option was used), i.e. the time when the contraction starts. Moreover, the EMG activity decreases after time point of 21s (i.e. 75s on the original scale), i.e. the time when the contraction decreases until there is no

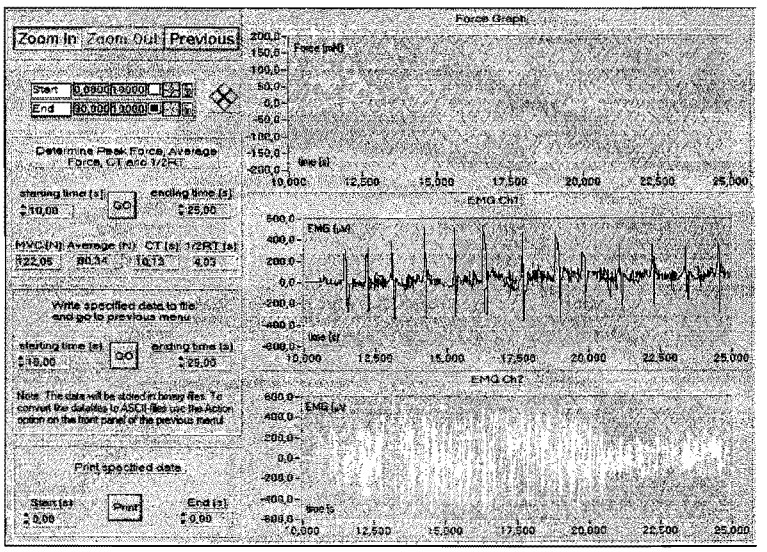

Figure 6.2: The acquired data ready to be analyzed with the 'Signal Analysis' option.

extension anymore.

Remark 1. *This test only shows how the SSDS operates within different neuromuscular studies, i.e. no clinical conclusion can be made from the results that are shown here.*

Another option on the 'Signal Analysis' menu is the 'Determine Peak Force, Average Force, CT and 1/2RT' option (Fig. 6.3). This option will calculate the force signal characteristics: 1 the Maximum Voluntary Contraction; 2 the Average Force; 3 Contraction Time; and 4 the one-half Relaxation Time. By entering a time interval in the previous menu for which these characteristics have to be determined, e.g. starting time is 10s and ending time is 25s, the graph will display the force signal and sets the 'start', 'end' and 'max' time cursors automatically. The operator has the option to change the positions of the cursor to a better position if the different time points are not clear enough. From these cursors the force characteristics will be determined and displayed in the previous menu after pressing the 'confirm choice location' knob.

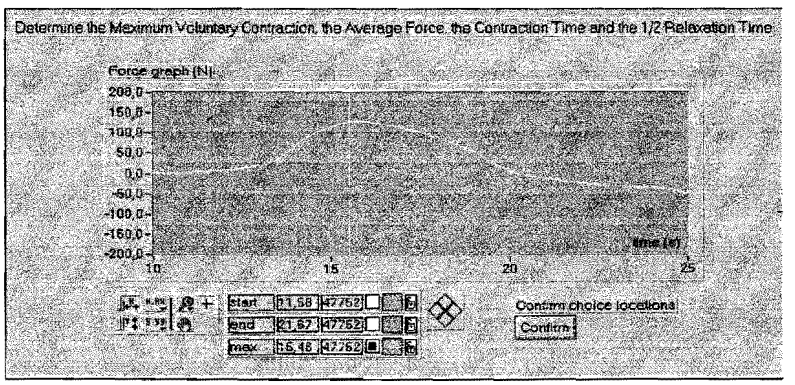

Figure 6.3: Determination of some force signal characteristics with the 'Determine Peak .....' option.

Beside the data processing and analyzing, the data can be stored into data files using the 'Write specified data to file and go to previous menu' option. The data will be stored in binary files and these files can be converted to more applicable ASCII files within the programming. Moreover, a log-file will be produced for any test that has been performed which contains information about the subject, operator, study point, type of test and time and date of the test.

