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Wientjes, R.

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Eindhoven University of Technology
Department of Electrical Engineering
Signal Processing Systems

TU/e technische
universiteit
eindhoven

SEIN

Stichting Epilepsie Instellingen Nederland

Potential value of surface electromyography for automated epileptic seizure detection for children in a home monitoring system

by Rens Wientjes

Summary

In this project the potential value of surface electromyography (EMG) for the automatic detection of nocturnal seizures of children with epilepsy in a home monitoring system is explored.

Children with untreatable epilepsy who frequently suffer severe epileptic seizures have to be monitored during night time. In a home situation this is often not possible. This often leads to institutionalization of the patient in a specialized epilepsy clinic or undesirable heavy burden to the parents because of the continuous need for monitoring their child. Monitoring the child with the help of an automatic seizure detection system from a remote location during night time could provide a solution.

In this project we will examine the potential value of surface EMG for the detection of, epileptic seizure related, muscle contractions. A distinction will be made between short lasting activity (clonic contractions) and longer lasting activity (tonic contraction). The use of simple signal processing (average rectified value, Gabor band pass filtering and wavelet analyses) and threshold detection will be examined to detect these muscle activities.

The properties of muscle activity during epileptic seizures will be examined to come to a detection proposal. The detection proposal for the detection of tonic muscle contractions will be examined by using three recorded nights of real data from three different patients. For the clonic muscle contraction a proposal is presented to detect the repetitive occurrence of these muscle contractions.

For the detection of tonic muscle contraction a sensitivity of 75% with a positive predictive value of 42% is achieved. For the detection of repetitive occurrence of clonic muscle contraction a proposal is presented but is not implemented or analysed in a quantitative manner.

Although the initial target for the performance of the automated detection of seizure related muscle contractions was set higher than the achieved performance we still believe that muscle activity detected by the use of surface EMG can provide useful information about the presence of potential dangerous seizures for the patients. Further research groups can possible use the proposed detection algorithms as building blocks for more advanced automated seizure detection systems.

Samenvatting

In dit project met de titel "Mogelijke waarde van oppervlakte elektromyografie voor automatische epileptische aanvalsdetectie voor kinderen in een thuis monitoring systeem" wordt onderzocht of nachtelijke epileptische aanvallen bij kinderen automatisch te detecteren zijn aan de hand van oppervlakte elektromyografie (EMG).

Kinderen met epilepsie die ondanks hun behandeling toch frequent nachtelijke aanvallen doormaken vragen 's nachts extra zorg. In een thuissituatie is dat vaak niet goed mogelijk. Dit leidt vaak tot opname in een gespecialiseerde epilepsie kliniek of een ongewenste thuis situatie. Als deze kinderen 's nachts op afstand in de thuis situatie met behulp van automatische aanvalsdetectie bewaakt kunnen worden zou dat een oplossing kunnen bieden.

In dit onderzoek wordt gekeken naar de mogelijke waarde van oppervlakte EMG bij het detecteren van, aan epileptische aanvallen gerelateerde, spiertrekkingen. Daarbij wordt onderscheid gemaakt tussen kortdurende trekkingen (clonieën) en langdurige trekkingen (tonische activiteit). Onderzocht wordt of met behulp van simpele signaalanalyse (gemiddelde gelijkgerichte waarde, energie in een spectrale band middels een Gabor filter en wavelet analyse) en een drempel, deze spieractiviteit te detecteren is.

De eigenschappen van spieractiviteit gedurende epileptische aanvallen worden onderzocht. Aan de hand hiervan worden detectie voorstellen uitgewerkt. Het detectie voorstel voor het detecteren van tonische spieractiviteit wordt geëvalueerd met behulp van data verkregen van drie patiënten gedurende één nacht per patiënt. Voor de detectie van clonische spieractiviteit word een voorstel gedaan om het herhaald optreden van deze activiteit te detecteren.

Van de tonische spieractiviteit was 75% detecteerbaar, daarbij is 58% van de detecties vals positief. Voor clonische spieractiviteit is een detectie voorstel gepresenteerd maar niet geïmplementeerd.

Hoewel de prestaties voor de detectie van tonische spieractiviteit lager is dan van tevoren als doel gesteld is, zijn wij toch van mening dat middels oppervlakte EMG gedetecteerde spieractiviteit informatie kan verschaffen over de aanwezigheid van, voor de patiënt mogelijk, gevaarlijke aanvallen. Vervolg onderzoek kan de voorgestelde detectie algoritmen gebruiken als bouwstenen voor een automatisch aanvalsdetectie-systeem.

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1 Introduction

Epilepsy is a disorder that expresses itself in seizures that temporarily impair brain function. Epilepsy affects almost 60 million people worldwide [46]. Approximately 0.5 – 1 percent of the Dutch population is diagnosed to have epilepsy [17]. Epilepsy is a name for a collection of various types of seizures and many syndromes. A correct classification is important for decision making for additional research, in starting with medication, therapy choice and for support of the patient [17]. Having epilepsy implies that patients suffer from seizures that may manifest themselves by a broad complex of possible symptoms. For a majority of patients this includes abnormal muscle activity and/or mental absence. The diagnosis of epilepsy is made by proper observations of the symptoms (seizures). Seizures, especially the beginning or onset of the seizures, are often missed. Detection of seizures can be valuable in observation for diagnosis, treatment and long term monitoring. In case of risk for suffocation or physical harm detection of seizures can be necessary for the safety of the patient [42].

Most of the patients (67%) can be treated with medication to get completely free of seizures, a small group (7-8%) is potentially curable with surgery. For approximately 25% of the patients the risk of unexpected seizures remains, even when the patients are stabilized by treatment [46]. Seizure detection will help to improve the quality of life of these patients. A major part of the 25% of epilepsy patients with untreatable seizures needs permanent monitoring because of the dangerous side effects of a seizure.

Children with epilepsy are preferred to stay at home with their family to grow up as normal as possible. During day time the detection of seizures can be done by their caregivers. During night time the risk of seizures is a problem that can lead to institutionalization of the patient or undesirable heavy burden to the parents because of the continuous need for monitoring their child.

The golden standard for detecting seizures for diagnostic purposes is recording electroencephalographic (EEG) signals in combination with video monitoring. This procedure, however, can only be applied in a specialized clinical setting and is not appropriate for long-term clinical and/or home monitoring. Consequently, other detection parameters and/or sources of information will have to be found for reliable seizure detection.

1.1 Objective for this thesis

The project "Seizure detection in epilepsy care" of the "Technische Universiteit Eindhoven" focuses on the development of multimodal signal processing strategies for automated seizure detection in the three major care settings: diagnostics, clinical monitoring and home monitoring. The objective is to improve efficiency and quality of the care and wellness of all epilepsy patients. Qualitatively, a detection performance is pursued of 90% sensitivity with a maximum false alarm rate of 50% in all types of seizures, even in the most difficult patients with severely deviating behavioural and physiological characteristics.

A bottom-up strategy is proposed in which first the potential of uni-modal (electromyography (EMG), accelerometry (ACM), electrocardiography (ECG) etc.) based

signal processing and classification strategies are investigated and, in the second phase, the sensitivity and/or false alarm rate, are optimized by introducing multimodal signal processing and/or classification strategies.

This project will focus on the seizure detection for home monitoring of children. The modality Surface Electromyography (SEMG) is selected as part of the multimodal signal processing strategy. This modality will be evaluated for its possible value as source for seizure detection.

Automatic seizure detection is not a new field of research. There have been several attempts in the past 30 years. Most projects focus on just one modality. This resulted in poor sensitivity and poor positive prediction values. Some commercially available systems detect less than 20% of the seizures but with 55% positive prediction value (e.g. KNOP 2000) [16]. Other systems accomplish a sensitivity of 30 % with a false alarm rate over the 95% (e.g. sound threshold) [35]. To our knowledge, no research has been published to date about automatic seizure detection based on EMG. The target of the project "Seizure detection in epilepsy care" of the "Technische Universiteit Eindhoven" is to help reduce the amount of missed seizures and false alarms by combining more than one modality.

1.2 Introduction about SEIN

Stichting Epilepsie Instellingen Nederland (SEIN) is a specialized tertiary epilepsy clinic. In the two clinics the main mission is tertiary diagnostics, care and cure for epilepsy patients. The clinic in Heemstede exists already for 125 years; the clinic in Zwolle since 1999. At both locations all facilities are present for optimal in- and out patient care. As extension from these facilities, SEIN has 10 out-patient clinics in all major cities in the Northern half of the Netherlands which makes SEIN the leading tertiary epilepsy facility for approximately 9 million people. The clinic in Heemstede has a long-stay facility for several hundreds of patients. A similar department will be opened in Zwolle in 1 year. Since the end of 2004 the clinic in Zwolle has a specialized sleep disorder department as well. Research in the various fields in epilepsy and in sleep is an important part of the mission of SEIN. Its content ranges from basic research to clinically oriented studies.

The current project will be carried out at the clinic in Zwolle with technical support from Heemstede. The subjects that are used for this project are selected from the normal patient population that where in our clinic for long term EEG and video monitoring.

1.3 Content of this thesis

First we will focus on the definition of epilepsy, seizure types and monitoring in chapter 2. In chapter 3 an overview is given about other automated detection programs. In chapter 4 we will discuss surface EMG and recording issues. In chapter 5 the current use of surface EMG in epilepsy and the potential value for automated seizure detection is described. In chapter 6 we will introduce the patient selection and methods used for this project. In chapter 7 we will make a detection proposal, followed by chapter 8 which focus on detection of tonic muscle contractions and chapter 9 which focus on the detection of clonic events. In chapter 10 the results will be discussed in the conclusion.

2 Epilepsy and monitoring of patients

In this chapter some backgrounds on epilepsy are presented. First a global overview of the disease is given. Then seizure classification and epileptic syndromes and their occurrence in different age groups are discussed. The increased risks for harmful situations for patients with epilepsy are explained to give an idea why automatic seizure detection can be valuable. At the end of this chapter we will discuss the properties of the automatic seizure detection system we will focus on in this thesis.

2.1 What is epilepsy?

Epilepsy may be caused by a variety of pathologic processes in the brain. It is characterised by occasional (paroxysmal), excessive and disorderly discharging of neurons. Neurons (nerve cells) are electrically excitable cells in the nervous system that process and transmit information. In vertebrate animals, neurons are the core components of the brain, spinal cord and peripheral nerves. The abnormal electrical activity during an epileptic seizure can be detected by the clinical manifestations and by electroencephalographic (EEG) recording. Paroxysmal discharges of neurons occur when the threshold to prevent spontaneous firing of the neuronal membranes is disturbed. The source of this attack can be localised and may remain restricted to its focus or can spread to other areas of the brain. When the size of the discharging area is sufficiently large, a clinical seizure occurs. This can be measured by EEG with electrodes on the scalp and appears as spikes, slow waves and spike-wave potential fluctuations. The specific site of the brain affected determines the clinical expression of the seizure [3].

2.2 Seizures

The period during which the seizure occurs is called the ictal period. Some patients experience a preliminary sign of an upcoming seizure, it is called an aura. This aura is often the only part of seizure that is remembered by the patient. It can be used as warning signal. The time immediately after a seizure is called the postictal period.[3]. Epilepsy is characterized by recurrent epileptic seizures. The seizures in epilepsy may be related to brain injuries or inheritance, but most of the time the cause is unknown [4].

2.3 Types of epileptic seizures and types of epilepsy: classifications

Epilepsy can be classified according to types of epilepsies and to type of epileptic seizures.

Types of epilepsy fall apart into two broad categories: generalized and localization related epilepsies and a third not classified group. In generalized epilepsies, the most frequent type of seizures begins simultaneously in both cerebral hemispheres. In partial epilepsies, seizures originate in one or more localized foci, although they can spread to involve the whole brain [4]. These categories contain epileptic syndromes and will be described below.

2.3.1 Classification of epilepsies and epilepsy syndromes

The International Classification of Epilepsies [7, 8] begins by dividing epilepsies according to overall seizure type: generalized or localization-related. Generalized epilepsies involve

seizures with initial activation of neurons in both cerebral hemispheres. Localization-related epilepsies involve seizures with initial activation of a group of neurons within one hemisphere. The next step is to divide epilepsies according to etiology: idiopathic (arising spontaneously from an unknown cause) or symptomatic (arising of symptoms of a known brain abnormality). Based on these categories, the epilepsies are divided into six groups. (see Table 1) Within each of these six groups of epilepsies are a number of specific syndromes based on clustering of seizure type, etiology, age, and evidence of brain pathology.

1.1	Localization-related/idiopathic epilepsies
	*Benign childhood epilepsy with centrotemporal spikes (C)
	*Childhood epilepsy with occipital paroxysms (C)
1.2	Localization-related/symptomatic epilepsies
	*Temporal lobe, *frontal lobe, *parietal lobe, or *occipital lobe (I, C, or A)
2.1	Generalized/idiopathic epilepsies
	*Benign familial neonatal seizures (N)
	*Benign neonatal convulsions (N)
	*Benign myoclonic epilepsy in infancy (C)
	*Childhood absence epilepsy (C)
	*Juvenile absence epilepsy (C or A)
	*Juvenile myoclonic epilepsy (C or A)
	*Epilepsy with tonic-clonic seizures on awakening (C or A)
	*Epilepsy with random tonic-clonic seizures (C or A)
2.2	Generalized/symptomatic epilepsies
	*West syndrome (infantile spasms) (I)
	*Lennox-Gastaut syndrome (C)
2.3	Generalized/either idiopathic or symptomatic epilepsies
	*Benign myoclonic epilepsy of infancy (I)
	*Severe myoclonic epilepsy of infancy (I)
	*Myoclonic-astatic epilepsy (I)
	*Progressive myoclonic seizures (C or A)
3	Both localization-related and generalized epilepsies
	*Neonatal seizures (N)
4	Situation-related epilepsies
	*Febrile convulsions (I, C)
	*Alcohol-related (A)
	*Drug-related (A)
	*Eclampsia (A)
	*Seizures with specific modes of precipitation (reflex epilepsies) (C or A)

Table 1 Summary of International Classification of Epilepsies and Epilepsy syndromes (with age of onset) A (juvenile and adults), 12 years and older; C (childhood), 1 – 12 year; I (Infancy), 2 – 12 months; N (Neonatal), birth to 2 months. *Specific epilepsy syndrome [3]

For this project the syndromes marked with C, I and N are of interest.

2.3.2 Classifications of seizures

Epileptic seizures are divided in two major categories: generalized seizures and partial seizures. A generalized seizure does affect the whole brain so also consciousness is lost. Partial means that only a small part in the brain is affected this results in a partial physical

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manifestation (e.g. one arm). In a partial seizure the patient does not always lose consciousness and can sometimes remember the seizure. A partial seizure can lead to a secondarily generalized seizure. Both groups of seizures are divided into subgroups [3, 17].

Partial Seizures

- Simple partial seizures are seizures where only one area in the brain is involved. The symptoms depend on the part of the brain that is involved. Consciousness is retained.

- Complex partial seizures interrupt consciousness to varying degrees. This is because more than one area of the brain is involved. Symptoms depend on the part of the brain that is involved.

- Secondarily generalized seizures; a partial seizure can spread through the brain and lead to a generalized tonic clonic seizure.

Generalized Seizures

- Absence seizures; Most times start at an age of four to eight years and often stop in teenage. During the seizure the patient stares and normal activity ceases. The seizures typically are short, less than 10 seconds.

- Myoclonic seizures involve short contractions of muscles which can lead to jerky movement of muscles or muscle groups.

- Tonic seizures consist of a sudden increase in muscle tone in the axial and/or extremity muscles, producing a number of characteristic postures.

- Atonic seizures lead to the loss of muscle tone. The loss of muscle tone may be confined to a group of muscles, such as the neck, resulting in head drop. Alternatively, atonic seizures may involve all trunk muscles. If the atonic period takes long enough the patient will fall.

- Clonic seizures occur almost exclusively in early childhood. The attack begins with the loss or impairment of consciousness and a brief tonic spasm. This is followed by one to several minutes of bilateral jerks, which are often asymmetric and may appear predominately in one limb. During the attack, the amplitude, frequency and spatial distribution of these jerks may vary greatly from moment to moment. In other children, particularly those aged 1 to 3 years, the jerks remain bilateral and synchronous throughout the attack. Postictal recovery may be rapid, or a prolonged period of confusion or coma may ensue.

- Tonic-clonic seizures involve an initial contraction of the muscles (tonic phase) which may involve tongue bite, urinary incontinence and absence of breathing. This is followed by bilateral rhythmic muscle contractions that become further apart (clonic phase).

2.3.3 Motor seizures
The classification of seizures of the Commission on classification and terminology of the International League Against Epilepsy dates from 1981. Lüders et al. have proposed a updated classification for seizures classification based exclusively on ictal semiology [32] in

1998. For this thesis only seizures that involve abnormalities in muscle contractions are of interest. Part of this classification consists of motor seizures which is presented below. Two major subgroups can be distinguished:

1. Simple motor seizures in which the motor movements are relatively "simple," unnatural, and consist of movements similar to movements elicited by electrical stimulation of the primary motor areas.

2. Complex motor seizures, in which the movements are relatively complex and simulate natural movements, except that they are inappropriate for the situation.

In this classification the terms simple and complex are used to denote the way the movement is expressed instead of the amount of consciousness impairment like it is used for in partial seizures in the classification of the International League Against Epilepsy.

The detection of complex motor seizures is out of the scope of this thesis. This would require an algorithm that differentiates between appropriate and inappropriate movement for certain situations.

2.3.4   Simple motor seizures
Simple motor seizures can be subdivided into the following subgroups:

a. Myoclonic seizures. Myoclonic seizures consist of short muscle contractions lasting <400 ms.

b. Tonic seizures. Tonic seizures consist of sustained muscle contractions, usually lasting >3 s, that lead to "positioning."

c. Epileptic spasms. The term epileptic spasm is used to identify muscle contractions of variable duration which affect predominantly axial muscles. Epileptic spasms frequently occur in clusters in which the duration of the muscle contractions may vary from a short myoclonic jerk to a sustained tonic posturing. Usually the epileptic spasm consists of abduction of both arms in a "salaam" posture.

d. Clonic seizures. Clonic seizures are a series of myoclonic contractions that regularly recur at a rate of 0.2-5/s.

e. Tonic-clonic seizures. Generalized tonic-clonic seizures are characterized by an initial tonic posturing of all limbs. The sustained muscle contractions that determined the tonic phase then tend to slow, evolving into a clonic phase with contractions of progressively decreasing frequency until the contractions disappear completely. The muscles included in the tonic and clonic phase should be essentially the same. Focal motor seizures showing such a tonic-clonic evolution are infrequent.

[32]

2.4 Prevalence of epilepsy among different age categories and groups
The prevalence of epilepsy in the United States is 5-8 in 1000 people. Similar numbers are mentioned for other countries. There are several patient groups with higher chances of suffering epilepsy. Children, for instance, suffer more often from epilepsy but they can overgrow it. Incidence is the occurrence of new cases of epilepsy per unit of person time.

Incidences can be split in seizure type. Figure 1 shows the prevalence of epilepsy among different age categories [3].
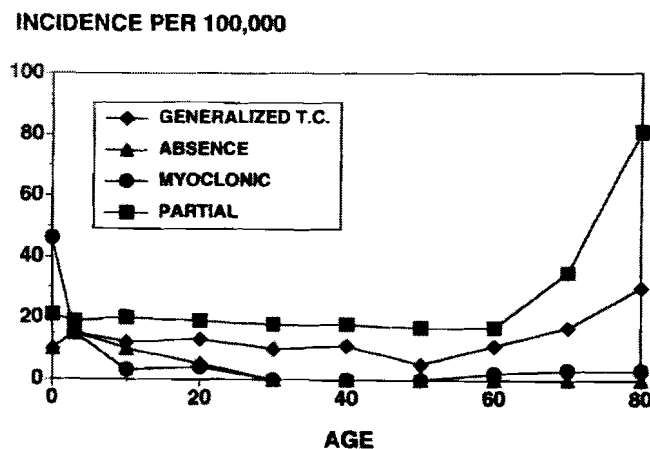
INCIDENCE PER 100,000

Figure 1 Incidence rate of epilepsy by seizure type and age. It can be seen that approximately the first two years after birth and the years after the 60th anniversary are the years with the highest risk to express or develop epilepsy [3].

Approximately one third of mentally retarded people suffer from epileptic seizures.

Epilepsy developed on a later age (>60 years old) is more related to some sort of brain injury [3].

2.5 Diagnosis of Epilepsy

Epilepsy is a diagnosis based on clinical observations. For the diagnosis epilepsy there should at least two seizures have been observed. The golden standard to diagnose epilepsy is recording electroencephalographic (EEG) signals in combination with video monitoring or clinical observations simultaneously. This procedure, however, can only be applied in a specialized clinical setting and is not appropriate for long-term clinical and/or home monitoring.

To help the recognition of seizure related motor events surface electromyography (EMG) is often used in a clinical setting. It can help to recognize patterns in multiple seizures of the same type. If the changes in the EEG and the surface EMG potentials are always in the same order as an already diagnosed epileptic seizure it is more likely that the recorded episode is of epileptic origin. Also the delay between epileptic activity in the EEG and muscle contraction in the EMG is often measured to determine the exact order of the spreading of the epileptic activity in the EEG to the expression in the body.

2.6 Medical risks in epilepsy

Epilepsy is associated with a broad spectrum of medical and other risks [42]. Epileptic seizures themselves usually cause no harm—the danger depend on where the patient is or what he is doing when the seizure occurs. There is always a risk of head injury, broken bones or other injuries from falling, or even drowning when the patient is swimming or bathing at the time of the seizure. Operating machinery or driving a car when a seizure

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occurs is also potentially dangerous. Suffocation during seizures caused by swallowing the tongue will not happen, but the patient can choke on food, vomit, or an object in his mouth, especially during the postictal phase when the airway's protective reflexes are inhibited.

A major concern for most people with epilepsy and their families is that seizures may have fatal consequences. Choking or an abnormal heart rhythm may cause sudden death, though this is rare. Untreated seizures that become more severe or frequent may lead to these problems. In studies based on populations from hospitals or epilepsy centres, standardized mortality ratios range from 1.9-3.6 [42].

2.6.1 Status epilepticus

One of the most dangerous complications of epilepsy is a condition in which seizures occur so frequently that the patient does not fully recover from one seizure before having another. Also a prolonged (tonic-clonic) seizure lasting more than 5 minutes becomes a status epilepticus and needs intervention. A seizure that lasts for more than 5 minutes has a high risk of lasting more than 30 minutes. Prolonged seizures are associated with brain damage. The mortality rate in seizures in the 5-29 minutes range is much lower than in seizures lasting more than 30 minutes [39], but both harbour dangers for cerebral brain impairment.

The mortalities of status epilepticus in the pediatric, adult and elderly populations are 2.5%, 14% and 38% respectively, with an overall rate of 22%. Death may result from the basic disease process causing status epilepticus, medical complications, or overmedication [3].

2.7 Risk factors associated with epilepsy

We will discuss shortly the medical risks that people with epilepsy may face.

Accidents and injuries are slightly more frequent among people with epilepsy compared to the general population. The majority of accidents occur at home. The most frequent injuries are contusions, wounds, fractures and brain concussions.

During a seizure the uncontrolled muscle contractions can lead to tongue bite or injuries due to movements of parts of the body. Also the loss of consciousness can lead to accidents. In studies comparing patients with documented epilepsy with different control populations found a seven fold relative risk (RR) of seizure related femur fractures in institutionalized patients and a twofold risk for non-institutionalized patients was found[42]. Risk factors are seizure type (atonic and tonic-clonic), frequency and severity.

There is also overwhelming evidence of increase from traffic accidents involving people with epilepsy as drivers. Risk factors for traffic accidents are complex partial seizures and tonic clonic seizures without aura (75% risk). Having a high frequency of seizures leads to significant more road traffic accidents.

Mortality rates are 2-3 times higher among people with epilepsy compared with the general population.

2.7.1 Sudden unexpected death in epileptic patients

Seizure related mortality is rare in new-onset epilepsy. Most fatalities occur in patients with chronic, therapy resistant epilepsy. The mortality seems to be seizure related and

often sudden unexpected deaths in epileptic patients (SUDEP) is the cause. In the chronic patient population, SUDEP accounts for 24-67% of all deaths [42].

Langan et al. (2000) performed a case control study and emphasized the risks factors for SUDEP on school age children. From the 14 SUDEP deaths among pupils, none of them occurred during supervision, but rather when they were less closely monitored during holidays. This implies that monitoring may reduce the mortality risk for children [28].

SUDEP can occur at any age, although most studies mention a mean age at death between 25 and 40 years. The highest risk is observed in patients with severe chronic epilepsy. Mental retardation is also a risk factor, just as duration of epilepsy. Early onset of epilepsy (0-15 years) increases the relative risk of SUDEP with 7.7 compared with onset after 45 years of age. A history of generalized tonic-clonic seizures is reported in at least 90% of SUDEP cases. Poor seizure control has been identified as the strongest risk factor for SUDEP. A surprising risk factor is the number of anti-epileptic drugs (AED), which is the second strongest risk factor. Taking 3 AEDs was associated with a RR for SUDEP of 8 compared with monotherapy. Frequent dose changes are also identified as a risk factor. These increased risks underline the importance of medicinal seizure control [42].

2.8 Monitoring and intervention

There is an indication that monitoring children with epilepsy does reduce the risk a seizure is the cause of death. Besides this, monitoring prevents children to pass away when they are in situations that require intervention. In case the patient is incontinent, is vomiting, has extreme saliva production or is psychically confused during or after their seizure, intervention is required.

All complications referred to above underline the importance of monitoring epileptic patients. With an adequate seizure detection system, caregivers can be alarmed when a seizure occurs, so appropriate actions can be taken.

2.9 Target group

The target group consists of children in the age of zero to sixteen year who are living at their parents' or caregivers home. Children are preferred to stay at home with their family to grow up as normal as possible. During day time the detection of seizures can be done by their caregivers, family or school personnel. During night time the risk of seizures is a problem that can lead to institutionalization of the patient or undesirable heavy burden to the parents because of the continuous need for monitoring their child. At night (20:00 – 08:00), 36% of the seizures in children occur [29].

The multimodal system that has to be developed in the future will consist of one or more sensors and video monitoring to validate automatic generated alarms during night time. This makes us focus on patients that are subject to video monitoring equipment in their bedroom. Privacy issues should be guarded carefully, but the assumption is that there are less objections against video monitoring of infantile patients that suffer from severe epilepsy than patients of older age. Further, when an epileptic seizure is detected, the system should warn someone in the neighbourhood of the patient. In general, parents are supposed to be good candidates.

The prevalence of severe forms of epilepsy among children and mentally retarded people is increased compared to other groups. Elderly also have a increased chance to develop epilepsy (see chapter 2.4). These two groups could be included in later studies.

To our believe, video monitoring will always be necessary to verify an automatic generated alarm before the caretakers are warned. This implies that the monitoring sites are restricted to video monitored rooms. The restriction to monitor the patient only during night time when in view of the camera in the bedroom is a consequence of this. This restricted area allow for easy wireless transmission of the signals.

2.10 Situations that require intervention

Monitoring of epileptic patients is not always strictly necessary. One can discuss the allowed risks and when monitoring becomes crucial. In either case there are situations that require intervention. These situations are;

- Status epilepticus needs medical intervention to stop the seizures
- Postictal oxygen and airway problems should be solved
- Incontinence, a patient that loses control over sphincters during a seizure and does not wake after a seizure should be taken care of
- Injuries are not common but can happen

2.11 Constraints for a monitoring system

Automatic detection of epileptic seizures is only valuable if a substantial number of seizures is detected and the false alarm rate is acceptable low. For this project we assume a sensitivity of 90% or better and a positive predictive value of 50% or better as acceptable. How these numbers are calculated is explained in more detail in chapter 7.2. The period over which these numbers are calculated is defined as the time that the subject is in his or her bedroom. This would be a realistic time frame in a home situation.

Furthermore after the generation of an alarm, the alarm should be verified by a trained expert at some remote location. When the situation requires intervention a care giver in the neighbourhood of the patient should be warned. This requires a total reaction time of minutes from seizure onset. This implies that the algorithm reacts within seconds.

3 Other automatic seizure detection programs

A lot of effort has been put in developing automatic seizure detection programs. The most important will be shortly discussed below. The results per program are expressed in sensitivity and positive predictive value (PPV) as far possible to compare them.

3.1 EEG

Several methods for automatic seizure detection based on EEG exists, but few can operate as an on-line seizure alert system. Saab and Gotman [38] designed a system for automatic seizure detection based on scalp EEG. The system performed well enough to be considered for use within a clinical setting. The performance measures are 78% sensitivity, 15 % PPV and a detection delay of 9.8 s. without individual tuning to the subject and 76% sensitivity, 70% PPV and a detection delay of 10 after individual tuning of the algorithm. Unfortunately scalp EEG does restrict the freedom of movement the patient, is labour intensive to apply and therefore not suitable for a home monitoring system.

3.2 Accelerometry

The use of 3-D accelerometry for automated seizure detection is investigated at Kempenhaeghe Epilepsy Centre in Heeze. The process of seizure detection consists of several steps. First 3-D accelerometry data is screened for motor activity. Next, detected motor activity events are checked for stereotypical seizure related waveforms [36]. In the early stage of this project about 48% of the seizures could be detected [35]. By our knowledge this system is evaluated off-line at this moment.

3.3 Video analysis

Automated seizure detection of neonatal seizures of epileptic origin has been one of the research areas of interest. Karayiannis et al. have focused on automated detection of videotaped neonatal seizures. In premature and low birth weight infants there is an increased rate of epileptic seizures in the first month of life. Seizures can occur in up to 20% of infants hospitalized in the neonatal intensive care unit (NICU). Their goal is to develop a stand-alone, non invasive, automated seizure detection system that could be used in the neonatal intensive care unit. This was accomplished by training computerised neuronal networks with quantitative motion information extracted from short video segments, focusing on myoclonic and focal clonic types of random infant movements. They found a reliable basis for detecting neonatal seizures by combining quantitative features obtained by analyzing motion-strength signals with those produced by analyzing motion-trajectory signals. They achieved a sensitivity and positive prediction values above 95% in a set of 120 segments. The set consists of fragments varying in length from 7.5 to 20 seconds. One third of the segments consists of random movements, the rest of myoclonic and clonic seizures [27]. It will be an interesting research area for the use of videotaped seizure analysis in a home monitoring situation, but for this moment it is only in development and only potentially usable in NICUs.

3.4 In furniture sensors

Hansen et al performed an analysis to assess the sensitivity of bed alarms used for the detection of epileptic seizures. Patients admitted to a Danish Epilepsy Centre were supervised by video-cameras during the time they spent in bed. Pictures from the video cameras were displayed in a central supervision unit, where a nurse was watching the video screens. The beds of the patients were equipped with a bed alarm, KNOP 2000. This alarm reacts to vibrations (threshold set to 7 vibrations and a delay time of 15 arbitrary units). The staff of the wards registered alarms and compared them with the information about seizures given by the central supervision unit. During monitoring they registered 2534 true epileptic seizures, in 363 cases the bed alarm produced a false alarm . The sensitivity of a bed alarm is 15-20% (380 – 507 true detections). The PPV is 55%. For home-monitoring these device are not valuable because of their poor performance [16].

3.5 Sound threshold

At the long stay departments of epilepsy clinics, prolonged exceeding of a sound threshold is used as seizure detection system during night time. The sound that triggers the alarm is recorded and played back at a central care unit to be judged by a trained care giver. Such a system has poor performance. It detects less than 30% of the seizures with a false alarm rate of more than 95% [35]. In spite of this poor performance such systems are still being installed in "specialized" epilepsy care long stay units because they are relatively cheap.

3.6 Oxygen saturation

Hansen et al. 2005 also performed an analysis to assess the specificity of a pulse oxymeter used for the detection of epileptic seizures. Patients admitted to a Danish Epilepsy Centre were supervised by video-cameras during the time they spent in bed. Pictures from the video cameras were transmitted to a central supervision unit, where a nurse was watching the video screens. The patients under supervision carried a pulse oxymeter. Nonin Avant 960030, which reacts in case of a change of pulse (limits set individually) or decrease in oxygen saturation (limits set to 85%). The staff of the wards registered alarms and compared them with the information about seizures given by the central supervision unit. During monitoring they registered 2534 seizures, in 1059 cases the pulse oxymeter produced a false alarm. The sensitivity of the pulse oxymeter is 30-35%. The PPV is 44%. The clinical value of this alarm type is not sufficient for home-monitoring [16].

3.7 Heart rate raise

Van Elmpt et al 2006 performed an explorative study to assess the value of a model for the automatic detection and characterization of heart rate (HR) changes during seizures in severe epilepsy. Changes in heart rate were found among 80% of the subjects (n=10) and in 50% of the seizures. In two out of three patients with more than 10 seizures a PPV of at least 50% yielded a sensitivity above 90%. They concluded that heart rate patterns can be accurately characterised with their developed curve-fitting algorithm. It can be used in automatic seizure detection in patients with severe epilepsy if the model parameters are chosen according to predefined patient characteristics. For the whole population included in this explorative study a sensitivity of 48% is reported without a PPV [9].

3.8 Summary

As can be seen in the above examples, none of the current available systems seems to be capable to detect all seizures accurately or are suitable for home monitoring. We expect these systems to be complementary to each other so the combination of such systems can perform in a useful way. Below, the various systems are presented in a table.

What	Where	Reported results
EEG	Montreal Neurological Institute & McGill University	sensitivity 78% PPV 15% [38]
Accelerometry	Kempenhaeghe	sensitivity 48% PPV ? [35]
Automated video analyses NICU	Houston university	sensitivity > 95%, PPV > 95% [27]
In furniture movement sensor	Danish Epilepsy Centre, Dianalund	sensitivity 15-20% PPV 55% [16]
Sound threshold	Kempenhaeghe	sensitivity <30% PPV <5% [35]
Oxygen saturation (SpO2)	Danish Epilepsy Centre, Dianalund	sensitivity 30-35% PPV 44% [16]
Heart Rate Rise	Kempenhaege	sensitivity 48% PPV ? [9]

Table 2 Automatic seizure detection programs and their performance

4   Surface Electromyography

First the basic idea of the origin of the surface electromyography (SEMG) will be explained, followed by considerations about the recording of these signals. Then, the idea of the potential value of SEMG for seizure detection will be discussed.

4.1   Origin of SEMG

With surface electromyography the potential fluctuations at the surface of the skin above a muscle are measured. These fluctuations are a result of a series of electrochemical processes. The process is first outlined in general below, a more detailed description of the most important processes is presented thereafter.

The origin of these series of processes lies somewhere in the neurological activity in the motor cortex within the brain. These activities lead to transport of action potentials towards groups of muscle fibres in the skeletal muscles via neurons that end on the motor endplate of the individual muscle fibres. In all muscle fibres of the motor unit the action potential is transported to both ends of the fibre and lead to contraction of the fibres. A single action potential is hard to detect on the skin surface. To contract an entire muscle the individual motor units are driven repeatedly which lead to a summation of action potentials on the skin surface. The amplitude of the signal at the surface can be 0 to 10 mV (peak-to-peak) and the frequency response lies between 0 and 500 Hz although most power is between 50 and 150 Hz [31].

The detection of seizures with the help of SEMG can only be done in a multi-detector setting. Only those types of seizures that involve some sort of motor action can possible be detected with the help of SEMG activity. Differentiating between normal muscle activity and activity correlated with a seizure will be the biggest challenge in the current project. On the other hand electrical activity in de muscle does not per se lead to limb movement. In case a limb is fixated or simultaneously contraction of two complementary muscles it is possible to detect activity with SEMG and not with any kind of detection based on movement.

4.1.1   Action Potential

The intracellular fluid of nerve and muscle cells are negatively charged compared to the extracellular environment. This potential difference is caused by the separation of different ion concentrations inside and outside the cell by the cell membrane. The potential is maintained by active ion transport and diffusion of ions in the opposite direction. This negative potential difference is called the resting potential. An action potential is a rapid change in the membrane potential followed by a return to the resting potential.

Neural and muscle cells are poor passive transmission lines. The high capacity of the cell membrane attenuates the amplitude of the signal rapidly. Without the generation of action potentials the signal will be reduced by 3 dB within 1 to 3 mm. The fading of the local response is observed at sub threshold stimulation. However, when the threshold is passed a new action potential is generated which propagates the signal. Threshold values are around -55 mV. Voltage sensitive ion ports in the cell membrane are responsible for the abrupt

change in cell potential. Initially the conductance for Na+ ions is increased which causes an influx of Na+ ions from the relatively higher Na+ concentration outside the cell. The cell potential will rise towards approximately +30 mV. This is followed by an increase in conductance for K+ ions. The K+ ion flux is in the opposite direction of the Na+ flux. The change in conduction for these specific ions is only temporary, they return quickly to their normal values and the resting potential is restored. Immediately after the generation of an action potential it is not possible to generate a new one, independent of the magnitude of the stimulus. This is called the absolute refractory period. This period is followed by the relative refractory period. During this period the cell can be triggered to generate an action potential, but a stronger than normal stimulus is required.
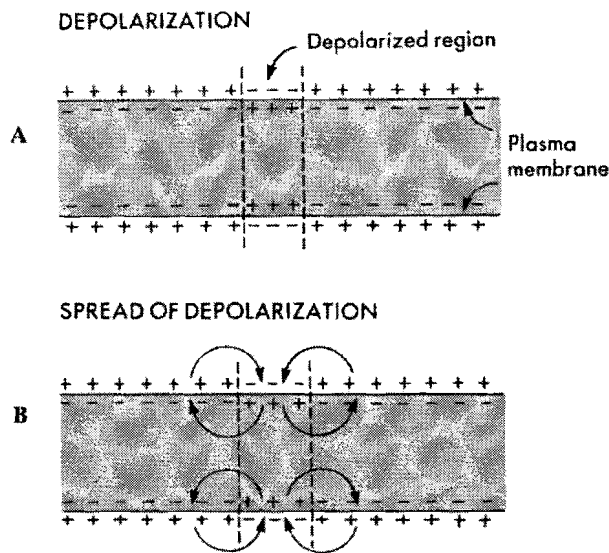
Figure 2 Depolarization and spread of depolarization. A depolarized region depolarizes the region direct adjacent on both sides which creates new depolarized regions [1].

Once an action potential is generated somewhere in the muscle it is an irreversible process and is always conducted towards both ends of the cell. A depolarized region in the cell creates an external membrane potential that is relatively negative to the adjacent membrane. These potential differences cause local currents to flow, which depolarize the membrane adjacent to the initial site of depolarization (see Figure 2) [1].
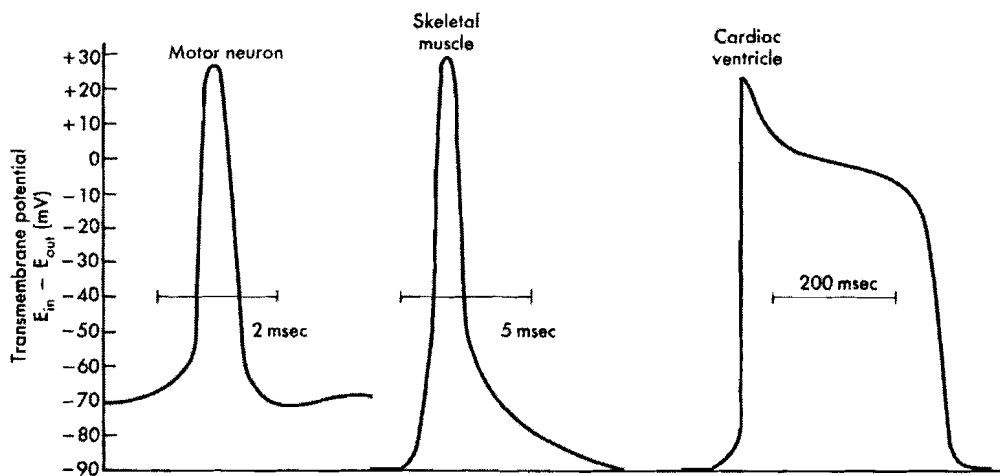
Figure 3 Action potential shape from three cell types. Note the different time scales [1].