6.3. Further Experiments

The SSDS has been able to meet the needs of this study, that is, different neuromuscular signals have been obtained in a synchronous manner. However, further experiments need to be done to test the complete system in terms of calibration and validation. At this time the development of a system like the SSDS is still in an early stage, yet, the main purpose of this study has been accomplished and therefore, some general conclusions and recommendations can be done to complete this study.

7. General Conclusions and Recommendations

7.1. Introduction

The causes of age-associated loss of muscle strength, muscle mass, and muscle efficiency are not completely known. At the neuromuscular level, the losses may be associated with age-related changes in the muscle, in the nervous innervation of the muscle, or with the circulatory factors that are involved with muscle homeostasis. Research in this area will give a better understanding of the neuromuscular changes and the aging process. This is important because a loss of mobility inhibits participation in physical activities, as well as successful performance of the necessary activities of the daily living.

Electrophysiological and contractile properties of human MUs in relation to aging, will be investigated in the BLSA. So far, this investigation was concerned with the measurement of individual neuromuscular signals, such as forces and EMG signals. However, an important relationship between these parameters seems to exist. Therefore, a new goal in the BLSA is to investigate this relationship between these parameters within the same muscle group.

7.2. General Conclusions

A system had to be developed which is able to record and process neuromuscular parameters synchronously in order to investigate their relationship between each other. From this system a few conclusions can be made:

1. The more appropriate way to develop a system for synchronized detection of neuromuscular signals is the use of a data-acquisition board implemented within a separate computer.

2. Some typical neuromuscular tests can be performed with the SSDS.

3. The system needs to be calibrated.

4. Further development is required to obtain a more sophisticated system to serve the needs of future neuromuscular studies, e.g. the possibility to decompose EMG signals to achieve single MUs.

Measurement systems to record neuromuscular signals are already available, however, these different devices are individual systems and therefore, it is hard to understand the relationship between the parameters that the different systems measure. Changing the hardware and software of these systems to be able to connect the systems together and get a synchronized detected signals is a solution to this problem. However, changing the hardware and software of these devices, if at all possible, might take a long time, but most of all the safety aspects of the devices can be affected. The use of a third computer is a better solution to this problem, because none of the aforementioned changes have to be made and one of the measurement devices (the TFM) still needed a data recording and processing device.

Using a data-acquisition board with programmable software to develop data processing schemes made it possible to do some typical neuromuscular tests synchronously as have been done before individually. A few tests have been done to look at the data recording, processing and analysis. These tests showed good results in terms of the synchronized detection of the neuromuscular signals and the analysis of these parameters, but no clinical conclusion can be made out of these tests, because the system needs to be calibrated.

However, a system has been developed which synchronized can detect neuromuscular signals and process the data for further analysis. This system is called the Synchronous Signal Detection System, or SSDS, and is a first step in the investigation to the relationship between neuromuscular signals with aging within the Baltimore Longitudinal Study of Aging. For more sophisticated properties, like for example deriving single MUs from surface EMG recordings as is done using the Advantage EMG system with the Decomposition programming, further development is required.

7.3. Recommendations

A few recommendations can be made concerning the SSDS with the investigation to the relationship between neuromuscular signals:

1. Expansion of the RAM memory and a higher CPU speed of the DAQ PC is highly recommendable to perform more sophisticated tests or,

2. Further development of synchronized detection software on the Advantage EMG might give good prospects.

3. Modify the SSDS software to be able to do more different studies within the BLSA.

4. Some basic artifacts of the TFM still need to be eliminated.

5. The use of better isolated connections between the different measurement devices will give better results.

6. The SSDS needs to be calibrated and results must be compared to results of other test devices for the same purposes and literature.

At this stage the system from which the whole data-acquisition is controlled is a 486DX2 66MHz 8MB PC with a 500MB hard disk. Using 'LabVIEW' as the programmable software to control the data-acquisition, the maximum sampling frequency to record data with a data storage of at least 30s for the 'KIN-COM Force Measurement' option and at least 5s. for the 'Thumb-Force Measurement' option is 1kHz and 5kHz respectively. For the 'Thumb-Force Measurement' option this means that good signals are obtained for a time interval of 50ms, which is fairly enough for this study. However, for the 'KIN-COM Force Measurement' option good signals are obtained for a time interval of 200ms, which might not be satisfying to look at signal MU potentials. Moreover, to be able to derive the number of MU and/or single MU action potentials from the interference pattern of surface EMG recordings and needle EMG recordings a sampling frequency of at least 20kHz is necessary as is used in the Decomposition Programming of the Advantage EMG system. So, a more powerful main PC might be the solution to this problem or the use of the synchronized recording software which has been installed on the Advantage EMG system, but has not been appropriate enough for being used.

To be able to do more signal analysis within the SSDS further programming is required. Although, some basic analysis of the different neuromuscular signals is possible with the SSDS (e.g. determine the peak force, average force, contraction and relaxation time, negative peak amplitude, peak-to-peak amplitude and negative peak area) more analysis might be necessary to get a better understanding

between the relationship of the force and EMG signals with aging. For example, the use of Fourier techniques might be very helpful in doing so. Although, a special analysis package, including Fourier Analysis, of 'LabVIEW' exists, there was none available developing the SSDS.

The KIN-COM and Advantage EMG systems are sophisticated measurement devices for neuromuscular signals. On the other hand, the TFM system is still in an early stage of development. Some basic artifacts are still present in this measurement device (Olmer, 1995).

The connections to the DAQ board of the different signal outputs of the measurement devices are not very solid yet. A plug-in/plug-out connection system would help a lot in connecting the measurement devices to the different analog input channels on the DAQ board. Moreover, the system and environmental noise need to be reduced as much as possible before the complete SSDS will be calibrated. With this calibration the test results of some basic signals will be compared to test results obtained under the same condition using the individual measurement devices. However, the test results of the SSDS using the TFM can not be compared to test results of the TFM under the same conditions, because the TFM system itself has to be calibrated. So, for the studies with the TFM measurement device the test results will be compared with reliable results obtained from literature.

Although a lot needs to be done to be able to operate on the SSDS and get reliable results of neuromuscular testing, the development of the SSDS has given good prospects to the development of a device to obtain knowledge and understanding about age-related changes in neuromuscular performance. However, many investigations still need to be done to get a more thorough understanding of the relationship between these age-related parameters.

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Appendices

A. Technical Specifications: Advantage EMG system

B. Technical Specifications: AT-MIO-16 DAQ Board

A. Technical Specifications: Advantage EMG system

Amplifiers

Input Impedance:	>200 Mohms/25 pF
Sensitivity:	2 μV/div to 10 mV/div in 12 steps
High Frequency Filter:	100 Hz to 15 kHz in 8 steps, 12 dB/octave
Low Frequency Filter:	0.5 Hz to 500 Hz in 8 steps, 6 dB/octave
Notch Filter:	>30 dB down at 60 Hz
CMRR:	>100 dB at 60 Hz
Noise:	<1 μV rms from 2 Hz - 10 kHz with input shorted
Calibration:	100 Hz squarewave, 2 μV/div to 10 mV/div in 12 steps
Electrode Impedance Check:	1 - 500 kΩ
Temperature Measurement:	20.0 °C - 40.0 °C

Stimulators

Stimulus Output:	Constant Current output to 100 mA adjustable in three ranges
Stimulus Duration:	0.05 to 1 msec in 5 steps
Repetition Rate:	0.1 - 100 Hz including Single Shot mode
Patient Protection:	overcurrent, overduration, and overfrequency, with automatic shutdown
Stimulus Monitor:	Seperate LED bargraph and monitor readouts