An action potential is propagated with the same shape and size along the whole length of the cell. The shape and size differs for different sensitive cell types (see Figure 3).

4.1.2 Muscle cell anatomy

A skeletal muscle is a collection of muscle cells or fibres (see Figure 4). These fibres are usually the same length as the entire muscle, so they can reach up to 30 cm in length [19]. Each fibre consists of multiple myofibrils. The myofibril is the part that can shrink to produce force by sliding filaments. Contraction of the fibre is controlled by membrane depolarization.
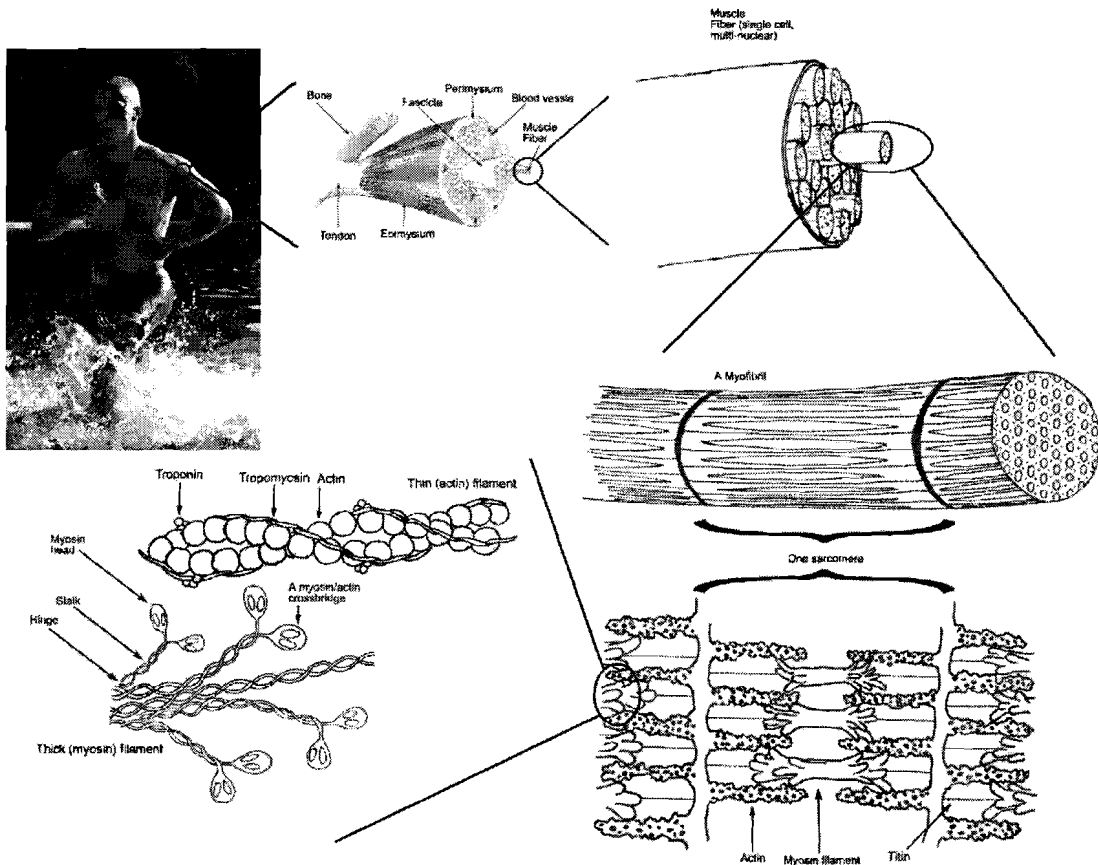
Figure 4 A top down view of a skeletal muscle [18]

4.1.3 Muscle cell depolarization

Depolarization of the muscle fibre is controlled by neurons that end on the motor end-plate near the middle of the fibre. This depolarization occurs when an action potential from a motor neuron reaches the motor endplate and triggers the release of a neurotransmitter (acetylcholine) in the junction cleft. After diffusion of this neurotransmitter through the synaptic junction cleft it binds to specific acetylcholine receptor proteins on the external surface of the muscle plasma membrane of the motor endplate. The binding of acetylcholine with the receptor protein transiently increases the conductance of the postjunctional membrane to Na+ and K+. Ionic currents result in transient depolarization of the endplate region. This transient depolarization is called end-plate potential (EPP). The EPP is transient because acetylcholine is quickly decomposed by the enzyme acetyl-cholinesterase.

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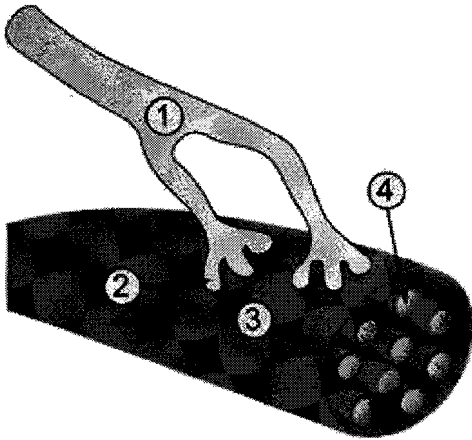
Figure 5 Global view of a neuromuscular junction. (1) Axon (2) Synaptical junction (3) Muscle fiber (4) Myofibrils [20].
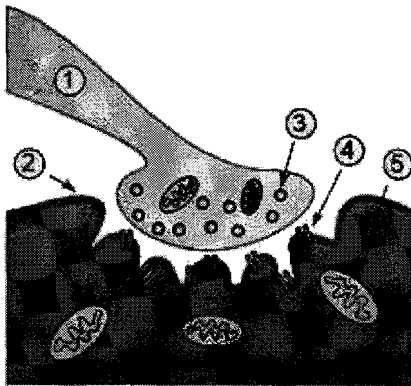
Figure 6 Close view of a neuromuscular junction. (1) presynaptic terminal (2) sarcolemma (3) synaptic vesicles (4) Acetylcholine receptors (5) mitochondrion [20].

The postjunctional plasma membrane of the neuromuscular junction is not electrically excitable and does not itself fire action potentials. After the postjunctional plasma membrane is depolarized, regions of the muscle cell membrane immediately adjacent to the neuromuscular junction are depolarized by electronic conduction. When these regions reach threshold, action potentials are generated. This action potential will travel from the motor end plate towards the end of the fibre on both sides [1].

4.1.4   Muscle cell contraction

A myofibril is constructed of a series of sarcomeres (see Figure 4). Contraction of the myofibrils inside the muscle cell is controlled by the amount of $Ca++$ ions that are released inside the myofibrils' sarcomeres. $Ca++$ release from the sarcoplasmic reticulum depends on the magnitude of the action potential. The threshold potential for opening $Ca++$ channels in the sarcoplasmic reticulum is about -50mV.

Action potentials in skeleton muscle cells are quite uniform. Hence, the electrical signal for muscle activation is constant, and it leads to the release of a reproducible pulse of $Ca++$. A

single action potential may release sufficient amount of Ca++ to fully activate the contractile mechanism. However, Ca++ is very rapidly pumped back into the sarcoplasmic reticulum before the muscle has time to develop its maximal force. Such a short contraction as reaction to a single action potential is called a twitch. Repetitive action potentials cause summation of twitches, which produces a partial or complete tetanus. The Ca++ pulses are added together to maintain saturating Ca++ concentrations [1].
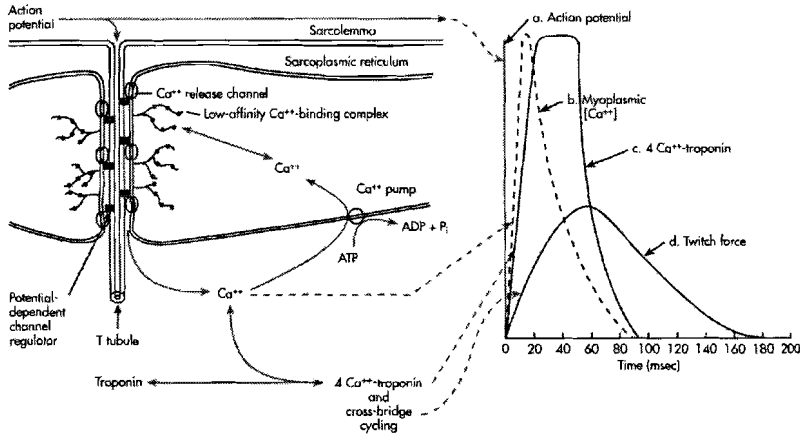
Figure 7 Twitch force duration compared to its predecessor process durations. The twitch force duration is much longer than the initial action potential [1].
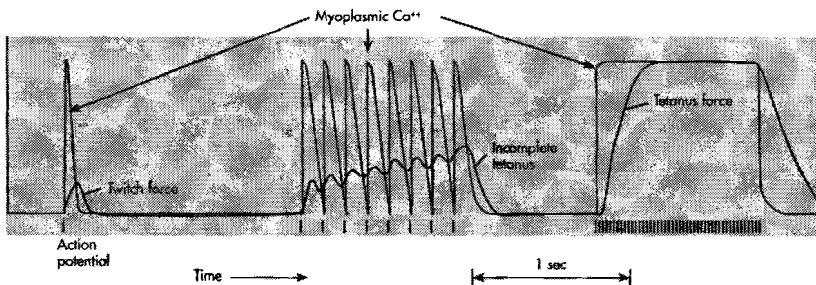
Figure 8 The force of contraction can be graded by repetitive stimulation. Because the twitch force duration is longer than the shortest time between two successive action potentials the total twitch force can add up [1].

4.1.5 Motor unit action potential

Motor nerves from the spinal cord branch in the muscle, with each branch innervating a single muscle cell. A motor unit consists of the motor neuron in the spinal cord, the ensuring nerve fibers and all the muscle fibres innervated by these nerve fibers. The motor unit is the functional contractile unit because all the muscle cells within a motor unit contract synchronously when the motor neuron fires.

The muscle cells of a motor unit are not segregated anatomically into distinct groups, and considerable intermixture of cells occurs among neighbouring motor units. A motor unit can consist of 2 to 1000 muscle cells. Precise movements (for example eye movements) require less simultaneously contracting muscle fibres than big forceful movements (for example

hamstring). When a motor axon fires, each muscle fibre in its motor unit is activated in a constant time relationship to the other fibres in the unit [1].
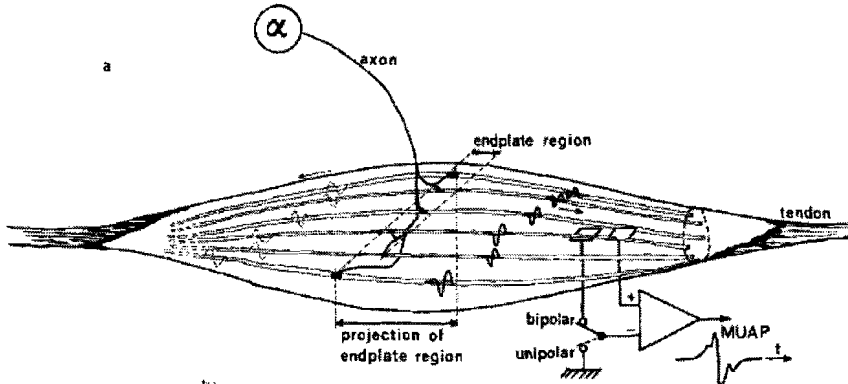
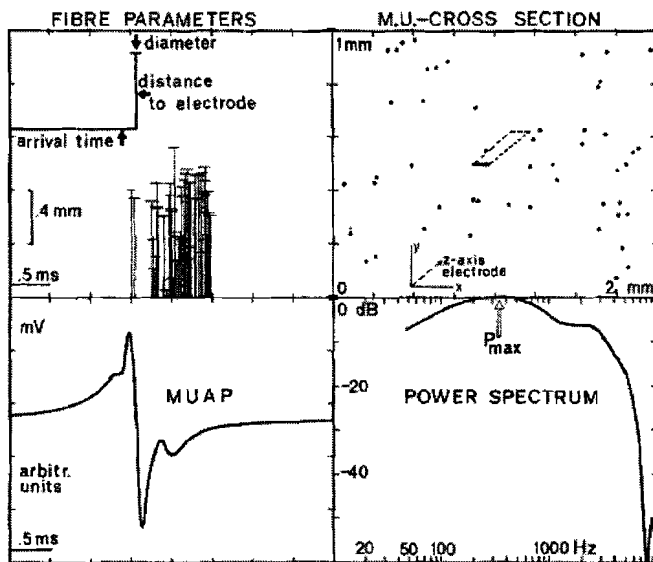**Figure 9 Spatial distribution of a motor unit and propagating action potentials [12].**

Figure 10 Simulated spatial distribution of fibres in one motor unit and accompanying MUAP and power spectrum. Note that this is measured inside the muscle not on the surface. During the propagation in the volume conductor most of the power is lost [12].

4.1.6   Recruitment of motor units

The central nervous system can increase the strength of muscle contraction by the following mechanisms:

- Increasing the number of active motor units (ie, spatial recruitment)
- Increasing the firing rate at which individual motor units fire to optimize the summated tension generated (ie, temporal recruitment)

Both mechanisms occur concurrently. The primary mechanism at lower levels of muscle contraction strength is the addition of more motor units, even though this increases the firing rate of the initially recruited motor units. The recruitment of different units takes

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precedence over increase in firing rate until nearly all motor units are recruited. At this level and beyond, motor units may be driven to fire in their secondary range to rates greater than 50 Hz [23].

The relationship between SEMG and MU firing behaviour is important both for gauging the state of muscle activation and for interpreting the significance of SEMG amplitude changes in disease. The strength of a muscular contraction is determined by the number of active MU s ('recruitment') and by their firing rates ('rate coding'). Different muscles use different control strategies. For example, the brachial biceps uses recruitment throughout almost its entire force range, whereas the adductor policis relies exclusively on rate-coding for contractions over 30% of maximum. In general, precise information is not available on recruitment and filing-rate characteristics for human muscles. Therefore attempts to model SEMG behaviour at different levels of effort are much more speculative than models of the MUAP [34].

4.1.7   Volume conduction

Intracellular action potentials are generated at the neuromuscular junction and propagated towards the tendons. The surface electrodes are separated from the sources by a non-homogeneous and anisotropic medium (the volume conductor, for example skin, subcutaneous fat etc.) and sample the potential distribution generated over the skin. The features of the detected signal depend on anatomical, physiological and detection system parameters [10]. The potential produced by a distribution of sources equals the sum of the potentials produced by the individual sources.

The simplest models of the volume conductor consider it as homogeneous and infinite or semi-infinite in extent. (The semi-infinite model has finite conductivity on one side of a plane representing the limb surface and zero conductivity on the other side.) A more accurate model considers the anisotropy of the muscle tissue: the fact that muscle has a greater conductivity in the axial direction (parallel to the muscle fibres) than in the radial direction (perpendicular to the fibres). These models are widely used because they are adequate for explaining the main morphological characteristics of the MUAP at different recording sites [34].
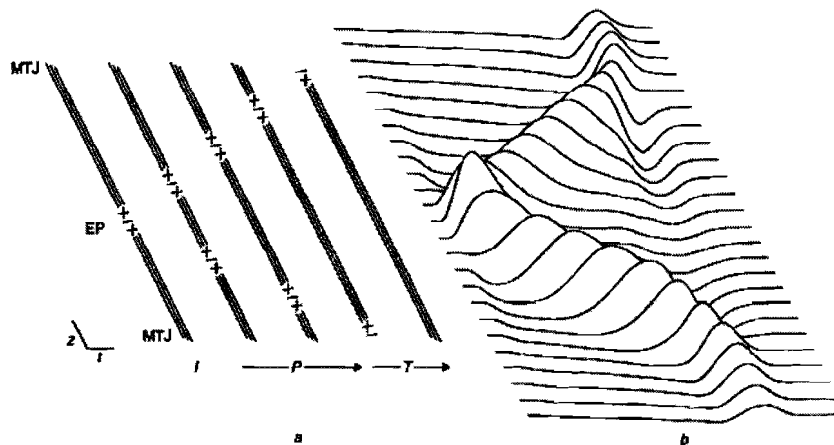
Figure 11 Schematic propagation of an action potential trough a muscle fibre and simulated surface potentials on different locations above the fibre [34].

The type of model that is used for the volume conductor is not of great importance for this project. The major effect of the volume conductor on the motor unit action potentials is the same for all the models. The MUAP is spatially smoothed and the amplitude is rapidly decreased with the increase of the distance between the source and skin surface. The potentials are proportional to the transmembrane potential as long as the distance between source and electrodes is not changed [44]. Furthermore the volume conductor has a low pass filtering effect on the MUAP's [11].

The static resting potential of the muscle fibre does not generate potential differences at the skin surface. A wave of depolarization or repolarisation travelling perpendicular to an electrode axis results in a biphasic deflection of equal positive and negative voltages if the velocity and the time constant of the depolarization and repolarisation are equal. Figure 11 depicts an illustration of the simulated surface potentials generated by a single travelling action potential on different locations on the skin surface.

4.1.8 Compound muscle action potential

Compound muscle action potentials (CMAP) are the sum of all motor unit action potentials that are generated almost simultaneously by stimulation of the nerve bundle. Because the conduction speed in the individual nerve fibre and muscle cells is not equal there will be some dispersion. The action potentials in the fibre will not be generated exactly simultaneously and all on a different location. Summation of the biphasic single fibre action potentials in the fibre leads to a slightly smoother and broader signal with a higher amplitude on the surface than a single MUAP.

Tetanic 50 Hz electrical stimulation of the motor strip in wake humans can elicit clonic muscle responses which resemble focal epileptic clonus [15] (figure 12).

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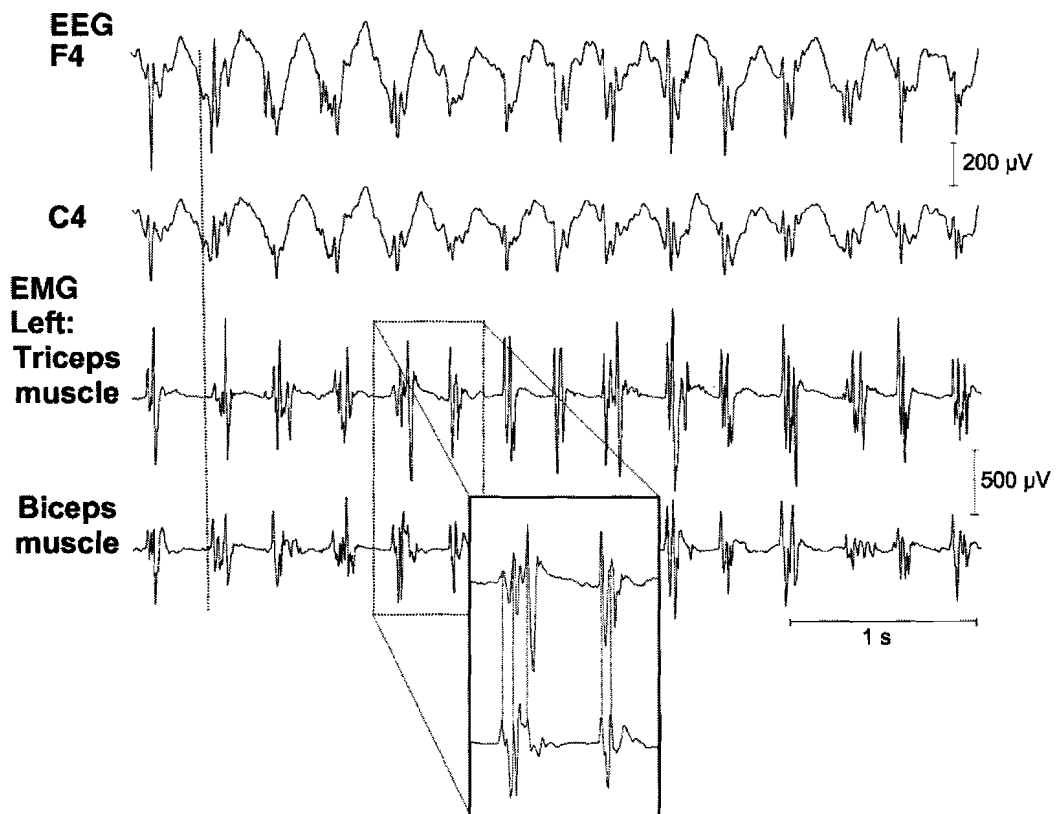
Figure 12 Example of EMG recording of CMAPs induced by an epileptic discharge in the frontocerebral (F4-C4) brain region. The enlargement shows synchronism between the agonist – antagonist pair [14].

4.1.9   Stochastic models for contraction

The SEMG signal recorded by a bipolar electrode reflects the electrical activity throughout a wide cross-section of the underlying muscle (or group of muscles). The signal is the summation of contributions from many motor units. The potentials from the different motor units occur at random times to produce a noise-like interference pattern. This signal is usually analysed in terms of its intensity and power spectrum, using such variables as the averaged rectified value, the root-mean-square value and the mean or median frequency of the power spectral density. These are referred to as 'global' surface EMG variables because they reflect the overall state of the whole muscle. Models of the SEMG as a stochastic process allow these global variables to be related to underlying physiological and anatomical parameters in the muscle [34].

4.2   Recording issues

The measurement of potentials on the skin surface is composed of more signals than just the desired EMG signal. There are other sources within the measurement set-up that produce unwanted noise and artefacts. This should be minimized during recording or removed after recording if possible. The disturbing sources (electrode noise, electrode motion artefacts, cable motion artefacts, alternating current power line interference, and

crosstalk of other muscles (i.e. cardiac muscle)) are listed below. The influence of the recording equipment is addressed very briefly.

4.2.1 Electrode noise

The EMG is detected using surface electrodes, which are fixed to the skin overlying the muscle of interest. The basis by which the electrodes function is the formation of a layer of charge at the interface between the metal electrode and an electrolyte solution. The presence of a charge gradient at the electrode–electrolyte interface produces a potential. This potential depends on the electrode material and a considerable DC voltage difference (e.g. more than 1 V) that can exist between electrodes of different metals and, to a much lesser extent, electrodes made of the same metal [5]. This is an extremely large compared to the recorded signal which is commonly in the range of 10 μV to 1 mV [6]. In EMG measurement, all recording electrodes should be made of the same material to minimize potential differences. Differential amplifiers and high pass filtering should always be applied. The measurement of DC values does not make sense.

The electrode-electrolyte potential is created by the thermal movement of metal molecules in the electrode to ions in the electrolyte. This is a dynamical equilibrium that is kept by the continuous transaction of metal to ion and visa versa. This is a stochastic process that introduces Gaussian noise. This noise is in a very broad spectrum but on a low level. For the current application this inference is negligible.

It is known that the electrode–electrolyte interface of silver (Ag) electrodes is stabilized by coating the electrodes with a layer of silver chloride (AgCl). Ag–AgCl electrodes are very stable electrically and are widely used as surface recording electrodes [5].

The electrode-electrolyte potential is sensitive for current density fluctuations. The use of large electrode surfaces and high impedance amplifiers minimizes this effect.

4.2.2 Electrode motion artefacts

There are two sources of motion artefact in surface electrodes: mechanical disturbance of the electrode charge layer and deformation of the skin under the electrodes. The first type of motion artefact occurs when there is relative movement between the electrode and the underlying skin. This type of artefact is greatly attenuated when the electrode–electrolyte interface is separated from the skin surface by a layer of conductive gel or paste. Any mechanical disturbances caused by relative motion between the electrode and the skin are damped by the intermediate layer, and their effect on the signal is limited. To minimize the effect the electrode should be mechanical fixated to the skin (i.e. with gauze dressing and collodion).

The second type of motion artefact arises because a potential difference, the skin potential, exists across the layers of the skin, and the value of this potential changes when the skin is deformed or stretched. This type of motion artefact is not attenuated by the use of recessed electrodes, but can be reduced by reducing the skin impedance [5].

Unfortunately motion artefacts tend to occur simultaneously with the signal of interest. Muscle contraction does often result in movements. Besides from this, the shock like movements, even in other muscles, in the body of the patient cause the whole body to move

and induces artefacts in many electrodes. The signal power of the artefacts can be enormous compared to the real signal if the skin-electrode resistance is high. Furthermore, it is likely that the resistance increases at some point in time.

4.2.3 Cable motion artefacts

The cables that connect the recording electrodes to the amplifier have an intrinsic capacity. When unshielded cables are moved through an ambient magnetic or electric field, or are subject to a time varying magnetic or electric field, current is generated. The magnitude of the voltage induced in the cable is the product of the displacement current and the electrode-skin impedance plus the voltage induced in the cable. This voltage can be comparable to the magnitude of the detected EMG.

Cable motion artefacts can be reduced by reducing the electrode-skin impedance. It is also reduced by using shielded cables, however, the shielded cables themselves can also be a source of cable motion artefacts. Frictions and deformations of the cable isolation generate static charges.

In general cable motion artefacts are reduced by low electrode-skin impedance and keeping the individual wires close to each other.

4.2.4 Alternating current (power line) interference

Ambient electromagnetic fields exist in the surrounding area of power lines and electric equipment. The power line interference signal can be much larger than the EMG itself. The magnitude of the interference can be reduced by moving away from the source and keeping the electrode-skin impedance low. Grounding and shielding can also be applied.

Even with good skin preparation and well designed instrumentation, it may not be possible to adequately attenuate power line interference before signal acquisition. A notch filter can be applied to remove the interference (but possibly also part of the signal of interest).

4.2.5 Crosstalk of other muscles (i.e. cardiac muscle)

Crosstalk of other skeletal muscles than the muscle of interest occurs when the muscles lie close to each other. There is not much to do about that. Chose the best position and use matched impedance for both electrodes to keep this effect as low as possible.

The potentials generated by the cardiac muscle can be recorded almost everywhere on the skin. Electro cardiogram can be removed by high pass filtering or by subtracting ECG recorded at another position on the body [5].

4.2.6 Sampling

Most of the signal power in surface EMG is below 400 – 500 Hz. The band of interest depends on the application. For muscle fatigue research the exact wave form is of importance. To estimate the muscle contraction (firing rate) only the rough amplitude is of interest. The effects of the firing statistics are largely limited to frequencies below 40 Hz, and the spectrum at higher frequencies is largely determined by the MUAP shape [34].

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4.2.7 Long term monitoring

Wearing electrodes direct on the skin for prolonged time is considered a drawback on surface EMG. In our clinic there is only experience with recording up to five days. Probably longer recordings can cause irritations to the skin. However it should be noted that for prolonged ECG monitoring electrodes are also placed on the skin. At cardiology departments of normal hospitals long term wireless ECG monitoring is already widely used. The monitored muscle in ECG recordings is anatomical different than skeletal muscles, but the recording technique has similarities. Knowledge of these systems can be valuable in future development of automatic seizure detection systems, but is out of the scope of this project. The same applies to carbon polymer electrodes used in ECG recordings for sports applications. This type of electrode can possible increase the comfort. One can also consider to remove the electrodes during day time when the automated monitoring is not carried out.

4.3 Advantages and disadvantages of electromyography

SEMG is not difficult to apply by a caretaker, the exact location is not critical, amplification is not difficult due to relative high voltages. This makes the surface EMG suitable for home monitoring applications.

SEMG seems to be vulnerable to motion artefacts. In the current project the subjects tend to move at the exact moment of interest. This can be a complication in the data acquisition.

Electrodes do need to be worn direct on the skin. Although there are comfortable self sticking electrodes with an adhesive edge, the direct body contact can be a disadvantage. Long lasting contact of the electrolyte that contains salts to improve the conductivity, in combination with the damage that has been done to the skin by the preparation, can lead to skin irritations.

5 Surface electromyography and epilepsy

There are only a few studies that mention the use of EMG for the classification of epileptic seizures. Surface electromyography is commonly used to detect subtle movements or muscle contractions during long term video monitoring in epilepsy care and polysomnography in sleep studies. To our knowledge, the use of surface electromyography for the (automatic) detection of seizures has not been described in the literature. However there is evidence that the analysis of surface EMG may improve the number of detected seizures during routine video analysis. The increase in muscle tone does not always result in significant movement or posturing and was not noticed without EMG [14]. It is also used to recognize relationships in time between events in the EMG and the EEG. Events in the EMG are even used as trigger for back averaging of EEG signals to discover correlated waveforms in the EEG that are masked in the noise [2].

5.1 Origin of simple motor seizures

The origin of epileptic seizures is per definition in the cerebral cortex. There are two theories about the exact part of the brain that is involved. Hamer et al [14, 15], suggest that tonic and clonic seizures (motor seizures) are both generated in the primary motor cortex (M1) (see Figure 13 and Figure 14) but the intensity of the seizure determines the way it is expressed. This is based on tests with stimulating M1. Stimulation with increasing magnitude starts with evoking clonic seizures but when the amplitude increases the clonic seizures are replaced by tonic seizures.
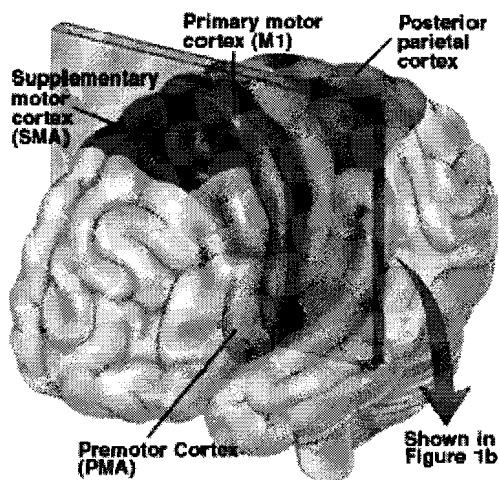
Figure 13 Principal cortical domains of the motor system [21].

The primary motor cortex (M1) lies along the precentral gyrus, and generates the signals that control the execution of movement. Secondary motor areas are involved in motor planning. The plane of section is elaborated below (see Figure 14).

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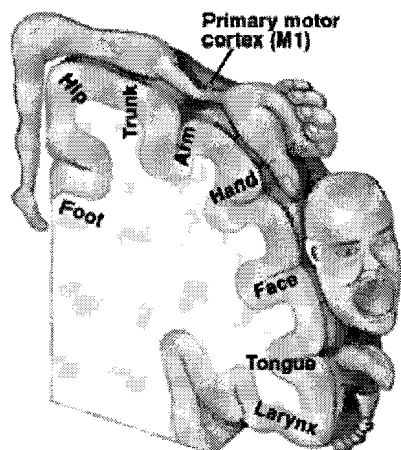
Figure 14 The motor homunculus in primary motor cortex. The section corresponds to the plane indicated in Figure 13. Body parts with complex repertories of fine movement, like the hand, require more cortical space in M1, while body parts with relatively simpler movements, like the hip, require less cortical space [21].

Hamer et al. [15] performed a study in which electrical stimulation was used to provoke epileptic seizures. Tetanic 50 Hz electrical stimulation of the motor strip in wake humans elicited clonic muscle responses which resembled focal (partial) epileptic clonus. The study mentioned in figure 12 suggests that focal clonic seizures in fact are focal tonic-clonic seizures of increased intensity. The epileptic clonus, generated by cortical stimulation, consisted of simultaneous contractions of agonistic and antagonistic muscles at regular intervals and was generated by localized polyspike-wave activity in cortical primary motor areas. Increasing intensity of stimulation at the same frequency converted an intermittent clonic muscle response to a continuous tonic response. High intensity cortical stimuli appeared to overcome the recurrent cortical inhibition occurring during clonus and recruit an increased number of pyramidal tract neurons [14]. (The pyramidal tract is a massive collection of axons that travel between the cerebral cortex of the brain and the spinal cord.) This observation supports the hypothesis that the transition from the tonic phase to the clonic phase during a tonic-clonic seizure reflects the decrease of epileptic activity in the motor cortex [15].

Ikedia et al. performed a study where ictal EEGs was investigated by subdural electrodes placed on the supplementary motor area (SMA) and M1. When epileptic activity includes the M1, a clonic convulsion of a certain part of the body results in the majority of the cases. Seizures arising from the SMA they mainly consist of sustained, tonic muscle contraction involving mainly the proximal parts of the extremities as well as the axial musculature. Thus, clonic or tonic convulsions seems to be one of the major differences in the two motor areas. A similar difference is also demonstrable by cortical electrical stimulation; when using a train of 50 Hz square pulses, SMA stimulation elicits tonic contraction whereas M1 stimulation elicits clonic contraction, although this difference is not always observed at the individual level. When comparing upper extremity movements elicited by cortical stimulation, between SMA and M1 in patients with intractable partial seizures, pure tonic contractions were seen in 77.5% of SMA and 22.2% of M1 stimulation, whereas pure clonic contractions were seen in 15% of SMA and 66.7% of M1 stimulation [26].

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5.1.1 Expression of simple motor seizures in surface EMG

As stated before we are focusing on the detection of simple motor seizures. The simple motor seizures are divided into the subgroups; myoclonic, tonic, epileptic spasms, clonic and tonic-clonic (see section 2.3.4). Clonic seizures consist of multiple myoclonic seizures. A tonic seizure is essentially a prolonged epileptic spasm. A tonic-clonic seizure is a combination of the tonic and the clonic seizure. These groups of seizures can be described with two EMG patterns; 1) CMAPs associated with the myoclonic short muscle contraction further on referred to as clonic muscle contraction, and 2) a stochastic, noise-like, signal that represents a longer muscle contraction where single CMAPs are not longer recognisable for the epileptic spasm and the tonic seizures in further on referred to as tonic muscle contraction.

5.1.1.1 Clonic

The clonic muscle contractions consist of bursts of compound muscle action potentials (CMAPs) which occur synchronously in agonistic and antagonistic muscles and are separated by periods of complete muscle relaxation. Alternating contractions of agonistic and antagonistic muscles are never observed. Each series of CMAPs follow the polyspikes in the EEG with a latency of 17-50 ms. The periods of muscle relaxation occur during the EEG slow waves. When the CMAPs occur repetitively the frequency of occurrence is typically 1.6 – 3.4 Hz [14].

The electromyographic burst length associated with the muscle jerk in epileptic myoclonus is usually less than 50 ms, although it can occasionally be in the 50 – 100 ms range. In a non-epileptic myoclonus the burst length is generaly 'long', 50 to 200 – 300 ms.

In epileptic myoclonus, muscles active in the same jerk are always activated synchronously. In non-epileptic myoclonus, muscle jerks can be asynchronous or even alternating although synchronous activating can be seen.

Reticular reflex myoclonus is part of the generalized epilepsies. Myoclonic jerks in this disorder typically affect the whole body. Proximal muscles are affected more than distal ones, and flexor muscle groups are more active than extensor groups [13].

Recording of muscle activities associated with myoclonus by using surface electrodes provides the most essential information on any kind of myoclonus. Myoclonus is caused by either abrupt instantaneous increase in muscle discharge (positive myoclonus) or interruption of muscle discharge (EMG silent period) (negative myoclonus). In fact, a combination of these two forms is often encountered. In this case, an EMG silent period is usually preceded by an abrupt muscle discharge, but the opposite can also be seen. EMG discharge associated with positive myoclonus of cortical origin is very brief, usually shorter than 50 ms (cortical myoclonus).

Simultaneous recording of surface EMGs from multiple muscles provides useful information on the distribution and spread of myoclonus. In case of upper limbs, the homologous muscles of the opposite limb may be involved 10 – 15 ms later, corresponding to the impulse propagation through the corpus callosum, which is the main connection between both cerebral hemispheres.

Cortical myoclonus is also characterized by the simultaneous involvement of agonist and antagonist muscles regardless of whether it is positive or negative. Surface EMGs are especially helpful for confirming the co activation of agonist and antagonist muscles.

The short duration of EMG discharge and the simultaneous contraction of agonist and antagonist muscles differentiate cortical rhythmic myoclonus from tremor [40].

5.1.1.2 Tonic

The EMG of the tonic contraction consists of a complete interference pattern in which single CMAP are not recognizable [14, 15]. The surface EMG of voluntary muscle contraction can be modeled as a noise-like process (see chapter 4.1.9). The action potentials of different motor units are assumed to occur at random times. This signal is usually analyzed in terms of its intensity and power spectrum. Some muscles have been found to exhibit a linear relationship between averaged rectified SEMG and force, whereas other muscles exhibit a non linear relationship. In general the averaged rectified SEMG intensity can be considered to be indicative for the overall instantaneous level of muscle excitation [34]. For this project the exact force of muscle contraction is not of interest, only the fact that the muscles are contracting and its timing, are important features.

There is no evidence that the wave form of the surface EMG of voluntary contractions differs from the waveform of seizure related tonic muscle contraction.

5.2 Surface electromyography during sleep

Surface EMG signals are widely used in polysomnographic sleep studies. Their utilization is based on the finding that, during sleep, muscle activity decreases. During sleep, 5 stages are distinguished. They are discussed below. Primary these stages are classified on electroencephalogram phenomena and eye movements. The properties of the chin EMG recordings are also described. During normal sleep the sleep stages occur in a cyclic way.

The night will start with the wake stage. The EMG will reflect the high-amplitude muscle contractions and movement artefacts. This is followed by drowsiness. This stage is defined as sleepy but awake with eyes closed. The EMG activity becomes less prominent. If, at any point, the subject rolls over, the record will reflect this as paroxysmal sustained increased artefact and high-amplitude activity. The subject may enter stage I of sleep for 1 or 2 epochs and then reawaken.

During stage I the EMG shows less activity than in wake stage, but the transition is gradual. Arousal from stage I is common and usually is represented by a burst of activity on the EEG, electrooculography (EOG), and EMG. Arousals can lead to a transition to wake stage. During stage II, III and IV, in general, muscle tone decreases gradually from stage II to stage IV. During rapid eye movement (REM) sleep, muscle activity is at its lowest point [22].

6 Patients and methods

In this chapter will be explained how the muscles that will be recorded, are selected, how the electrodes are placed and which equipment is used. Further, the subjects are introduced and the way the recordings are marked is described.

6.1 SEMG application

To select the most suitable muscles for detection of simple motor seizures, the movement patterns of the seizures of all the 56 patients within the target group that where subject to long term video EEG observation at SEIN Zwolle in the period April to June 2006 were analyzed. Movements during seizures where visually observed. The parts of the body and the direction were scored to predict the muscle most likely to contract during a seizure. Unfortunately there were no muscles that were involved in each seizure. So the position of the SEMG was chosen individually for each patient based on previous seizures of these patients.

The same analysis were used to predict what type of seizures would likely be recorded during the data collection stage of this project. In the 56 recorded nights one patient showed a tonic colonic seizure, 6 showed tonic seizures and 6 showed myoclonic seizures. The same number of seizures where expected in an equal data acquisition time frame.

6.2 Muscle selection

The selected muscles must be part of the clinical symptoms of the seizure and lie relatively close to the surface. It is preferred that the antagonist and the agonist can be recorded simultaneously. This is the case for the musculus triceps brachii and the musculus biceps brachii. For the musculus deltoideus the complementary muscle consists of more than one muscle and these muscles are not on the surface, covered with other muscle groups or simply not suitable to stick electrodes on. This drawback is accepted in some cases.