Display

Display CRT:	16-inch diagonal anti-glare screen
Digital Resolution:	1280 × 1024 pixels non-interlaced
Number of Colors:	4096 available
Graphic Display Controller :	50 MHz TMS 34010, 32 bit processor with graphics accelerator allowing advanced windowing capabilities
Vector Drawing Rate:	100,000 vectors/sec allowing true real-time display
Display Memory:	2.5 Mbyte

Data Acquisition

Resolution:	12 bit
Maximum Sampling Rate:	350 kHz throughput to memory
Acquisition Memory:	128 kbyte dual port ram
Delay Line:	4-channel hardware delay continuously selectable from 0 to 10 divisions
Signal Trigger:	Level or Window discriminator controlled
Time Base:	1 msec to 100 sec full sweep

System Architecture

Central Processor:	80386 25 MHz 32-bit processor
System Memory:	5.0 Mbyte
Mass Storage:	85 Mbyte hard disk and 1.4 Mbyte 3 1/2-inch floppy disk drive
Hardcopy Device:	Laserjet printer with 300 dots/inch resolution
Interfaces:	Parallel printer port and RS-232
Keyboard Entry:	Enhanced AT-style keyboard

General

Dimensions:	53" × 30" × 30"
Weight:	250 lbs (Approx.)
Power Supply:	110/220 VAC 50/60 Hz with shielded isolation transformer
Power Consumption:	500 VA (Approx.)
Patient Safety:	Complies with CSA 22.2 No.125 and UL 544 standards

B. Technical Specifications: AT-MIO-16 DAQ Board

Input Characteristics

Number of Channels: 16 single-ended or 8 differential, jumper-selectable
Type of ADC: Sampling, successive approximation
Resolution: 12 bits, 1 in 4,096
Max Sampling Rate: 100 kS/s
Input Signal Ranges:

Board Gain (Software Selectable)	Board Range (Jumper Selectable)		
	±10 V	±5 V	0 to 10 V
1	±10 V	±5 V	0 to 10 V
2	±5 V	±2.5 V	0 to 5 V
3	±2.5 V	±1.25 V	0 to 2.5 V
4	±1.25 V	±0.63 V	0 to 1.25 V

Input Coupling: DC
Max Working Voltage: Each input should remain within 12 V of AIGND
Overvoltage Protection: ±35 V powered on, ±20 V powered off
Inputs Protected: ACH <0..15>
FIFO Buffer Size: 16 samples
Data Transfers: DMA, interrupts, programmed I/O
DMA modes: Demand

Transfer Characteristics

Relative Accuracy:	±0.9 LSB typical, ±1.5 LSB max
DNL:	±0.50 LSB typical, ±0.95 LSB max
No Missing Codes:	12 bits, guaranteed
Offset Error	
Pregain error after calibration:	±2.44 μV (-L board)
Pregain error before calibration:	±153 μV (-H board)
Postgain error after calibration:	±1.22 mV max
Postgain error before calibration:	±85 V max
Gain Error (relative to calibration ref.)	
After calibration:	0.0244% of reading (244 ppm) max
Before calibration:	0.85% of reading (8,500 ppm) max
Gain $\neq$ 1with gain error adjusted to 0 at gain = 1	0.02% of reading (200 ppm) max

Amplifier Characteristics

Input Impedance:	1 GΩ in parallel with 50 pF
Input Bias Current:	±25 nA
Input Offset Current:	±15 nA
CMRR:	

Gain	CMRR DC to 100 Hz
1	75 dB
10	95 dB
100	105 dB

Dynamic Characteristics

Bandwidth

Small Signal (-3 dB): 650 kHz @ gain = 1

System Noise :

(including quantization error)

Gain	20 V Range	10 V Range
$\leq$10	0.10 LSBrms	0.20 LSBrms
100	0.15 LSBrms	0.20 LSBrms
500	0.30 LSBrms	0.40 LSBrms

Slew Rate: 5.0 V/μs