6.2.1 Muscles with more than one counterpart

The antagonist of the musculus deltoideus will be the musculus teres major with the musculus teres minor and the musculus pectoralis as synergists. Although the deltoideus lies near to the surface and often generates a signal with high signal to noise ratio, it is not usable in an agonist-antagonist couple. There are tree muscles involved in the downwards movements of the arm. These muscles are partly covered with other muscles and therefore the signal is disturbed by interference of the other muscles. These muscles lie also close to the heart so it is also likely to pick up ECG interference. Nevertheless the deltoideus is located in such a way that the electrodes and wires are easy applied and therefore it is relatively easy to register SEMG signal of good quality.

6.2.2 Selected muscles

In the first place we tried to record at least a complementary muscle pair; the biceps and the triceps. In case we were in short of channels or an odd number of cannels was available on the recording device the SEMG of the deltoideus is recorded. The data of one subject

that was recorded before the data collection period had started. This recording does not include a complementary muscle pair but two symmetric pairs.

The biceps and triceps are used to bent and stretch the arm. The deltoideus is used for the lifting of the arm in the sideway direction. The gastrocnemius is used to maneuver the foot downwards. All these muscles lie relatively close to the skin surface (superficially).

For our subjects the following muscles are used;

- Biceps
- Triceps
- Deltoideus
- Gastrocnemius
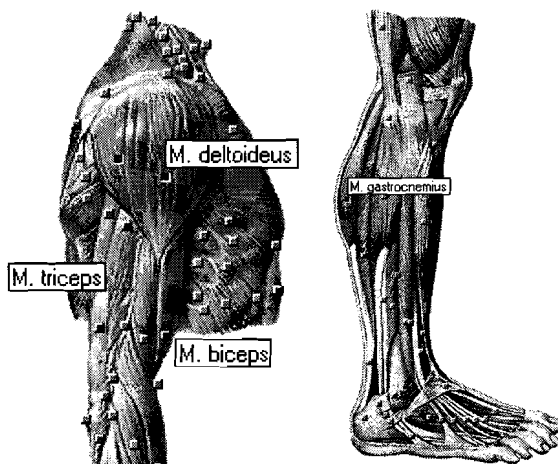
Figure 15 Drawing of the anatomy of the upper arm and lower leg depicting the muscles deltoideus, triceps, biceps and gastrocnemius [37].

6.3 Electrode placement

Electrodes are applied according to the recommendations of SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles). The SENIAM project is a European concerted action in the Biomedical Health and Research Program (BIOMED II) of the European Union (1996-1999). There is no international standard for applying SEMG. The SENIAM recommendations are adopted as standard to improve the reproducibility.

The electrodes used for this recording are one centimeter (diameter) Ag/AgCl disc/cup electrodes applied on scrubbed with conductive EEG paste. The electrode was fixated with a gauze dressing and collodion. The target resistance was less than two kilo ohm. This target was not often met.

Figure 16 The orange mark is the point where the electrodes have to be placed. From left to right are shown the deltoideus, biceps triceps and gastrocnemius [25].

6.4 Sample frequency

Because the duration of compound muscle action potentials (CMAP) elicited by cortical stimulation is around 20 ms, a low pass filter of 85 Hz allows recording of these potentials. Using a 85 Hz low pass filter, the sampling frequency of 200 Hz was sufficient to digitally depict the potentials. However, we cannot guarantee that the amplitude and waveform of the CMAP were different in this setup as compared to recordings with wider filter settings and higher sampling rates [15].

6.5 Used recording equipment

For the recording of the SEMG signals a Stellate LANotta 44 channel EEG recorder was used. Not all the EEG channels where always used for long term video and EEG monitoring for which the patient came to our clinic in the first place. The used EEG leads differ per patient. The spare channels are used to create additional EMG channels. A bipolar signal is constructed from two uni-polar channels. The same reference electrode, located on the head between Cz and Fz of international 10-20 system, is used for the EMG channels as for the EEG channels. The output sample frequency of this recorder is 200 Hz. Before quantification a 100 Hz low pass filter (12 dB/octave Butterworth) and a 0.16 Hz high pass filter (6 dB/octave Butterworth) is applied inside the recorder. The actual sample rate is 800 Hz. An additional 83 Hz 67 taps anti aliasing low pass filter is applied in software before down sampling.

6.6 Subjects

The subjects that are included for this study were selected from the patient population that visited SEIN for long term EEG and video monitoring in the period from February to May 2007. The initial target was to apply extra EMG leads to all children that wanted to participate and where in the age of our target group. Nocturnal seizures occurred frequently, Unfortunately, the combination of well applied EMG leads and the occurrence of nocturnal seizures was not very common. In this period only four candidates were included. An additional recording has been added because of the low number of new patients. During the analysis period subject AF64 was excluded because the recorded potentials were probably only motion artefacts that occurred simultaneously with epileptiform activity rather than signals of myographic origin.

subject code, gender	Impedance	events	Date of birth	Registration date	Age at registration date	description
SM61, F	Deltoideus R 1 & 2 k Deltoideus L 5 & 13 k Gastrocnemius R 6 & 17 k Gastrocnemius L 8 & 33 k	Tonic + intervent ion	March 10 2005	August 24 2006	1 year 5 months	624 brief tonic jerks, at night a prolonged cluster of seizures, extra medication was applied because of the cluster of seizures. Only epileptic jerks are marked. All other muscle activity may be assumed normal
AF64, M	Triceps R 24 & 39 k Biceps R 7 & 9 k Deltoideus R unknown	Clonic + Tonic	February 27 1993	February 12 2007	13 year 11 months	Excluded; recorded potentials where predominantly motion artefacts that occurred simultaneously with epileptiform activity rather than of myographic origin
RB65, M	Biceps 139 & 84 k Triceps 35 & 57 k Deltoideus unknown	Clonic	November 3 1994	February 15 2007	12 year 3 months	about 20 epileptic isolated clonic shocks; 3 episodes with repetitive myoclonic shocks, at one of these episodes consciousness is lost and intervention was appropriate
WK70, M	Deltoideus unknown	Tonic	November 28 1994	April 12 2007	12 year 4 months	284 nocturnal seizures are marked, not all with muscle contraction in the recorded EMG signal, three bigger seizures (21:32, 22:41, 01:24)
IK71, F	sp1 14, sp2 52, x29 13, x30 13 position of electrodes unknown	Tonic + intervent ion	September 21 2004	May 15 2007	2 year 7 months	182 nocturnal seizures are marked, at 4:41 extra medication is applied

Table 3 Subjects

6.7 Marked events

During and after the recording process notable events were marked by the EEG-technicians. During the recording process information about the daily activity of the patient was added. After the recording process was stopped the EEG of the whole night was visually inspected by the technician. Al epileptic seizures were marked. In the report created for each recording the type and moments of the epileptic seizures are noted. A neurologist checks the findings and writes the final conclusion. In some cases the technician is asked to mark clonic or tonic muscle contraction in more detail. This team of technicians and neurologist will be called the expert in the rest of this document.

A sleep stage hypnogram is also created by the expert as part of the long term monitoring. To this hypnogram we will occasionally refer to in determine if the subject is awake or asleep.

7 Detection proposal

After the description of the properties of surface EMG potentials of tonic and clonic muscle contraction in section 5.1.1 and the description of normal surface EMG reading during sleep in section 5.2, this chapter will focus on a proposal to distinguish between normal and seizure related EMG recordings.

During normal sleep, muscle activity is generally low. During the transitions between awake and sleep and visa versa most muscle action is seen. Normal movements like roll over, repositioning and scratching do occur, in those cases muscle activity is observed in the SEMG. In general the EMG recording of a subject asleep is a flat line.

The waveform of a CMAP associated with (myo)clonic contraction differs from the stochastic pattern associated with tonic contraction. These two events are extracted from the selected EMG signal individually. After the detection of these events there can be a time related detection step. A single short event does not require intervention in most of the patients. Repeated occurrence of events for a prolonged time can be a trigger for an alarm. Other properties of seizures have been discussed before. Some of them involve synchronicity and order of occurrence in different parts of the body.

For this reason the detection proposals for the separate detection steps will be split in three parts; detection of CMAP's, detection of tonic phase and detection of time related information of the detected events. In this project we will focus on the detection of the primary motor events. The last step may be applied in further research. Before the detection algorithm is applied to the recordings signal, pre-processing is required.

7.1 Signal pre-processing; noise reduction and artefact removal

The reduction of noise in the recorded signal should be accomplished in the first place by the use of proper equipment and suitable skin preparation to obtain sufficiently low skin impedances. The electrodes should be mechanically fixed as good as possible to the skin by, e.g., using a gauze dressing and collodion. After the signal is recorded some low frequency movement artefacts can be removed by a high pass filter without distorting the signal of myorgaphic origin. The power density of the signal induced by motion artefacts is mostly below 20 Hz. To avoid loss of myoelectric signal power, the filter edge frequency of the high pass filter should be set below 10 – 20 Hz [5]. In the current project, filtering with a second order Butterworth filter with a filter edge frequency of 5 Hz is used as high pass pre processing for the detection of muscle contraction if needed.

7.2 Calculation of FP, TP and FN

The signal will not be segmented to compare the results of the computer generated events to the golden standard created by the expert. The algorithm will be evaluated by the comparison of automatically generated events and the expert score. Because the accuracy of the marks that are placed by the expert and by the algorithm can differ in time, some mismatch will be allowed. At the start of this project it was assumed that the time resolution of the marks placed by the technician could be below 1 second, later on we will

see that one second is probably too short. So the beginning and the end of an event may differ one second at the start and one second in the end of an event. Furthermore events that are marked by the expert or the automated detection algorithm within one second of each other will be linked together to one event.

Sensitivity and positive predictive value will be calculated on an event basis. The marked events will be counted after the linking of events that are closer to each other than one second is performed. The sensitivity is the number of correct detected events (true positive) divided by the number of events marked by the expert. The positive predictive value (PPV) is defined as number of correctly generated events (TP) divided by the total number of generated events (TP + FP). A true positive (TP) is scored when the start and the end of an event are within one second correct. If the algorithm detects an event with a onset more than one second away from the onset of the events scored by the expert, it will be counted as a false positive (FP) and the event marked by the expert will be marked as a false negative (FN). The same rule applies to the end of a marked event. Figure 17 displays an illustration of the linking and scoring of marked events, detected events FP, FN and TP.
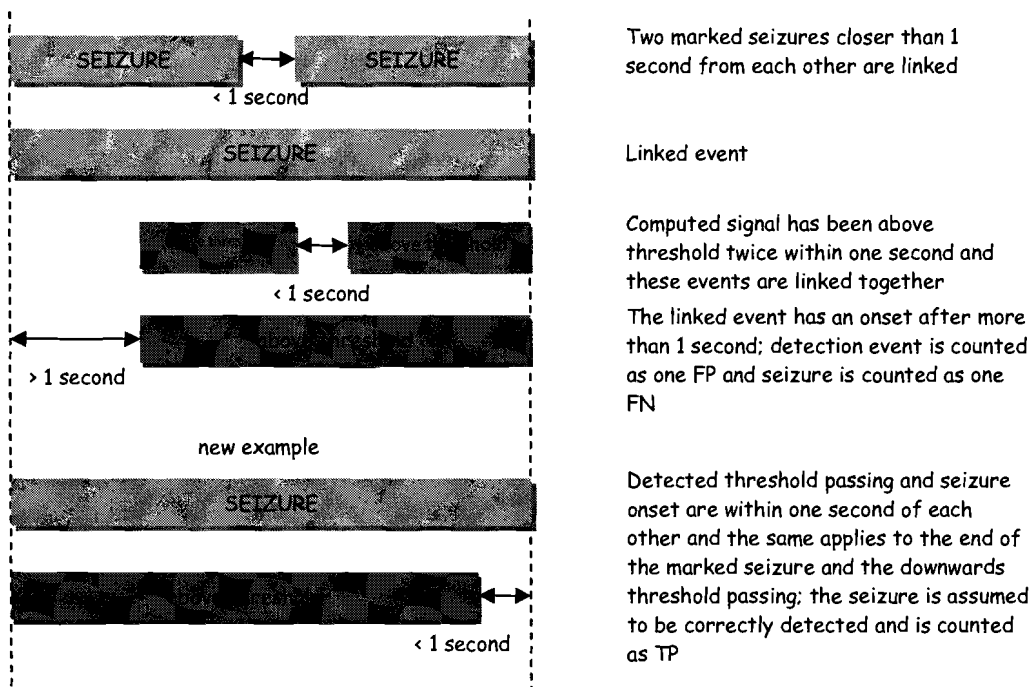
Figure 17 Illustration of the way events are handled for determining sensitivity and PPV.

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8 Detection of tonic events

Tonic muscle contraction result in an SEMG signal that is a summation of contributions of many motor units. The motor units fire at random times and produce a noise-like signal. The signal energy is usually assumed to be proportionally to the muscle force. The root-mean-square value is often used as measure [5]. The power density spectrum is largely determined by the waveform of the MUAP [34]. No evidence has been found that the power density spectrum of tonic muscle contraction differs from normal voluntary muscle contraction or contraction during arousals.

In this chapter the surface EMG signal of tonic muscle contraction is further explored. Two detection proposals are presented; Band pass filtering based on a Gabor filter and smoothed absolute value.

8.1 Example signal

To explore the features of the surface EMG signal observed during tonic muscle contraction some example signals are presented. First, we start with representing the signals in the way they are presented to the expert. Next, some simple analyses are applied to verify the assumptions about the properties of the signal.
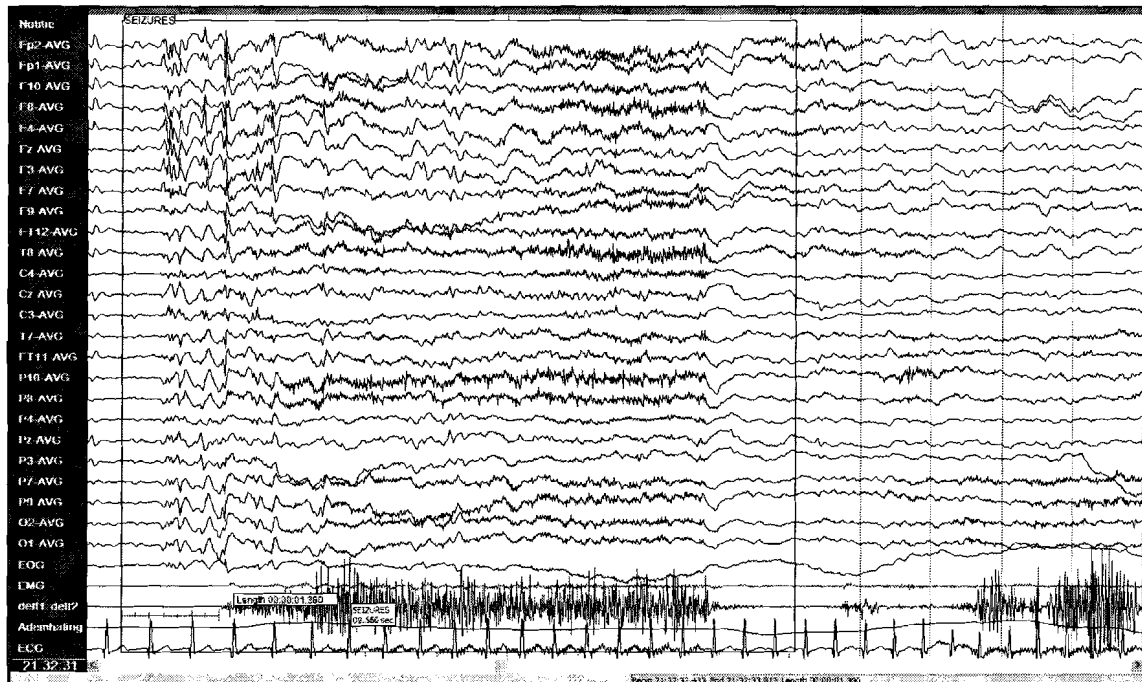
Figure 18 Screenshot of tonic marked seizure of patient WK70 as seen by the expert. 5 Hz HP filtered on deltoideus (delt1-delt2). The onset of the EMG burst is more than one second away from the onset of the marked seizure (yellow area).

Figure 19 shows a close up of a segment marked by the expert as being a tonic phase. The DC offset has been removed by the MATLAB function "detrend" before the plot was made, there are no additional filters used before the plot is made; this is the raw signal as recorded. High frequency components are removed by a hardware low-pass filter and additional software implemented anti aliasing filters at the recording process (see section 6.5 for filter settings). In this example, the frequency band between 15 and 30 Hz clearly contains more energy than other frequency ranges of similar bandwidths, but this does not hold for all tonic marked events.
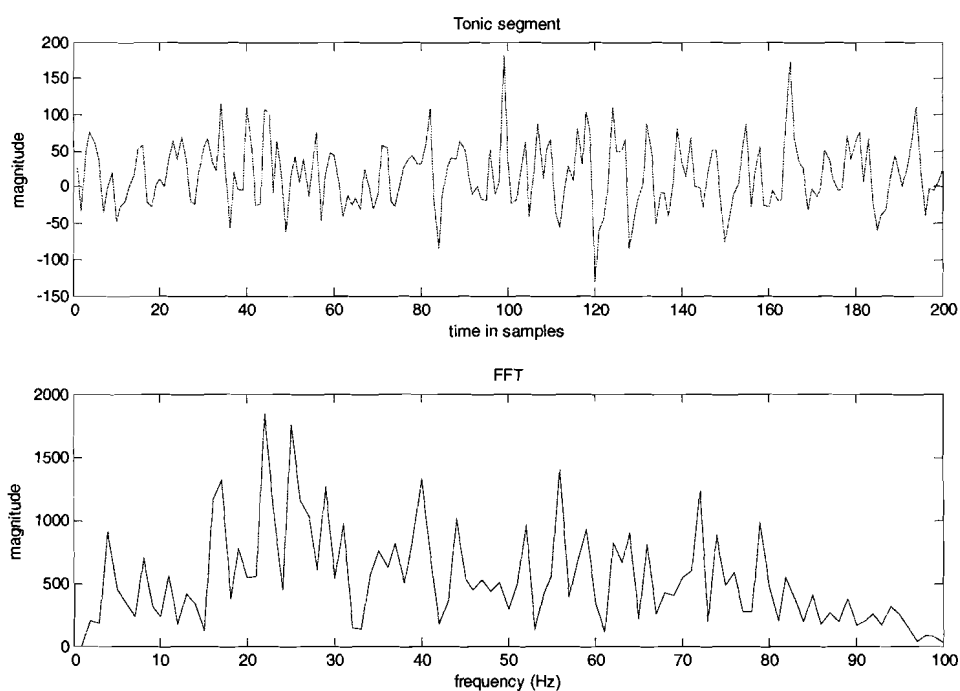
Figure 19 One second of tonic marked muscle contraction of subject SM61 (Fs = 200Hz) and its Fast Fourier Transform (FFT) (no window used).

To see if tonic marked SEMG contains specific frequency bands that contain more energy than normal SEMG signals, the sum of the modulus of the FFT of all the 129 tonic phases in one hour are compared with the sum of the modulus of the FFT of the same number of random selected segments.
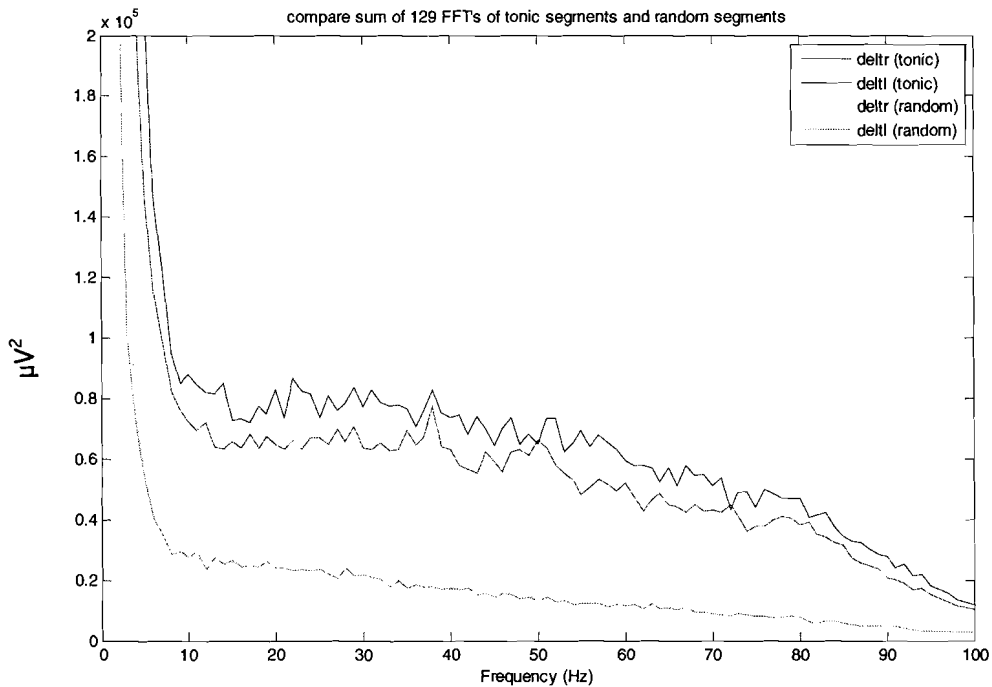
Figure 20 Randomly selected EMG recordings are compared with tonic marked segments. The sum of the FFT of 129 segments of one second tonic marked EMG is compared with the same number of equal length randomly selected EMG recordings. Below 10 Hz the effect of motion artefacts is shown.

It can be seen (in Figure 20) that the energy of tonic marked events is higher than of that of randomly selected segments, this was expected because there is more muscle activity. The DC offset is also somewhat higher because during muscle contraction it is more likely that low-frequency motion artefacts disturb the signal. The two low pass filters in the recording equipment have a attenuation of 3 dB at 83 and 100 Hz respectively. Especially the 83 Hz anti aliasing filter introduces attenuation. The manufacture of this recorder reports 3 dB attenuation at 83 Hz and that the filter length is 67 taps. What sort of anti aliasing filter is used is not mentioned (see section 6.5). This implies that somewhat before the 83 Hz the spectrum is attenuated. Keeping this in mind, it can be concluded that the spectrum of myographic origin during tonic muscle contraction is comparable to the energy distribution of the randomly selected EMG segments.

8.2 Detection proposal for tonic muscle contractions

Two methods are evaluated for detection of tonic muscle contraction. One approach is to use the entire available recorded bandwidth after removing frequency bands that possible contain artefacts. The other approach is calculate the power in a frequency band that

potentially contains few noise and where SEMG signal power may be expected. So, instead of using multiple filters to remove the noise, use one filter to take a part of the spectrum where low-noise is expected. Both approaches are introduced below.

In theory, the averaged rectified value of the SEMG signal can be computed relatively easy. Unfortunately the presence of artefacts complicates such a straight-forward approach. Artefacts should be removed before the calculations are carried out (see Figure 21).
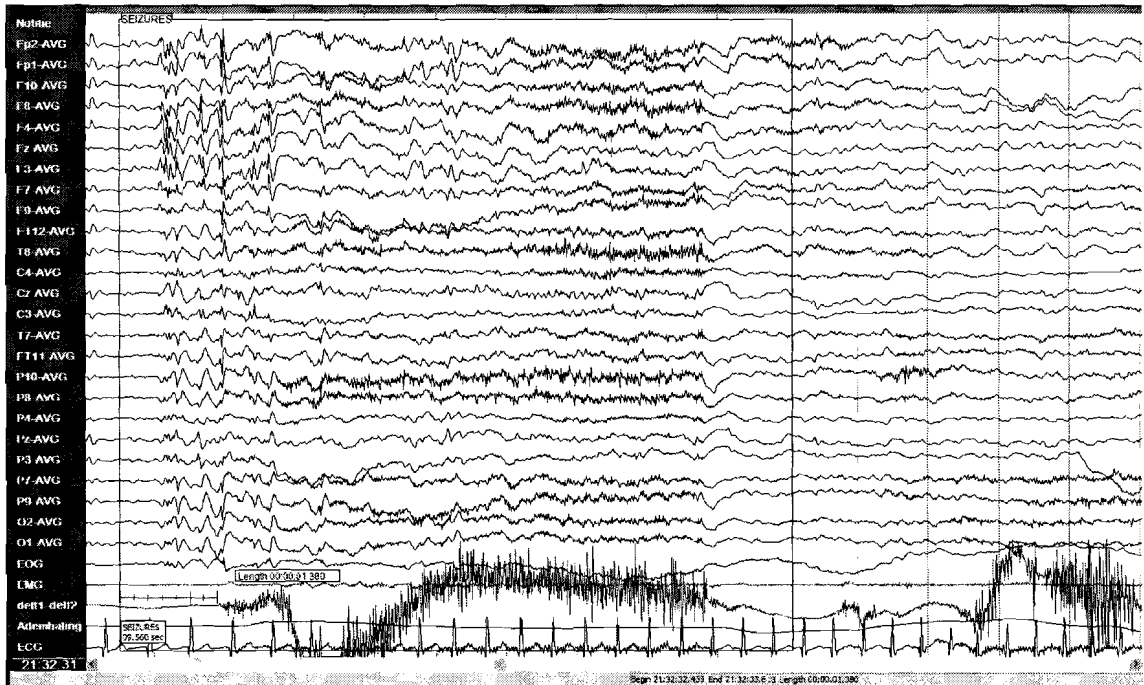
Figure 21 Same picture as Figure 18, but without the high pass filter on the deltoideus channel.

Artefacts should be removed to make the detection algorithm more robust. A high pass filter should be applied to remove motion artefacts and a notch filter to remove power line interference. A low pass filter is already applied at the recorder side before the AD-conversion and after the AD conversion before the down-sampling inside the recorder.

An alternative approach is to use a band pass filter to take a relatively noise free frequency band out of the signal and calculate the energy inside that band. Because the signal energy is spread over almost the whole spectrum detection based on a single band is a valid proposal. Furthermore the choice of the used band is not critical. The filter can be designed in multiple ways. Here a Gabor filter is used as band pass filter. The results will be compared with a straight forward approach based on smoothed absolute values.

The SEMG signals associated with tonic muscle contractions as recorded at our clinic are comparable with the description found in literature as described in section 5.1.1.

8.2.1 Gabor filters

Gabor filters are actually designed to be applied as a set and decompose a signal into multiple coefficients and rebuild them after transport or manipulations. Here only one filter is used to estimate band power. Gabor filter sets are described as follow;

$$g(t) = \beta e^{2\pi i t \omega_0} e^{-s(t-t_0)^2}, \qquad \beta \in C, s > 0 \quad \text{(where } C \text{ denotes complex numbers)}$$

So a complex quadrature pair is created. The centre frequency is controlled by ω_0 and the width by s, β is a scaling constant. This is set to normalize the filter response to zero dB in the pass band.

From visual analysis, it became clear that a centre frequency of 40 Hz gives is a proper choice to differentiate between signal and noise. So a Gabor filter with a centre frequency of 40 Hz and a length of 128 samples is selected. The filter is chosen in such a way that approximately ten periods of the base frequency are present in the filter. See appendix for MATLAB code and Figure 22 for an example.
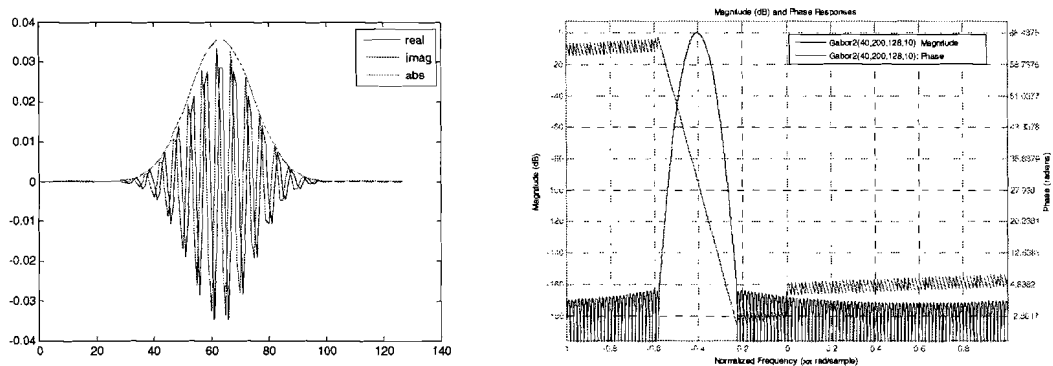
Figure 22 Gabor filter with centre frequency of 40 Hz left and its magnitude and phase response right

8.2.2 Average of rectified EMG

Before the absolute value of the recorded SEMG signal is taken, the movement artefacts, power line artefacts and DC offset should be removed to approximate the amount of muscle contraction. The filters that are used for this are simple IIR filters designed using the filter design toolbox in the mathematical program MATLAB. A second order Butterworth filter with a filter edge frequency of 5 Hz is used for pre processing in combination with a 50 Hz notch filter. The notch filter is of the same family but of the fourth order. The edge frequencies are set to 45 and 55 Hz. Furthermore the averaging does require a form of segmentation. An overlapping segmentation should be considered to avoid spreading of the power in two adjoining segments. The length of the segment should not be too long to miss changes of short duration. The rectified EMG will be averaged over 64 samples (320 ms) using a sliding window.
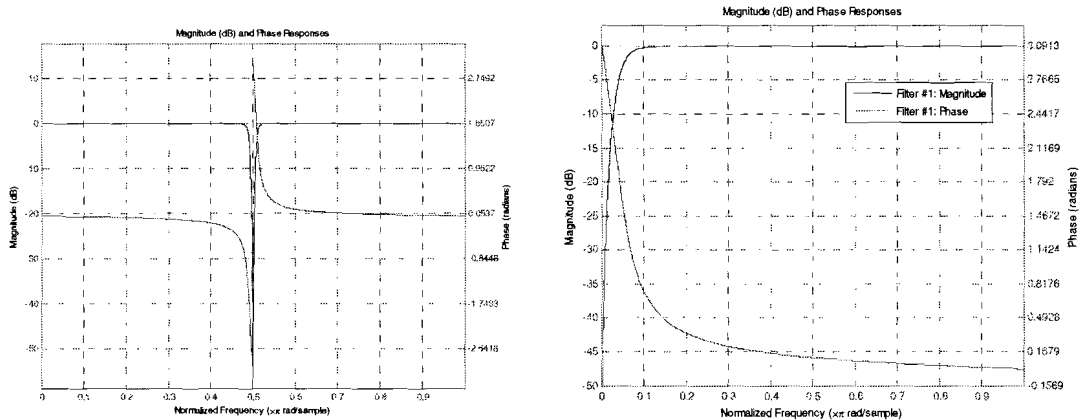
Figure 23 Magnitude and phase response of the selected filters for artifact removal.

The average over 320 milliseconds of the absolute values of the filtered EMG signal is used as input to the threshold detector. Here is an example of a pre processed EMG reading of a tonic muscle contraction, the averaged rectified value and the mark of the expert (Figure 24). As can be seen, for this short segment a simple threshold would detect the tonic muscle contraction correctly.
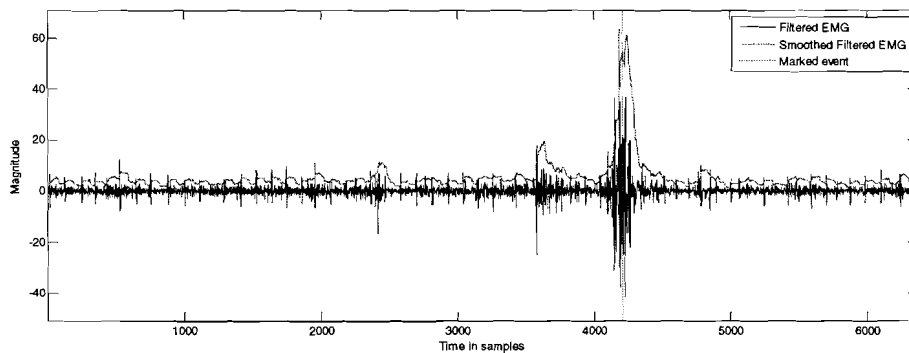
Figure 24 Segment of the recorded EMG of subject SM61 start at 3H00M. It can be seen that the averaged smoothed absolute value of the EMG signal forms a good envelope detector. Also ECG artefacts can be seen.

8.2.3 Comparison of processing power

The filtered averaged rectified signal proposal requires little processing power; one second order and one fourth order filter is used. To calculate the absolute value only the sign mark has to be thrown away. The average-filter requires 64 additions. The last multiplication can be left out when the threshold is scaled by 64. If all the 64 samples are stored in a cyclic buffer the oldest value can be subtracted of the sum of the values when a new value is added.

The Gabor filter consists of two 128 taps long filter; one for the imaginary part and one for the real part. The absolute value has to be calculated from this signal by raising to the square, adding and take the square root. An alternative approach would be to take the absolute value of the FFT of the used Gabor filter (most of the coefficients are zero) and

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the FFT of the signal; multiply them and take the IFFT. Whatever requires less processing power.

For this moment processing power is not an issue and will not be estimated in more detail; the signal analysis is performed offline on a personal computer, but in the case of a battery powered implementation in the far future, processing power may become an issue. In that case the filtered averaged rectified signal calculation probably requires less processing power.

8.3 Threshold determination

Because the amplitude of SEMG recordings differs for each subject and the exact position of the electrode, for each muscle and patient an "optimal" threshold (with respect to the target detection performance) is determined based on a short segment. The optimal threshold to detect muscle contractions may differ from the optimal threshold to detect seizures, they are estimated and chosen separately.

As mentioned before, the target sensitivity is 90% together with a PPV of 50%. Thresholds are chosen to maximize both performance measures, but sensitivity is more important as PPV. When the threshold is set high, the number of times the threshold is passed is likely to be lower, resulting in less false positives, but sensitivity is likely to decrease too. On the other hand, when the threshold is set low, one would expect to achieve a sensitivity near 100%. This is not the case with our algorithm which determines sensitivity and PPV. When the threshold is set too low, the threshold is likely to be passed more than one second before the onset of the marked seizure or more than one second after the end of the marked seizure the other way around. In this case the seizure is counted as FN so the sensitivity does decrease.

The determination of the threshold occurs by iteratively increasing the threshold and calculating the corresponding sensitivity and PPV based on a short segment of 30 minutes. These values are represented in a plot. Form this plot the "optimal" values are chosen. This is a "best effort" decision. The sensitivity and the PPV usually do not reach their maximum values at the same threshold. When only one of the both values is above target, the threshold can be chosen to optimize the other. If both values reach target their values at some point, the sensitivity is considered the most important and the threshold is altered in the region where the sensitivity is above target to improve the PPV towards its own target. When sensitivity and PPV are both below or above the target value best effort is done to chose a robust threshold, i.e. not close to steep downwards curve. A threshold determined in this way is referred to as optimal.

8.4 Results for tonic event detection

Results for individual patients will be represented in separate sections. First a short description of the recording will be represented. Then the optimal thresholds to detect seizures or muscle contractions per detection algorithm are determined based upon short segments. These thresholds are used to analyse the whole night and the results will be presented per patient.

8.4.1 IK71

Subject IK71 (female, age 2 year and 7 months) has been in her bedroom for 11 hours and 8 minutes from 21:03 to 9:55 the next day. The electrode positions are not exactly known, but it is certain that one pair was applied to the triceps and one to the biceps on the same arm. Impedances where 14, 52, 13, and 13 k for the four electrodes. During the night 182 seizures where marked by the expert. There were 221 (mostly seizure related) muscle contractions marked (see Figure 25).
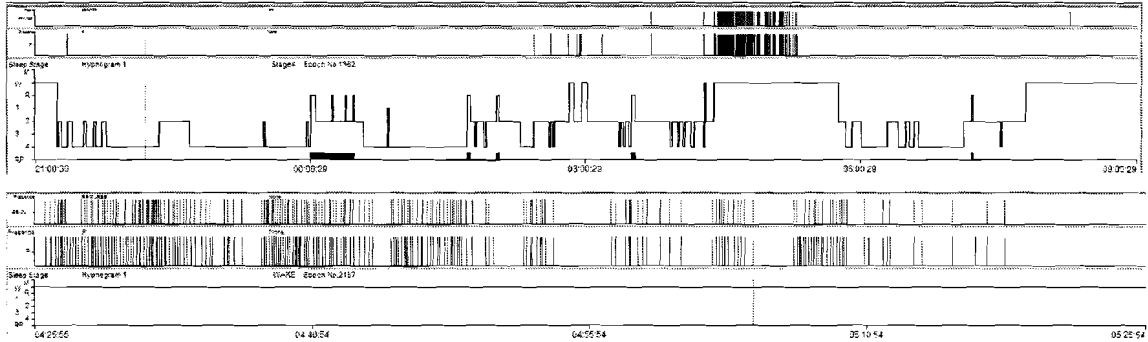
Figure 25 Overview of the night of IK71. Seizures are marked in red, muscle contraction in green. In the third graph the sleep stage hypnogram is displayed. At 4:41 extra medication is applied. The bottom three plots show a close up of the upper plot to show that there are individual events marked.

First the optimal threshold is estimated for the two detection proposals and the two recorded channels based on the marked muscle contraction are determined. Because the calculation time for MATLAB is somewhat high when evaluating the whole night for optimal threshold estimation, here is only 30 minutes used. The selected sample runs from 4:21:07 to 4:51:07. In this segment 139 tonic contractions are marked.
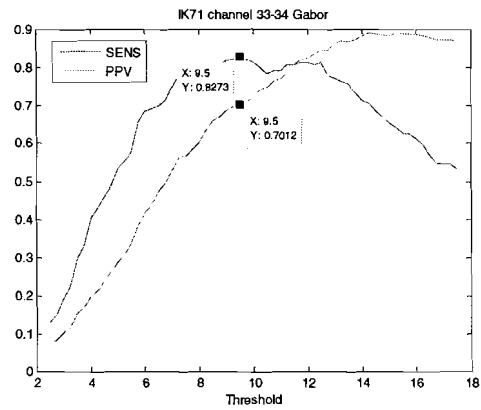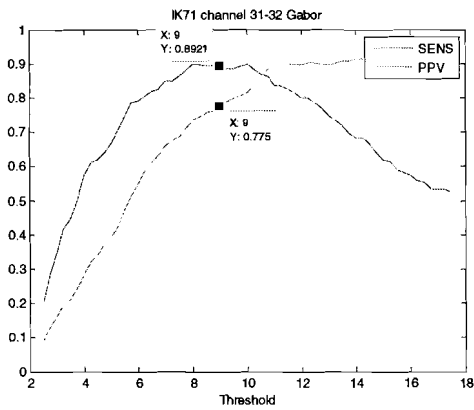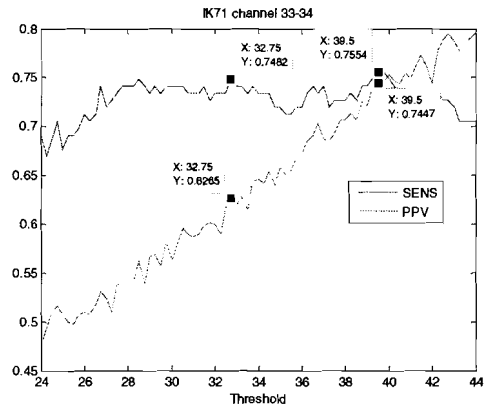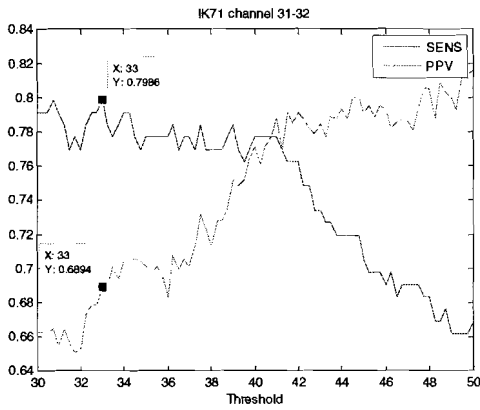
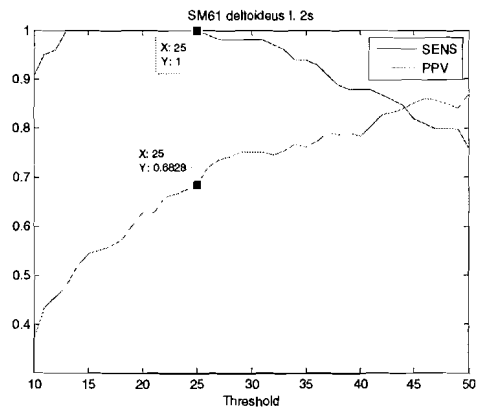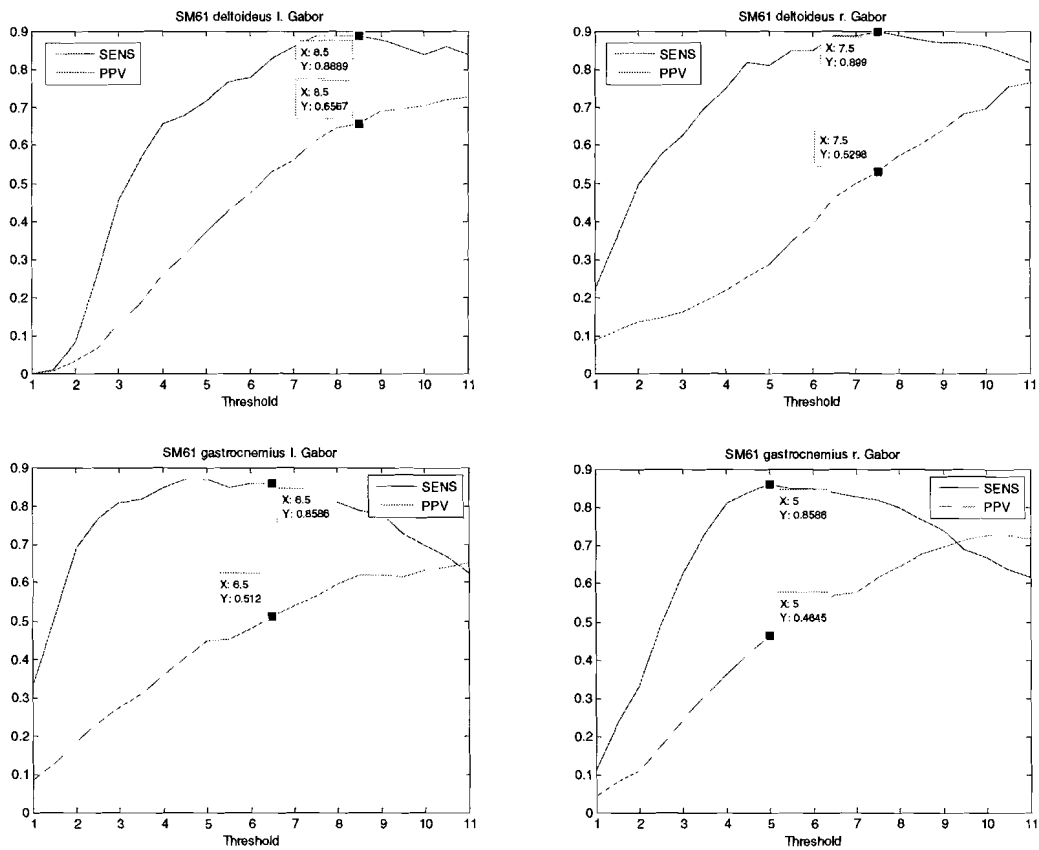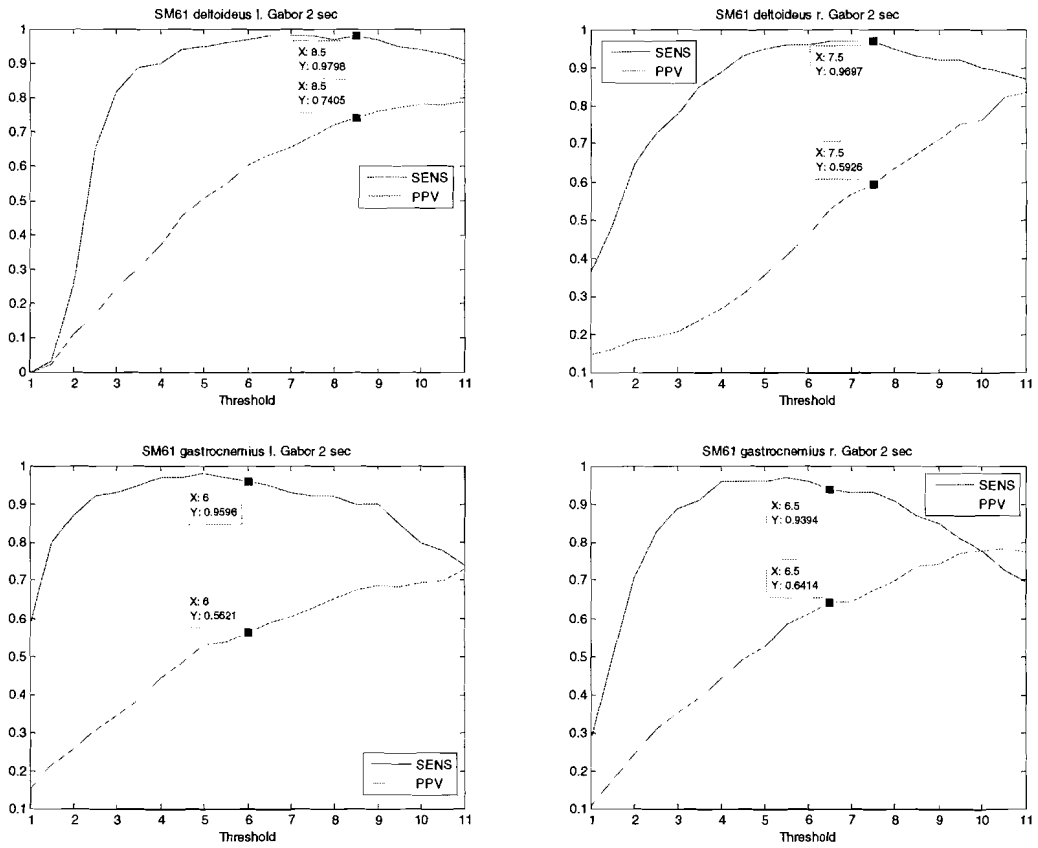Figure 26 Threshold selection for the two individual muscles with an allowed error in the marks of one second when using averaged rectified envelope (top two figures) and Gabor filter (bottom two figures) when using marked muscle contractions as reference. The selected thresholds are displayed in the figures.
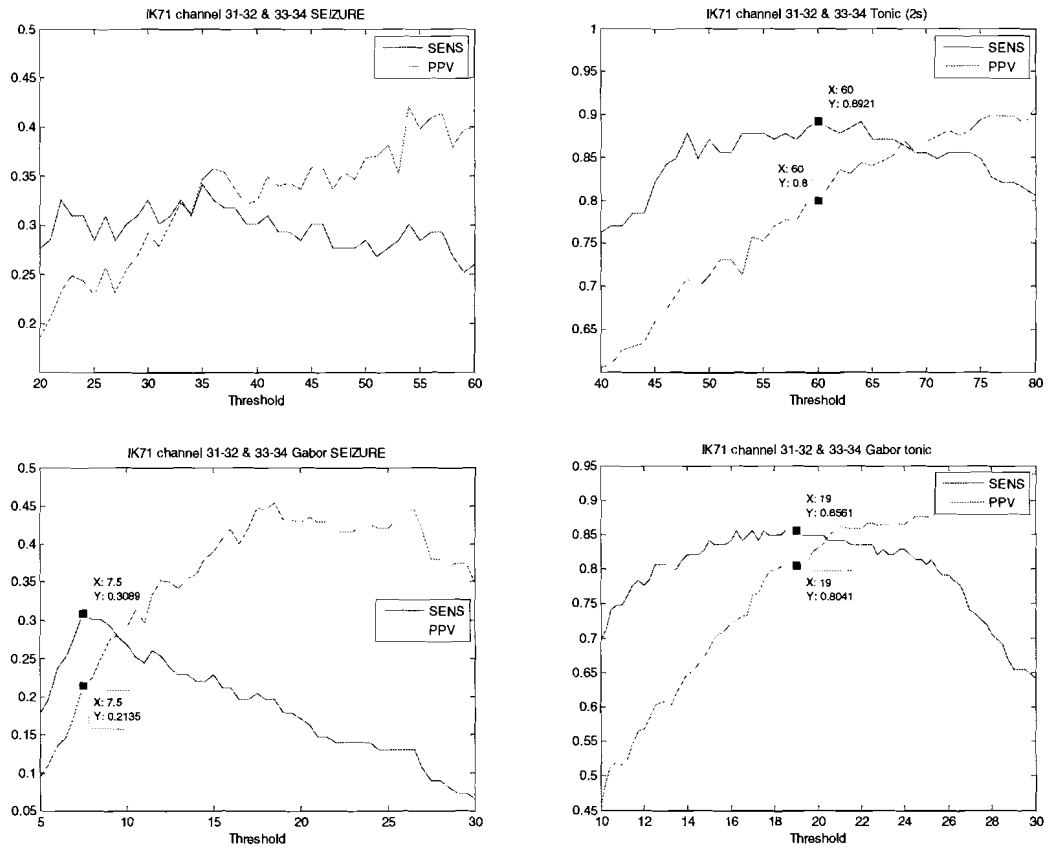
Figure 27 Threshold selection for the four individual muscles with an allowed error in the marks of one second when detecting events marked with seizure.

Channel	Threshold	Signal processing	Allowed mismatch	Reference mark	SENS	PPV
Sp 31-32	33	Rectified	1 sec	muscle contr.	0.667	0.664
Sp 31-32	9	Gabor	1 sec	muscle contr.	0.773	0.699
X 33-34	32.75	Rectified	1 sec	muscle contr.	0.694	0.577
X 33-34	39	Rectified	1 sec	muscle contr.	0.667	0.676
X 33-34	9.5	Gabor	1 sec	muscle contr.	0.778	0.537
Sp 31-32	33	Rectified	1 sec	seizure	0.229	0.363
Sp 31-32	9	Gabor	1 sec	seizure	0.173	0.272
X 33-34	32.75	Rectified	1 sec	seizure	0.201	0.245
X 33-34	39	Rectified	1 sec	seizure	0.184	0.311
X 33-34	9.5	Gabor	1 sec	seizure	0.218	0.203
Sp 31-32	33	Rectified	2 sec	seizure	0.581	0.658
Sp 31-32	9	Gabor	2 sec	seizure	0.615	0.598
X 33-34	32.75	Rectified	2 sec	seizure	0.575	0.537
X 33-34	39	Rectified	2 sec	seizure	0.508	0.615
X 33-34	9.5	Gabor	2 sec	seizure	0.654	0.457

Table 4 Results for the detection of seizures or muscle contractions for the whole night. Rectified = filtered, rectified, averaged; Allowed mismatch = the allowed time between mark onset and detection onset and also applies to the end of the mark and detection; Muscle cont. = marked muscle contractions are used as reference to determine sensitivity and PPV; SENS = Sensitivity.

As can be seen, the performance -on the detection of seizures- of this algorithm is not very high. There is not much difference in the performance of the averaged rectified detection proposal and the Gabor filtering. When allowing the algorithm to have an increased mismatch between the onset and the end of the marked events and the detected events the performance measures could be improved. This suggest that a lot of false positives and false negatives are close to each other in time, or that manual marking is not very accurate time-wise.

Because, for this subject, there are two antagonist muscle recordings available, both of good quality and both activated simultaneously during tonic contractions and seizures, the effect of adding the filtered signal before threshold detection is explored to detect possible simultaneously muscle contractions more accurate.

Channel	Threshold	Signal processing	Allowed mismatch	Reference	SENS	PPV
Both	60	Rectified	1 sec	Muscle cont.	0.722	0.614
Both	19	Gabor	1 sec	Muscle cont.	0.750	0.681
Both	60	Rectified	2 sec	Muscle cont.	0.801	0.730
Both	19	Gabor	2 sec	Muscle cont.	0.810	0.732
Both	60	Rectified	1 sec	Seizure	0.251	0.310
Both	35	Rectified	1 sec	Seizure	0.408	0.205
Both	19	Gabor	1 sec	Seizure	0.184	0.268
Both	7.5	Gabor	1 sec	Seizure	0.380	0.097
Both	60	Rectified	2 sec	Seizure	0.631	0.598
Both	35	Rectified	2 sec	Seizure	0.710	0.336
Both	19	Gabor	2 sec	Seizure	0.603	0.575
Both	7.5	Gabor	2 sec	Seizure	0.765	0.192

Table 5 Performance for seizure and muscle contraction detection for the sum of the two opposite muscles. Rectified = filtered, rectified, averaged; Allowed mismatch = the allowed time between mark onset and detection onset and also applies to the end of the mark and detection; Muscle cont. = marked muscle contractions are used as reference to determine sensitivity and PPV; SENS = Sensitivity.

The sum of filtered Sp and X signal which were applied to the biceps and triceps of the subject does improve the performance. When one second mismatch is allowed the seizure detection reaches a maximum sensitivity of 0.408 at a PPV of 0.205 which is better than the individual channel performance. When two seconds mismatch are allowed the performance increases but the effect of the trade of between sensitivity and PPV becomes more clear.

8.4.2   SM61

Subject SM61 (female, aged 1 year and 5 months) has been in her dormitory for 13 hours from 19:09 to 8:09 the next day. The electrodes are symmetrically applied to the deltoideus and gastrocnemius left and right. Impedances where: deltoideus R 1 & 2 k, deltoideus L 5 & 13 k, gastrocnemius R 6 & 17 k, gastrocnemius L 8 & 33 k. The expert has marked 359 epileptic seizures during the night.
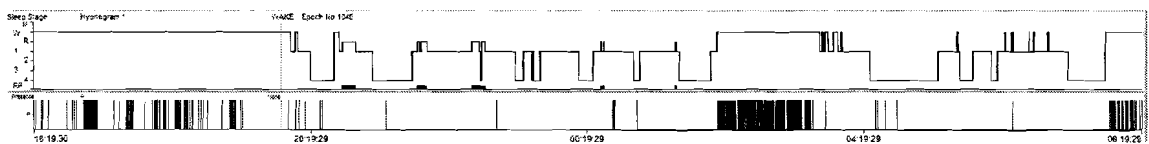
Figure 28 Overview of the night of SM61. Seizures are marked in green. At 3:25 extra medication is applied. On top the sleep stage hypnogram is displayed.

First the optimal threshold is estimated for the two detection proposals based on the marked epileptic tonic muscle contraction. Because the calculation time for MATAB is somewhat high when evaluating the whole night for optimal threshold estimation, here is only 30 minutes used. The selected sample runs from 2:13:31 to 2:43:31. In this segment 99 tonic contractions are marked.
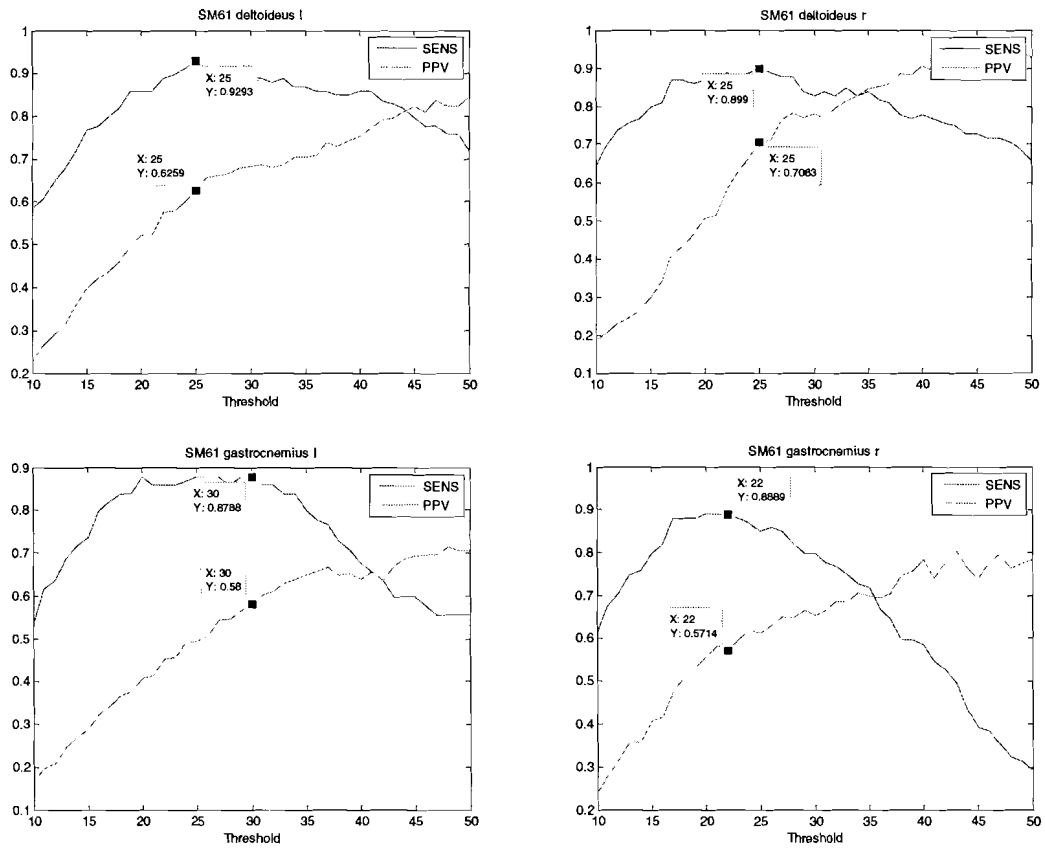
Figure 29 Threshold selection for the averaged rectified signal for the four individual muscles with an allowed error in the marks of one second.
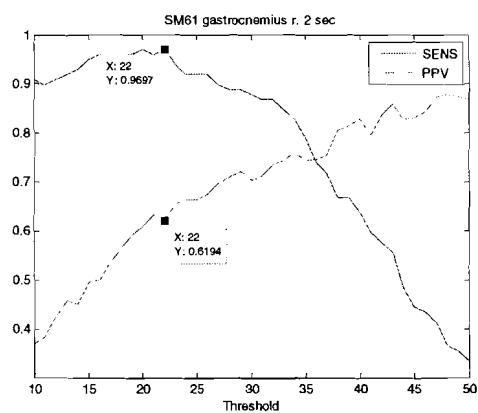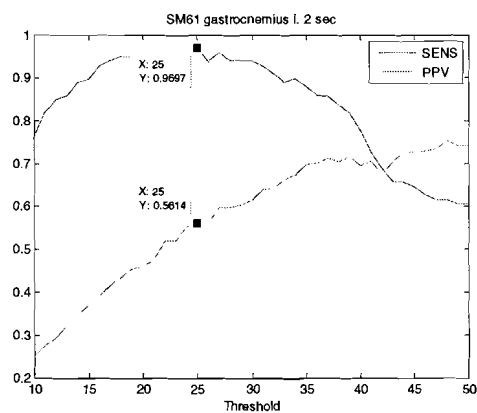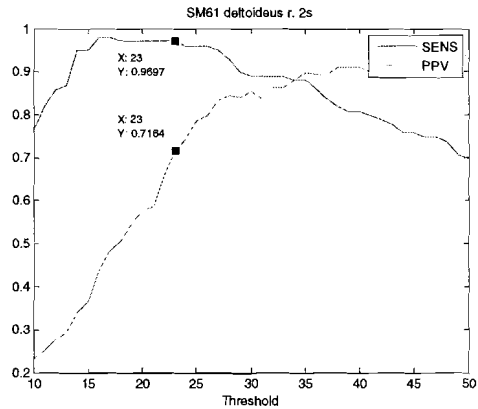
Figure 30 Threshold selection for the averaged rectified signal for the four individual muscles with an allowed error in the marks of two seconds.

Figure 31 Threshold selection for the four individual muscles with an allowed error in the marks of one second using Gabor filter approach.

Figure 32 Threshold selection for the four individual muscles with an allowed error in the marks of two seconds using Gabor filter approach.

Muscle	Threshold	Signal processing	Allowed mismatch	SENS	PPV
Gastrocnemius l	30	Rectified	1 sec	0.630	0.326
	6.5	Gabor	1 sec	0.755	0.300
Gastrocnemius r	22	Rectified	1 sec	0.783	0.356
	5	Gabor	1 sec	0.783	0.288
Deltoideus l	25	Rectified	1 sec	0.822	0.401
	8.5	Gabor	1 sec	0.752	0.390
Deltoideus r	25	Rectified	1 sec	0.702	0.465
	7.5	Gabor	1 sec	0.660	0.382
Gastrocnemius l	25	Rectified	2 sec	0.783	0.324
	6	Gabor	2 sec	0.861	0.314
Gastrocnemius r	22	Rectified	2 sec	0.864	0.390
	6.5	Gabor	2 sec	0.830	0.404
Deltoideus r	23	Rectified	2 sec	0.780	0.471
	7.5	Gabor	2 sec	0.780	0.450
Deltoideus l	25	Rectified	2 sec	0.875	0.427
	8.5	Gabor	2 sec	0.855	0.434

Table 6 Results for the detection of seizure related tonic muscle contraction for the whole night of subject SM61 spent in the bedroom. Rectified = filtered, rectified, averaged; Allowed mismatch = the allowed time between mark onset and detection onset and also applies to the end of the mark and detection; Muscle cont. = marked muscle contractions are used as reference to determine sensitivity and PPV; SENS = Sensitivity.

8.4.3 WK70

Subject WK70 (age 12 years and 4 months) has been in his bedroom for 11 hours and 40 minutes from 19:30 to 7:10 the next day. The electrodes are positioned on the deltoideus muscle, but it is not know on which side. Impedances are also not known. During the night 284 seizures where marked by the expert. Muscle contraction is marked separately, there are 324 muscle contractions marked. (see Figure 33 for a distribution of the seizures and muscle contraction).
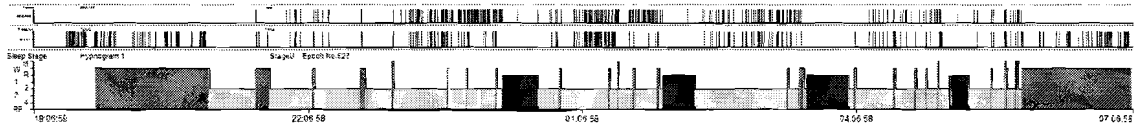
Figure 33 Overview of the night of WK70. Seizures are marked on top in red, muscle contraction in the middle in green. At the bottom the sleep stage hypnogram is displayed, green means awake. Till 21:02 and from 5:55 the subject is awake for a longer time and generates voluntary muscle contractions, which are also marked in green in the middle plot.

This recording was analyzed twice, one time without the time spent awake in the begin and the end of the night and one time for the entire time spend in the bedroom. From 21:02 till 5:55 there were 179 muscle contraction events marked and 284 seizures. Of the 284 marked seizures 143 have a muscle contraction marked inside. This means that 181 seizures have no marked muscle contraction. It is likely that the threshold for optimal seizure detection will be set lower than for optimal muscle contraction detection because also subtle EMG changes have to be detected. This is likely to generate more FPs and thus worse PPV.

The 36 marked muscle contractions outside the marked seizure area are likely to produce FPs to decrease the PPV further when detecting seizures.

8.4.3.1 Threshold determination for sleep segment

Optimal threshold will be determined separately for detection with marked muscle contraction as reference and with the marked seizures as reference. The segment used for the determination of the threshold starts from 1:00 hrs and is 30 minutes long. 40 seizures are marked in this period and 33 muscle contractions.

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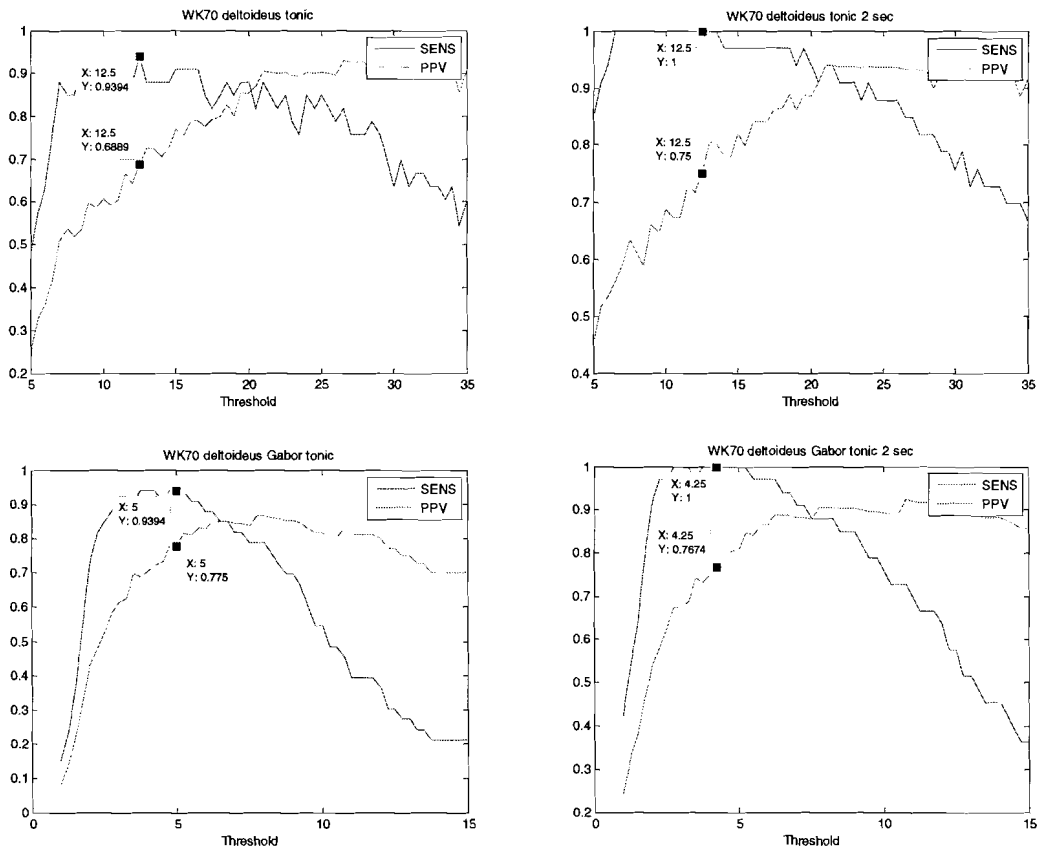
Figure 34 Plots of sensitivity and positive prediction value at different values of the threshold. Top left, averaged rectified with 1 second mismatch allowed, top right, the same with 2 seconds mismatch allowed, bottom left, Gabor filtered with 1 second mismatch allowed and the last Gabor with 2 seconds mismatch allowed.

The detection of seizures, which is the main goal, is not possible for this patient unless we loosen the demands for the mismatch between the marked seizures and the crossing of the threshold of the detected signal. The seizures are marked based on the epileptiform patterns in the EEG. Seizure onsets are marked up to 6 seconds before the start of a marked tonic event and seizure end up to 6 seconds after the end of such an event. See Figure 35 for an example of the mismatch and a seizure without tonic contraction in the recorded signal. Threshold for this new time resolution may differ from estimations made before and will be determined separately.

8.4.3.2 Extended analysis period

Since the subject did not suffer seizures while awake before and after the sleep period at night, the number of detected seizures and seizures with muscle contraction marked inside do not change with the extended analysis time. There are still 284 seizures marked. Of the 284 marked seizures 143 have overlap with a marked muscle contraction. The total number of marked muscle contractions is increased to 324. This means that the potential number of FP increases from 36 to 181.
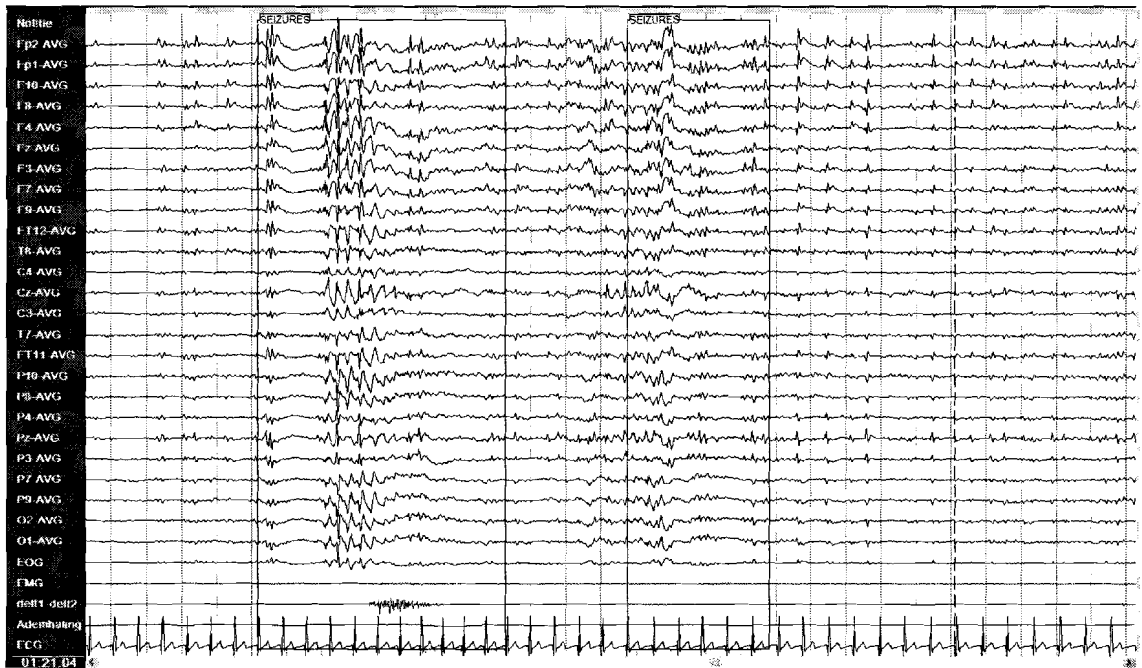
Figure 35 Screenshot of two marked seizures of WK70. Only one of them contains tonic muscle contraction in the recorded channel. The seizure mark starts 3 seconds before and stops 2 seconds after the tonic muscle contraction. The mark for the tonic muscle contraction has been removed to improve the visibility.
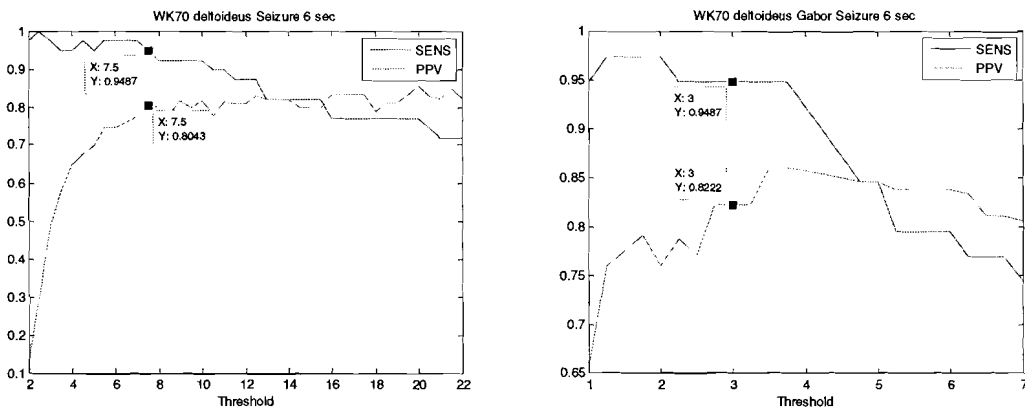
Figure 36 Threshold estimation based on a 30 minute segment for subject WK70. In the left figure the averaged rectified signal is used, on the right the Gabor filter.

8.4.3.3 Results for WK70

The results are calculated twice, one time for the segment where the subject is asleep and one time for the whole period the subject spend in his bedroom.

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				While asleep		Asleep and awake	
Signal processing	Allowed mismatch	Reference	Threshold	SENS	PPV	SENS	PPV
Rectified	1 sec.	Muscle contr.	12.5	0.847	0.445	0.602	0.263
Gabor	1 sec.	Muscle contr.	5	0.903	0.605	0.750	0.349
Rectified	2 sec.	Muscle contr.	12.5	0.926	0.487	0.719	0.318
Gabor	2 sec.	Muscle contr.	4.5	0.972	0.615	0.818	0.389
Rectified	6 sec.	Muscle contr.	7.5	0.949	0.328	0.698	0.239
Gabor	6 sec.	Muscle contr.	3	0.994	0.574	0.821	0.369
Rectified	6 sec.	Seizure	7.5	0.732	0.418	0.732	0.210
Gabor	6 sec.	Seizure	3	0.711	0.656	0.711	0.242

Table 7 Results for subject WK70. Rectified = filtered, rectified, averaged; Allowed mismatch = the allowed time between mark onset and detection onset and also applies to the end of the mark and detection; Muscle cont. = marked muscle contractions are used as reference to determine sensitivity and PPV; SENS = Sensitivity.

As can be seen in the above table the detection of muscle activity is approaching the target values of 90% sensitivity and 50% PPV only during the period when the subject is asleep. This shortened period, however, is not according to our initial intension. For the whole period when the subject is in the bedroom the performance is lower.

For the detection of seizures first of all it should be noted that the allowed mismatch between seizure detection and mark of the expert is set to a 6 times higher value than initially was agreed. Sensitivity stays the same for the whole time in the bedroom as for the shortened analysis time. This is obvious because the threshold stays the same and the number of seizures is also the same. With the additional muscle activity generated during the wake period spend in bed the PPV decreases.

8.5 Discussion for the automatic detection of tonic muscle contraction

Muscle contraction detection was analyzed using the two proposed signal processing approaches in combination with setting a threshold individually per muscle. The differences in performance between band pass filtering using the selected Gabor filter or the averaged rectified value are about 5% in the advantage of the Gabor filter (see Table 8).

The amount of detected simple motor events and PPV are a trade-off. Increasing one value will likely decrease the other. Below a summary of the performance per recorded muscle is presented. The numbers vary per subject. It should be noted that the performance not only depend on the used algorithm but also on the accuracy of the placed marks, not all the marks are placed by the same technician.

Subject	Channel	Averaged rectified		Gabor	
		Sensitivity	PPV	Sensitivity	PPV
IK71	Sp	0.667	0.664	0.773	0.699
	X	0.694	0.577	0.778	0.537
SM61	gastrocnemius l	0.630	0.326	0.755	0.300
	gastrocnemius r	0.783	0.356	0.783	0.288
	deltoideus l	0.822	0.401	0.752	0.390
	deltoideus r	0.702	0.465	0.660	0.382
WK71	deltoideus	0.602	0.263	0.750	0.349
mean		0.70	0.43	0.75	0.42
std		0.079	0.143	0.042	0.148

Table 8 Overview of values for detection of tonic simple motor events with one second allowed between mark onset and detection onset. The same interval applies to the end of the mark and detection. In the bottom two lines Gabor and averaged rectified value for threshold detection are compared.

For this project the target is set to detect simple motor events in an accurate way and evaluate the potential value of these detected events for automated seizure detection. The decision about at what exact moment an alarm should be generated is always open for discussion. However it should be noted that during normal sleep muscle activity is far less then recorded in our subjects. If there is more than a certain, to be determined by the clinical user(s), amount of muscle contraction in a time frame an alarm is appropriate. This may imply that the subject is awake or is having a seizure. The current sensitivity and PPV can be improved by adapting the way the automated detections are judged. The time resolution is not of extreme importance and muscle contractions of higher force are in general more interesting than that of low force. The threshold could be set higher to detect the more serious seizures and decrease the false alarm rate.

The constrains for the determination of the sensitivity and PPV are more strict chosen than used to evaluate most other automatic seizure detection systems. Especially the timing constrain at the end mark is rather firm and in our disadvantage because after a seizure repositioning movements are often seen. Other projects tolerate a timing difference of 3 seconds [36] and others are only interested in detecting the onset of a seizure [38].

The data which is used for the determination of the threshold is included in the analysis. It would probably be better to exclude it. The effect is shown in the Table 9. The sensitivity decreases by 9 and 7 percent for the filtered averaged rectified and the Gabor filter proposal respectively. The PPV decreases by 17 % in both cases.

Subject	Channel	% in training set	Training set included Sensitivity	PPV	Training set excluded Sensitivity	PPV
IK71	31-32 R	139 / 221 ≈63 %	0,667	0,664	0,439	0,371
IK71	31-32 G		0,773	0,699	0,573	0,359
IK71	31-32 R		0,694	0,577	0,598	0,329
IK71	31-32 G		0,778	0,537	0,695	0,268
SM61	Gastrocnemius l. R	99 / 359 ≈28 %	0,630	0,326	0,535	0,204
SM61	Gastrocnemius l. G		0,755	0,300	0,715	0,202
SM61	Gastrocnemius r. R		0,783	0,356	0,742	0,233
SM61	Gastrocnemius r. G		0,783	0,288	0,754	0,198
SM61	Deltoideus l. R		0,822	0,401	0,781	0,256
SM61	Deltoideus l. G		0,752	0,390	0,700	0,246
SM61	Deltoideus r. R		0,702	0,465	0,631	0,297
SM61	Deltoideus r. G		0,660	0,382	0,569	0,247
WK70	Deltoideus R	33 / 324 ≈10 %	0,602	0,263	0,564	0,190
WK70	Deltoideus G		0,750	0,349	0,729	0,244
MEAN	**Rectified**		**0,70**	**0,44**	**0,61**	**0,27**
STD	**Rectified**		**0,08**	**0,14**	**0,12**	**0,07**
MEAN	**Gabor**		**0,75**	**0,42**	**0,68**	**0,25**
STD	**Gabor**		**0,04**	**0,15**	**0,07**	**0,05**

Table 9 Results compared with and without training set included in analysis. R = filtered, rectified, averaged; G = Gabor; l. = left; r. = right.

No difference between seizure related muscle contractions and voluntarily or normal muscle contraction could be found. The reason that this approach to detect muscle activity can be used to detect seizures is primarily because these subjects frequently show seizures. The younger subjects tend to have less voluntarily movement during time in their bedroom than the older subject.

8.6 Selected detection proposal

The differences in performance between the two detection proposals are in favour of the Gabor band pass filter. Therefore, it is suggested to use this type of filters.

8.7 Further detection proposals

No difference between seizure related muscle contractions and voluntarily or normal muscle contraction could be found. The detection of a cluster of tonic seizures can be based on the current detection proposal for detection of simple tonic motor events. The challenge will be to determine the optimal settings for the threshold for the amount of motor events per time frame in combination with the threshold for the detection of motor events itself and to set up a set of rules that determine when a alarm is really needed.

The use of the fact that tonic muscle contraction seems to affect agonist and antagonist simultaneously can be explored in further extend. For subject IK71 a first attempt had

been made to add the two rectified signals before threshold detection, but one could try to use separate thresholds for the separate channels and design a set of rules about the interval that both signals need to be above threshold.

In this project the data which is used for the determination of the threshold is included in the analysis. It would probably be better to exclude it. It would be interesting to investigate the effect of the use of one fixed threshold for all patients. Determination of the threshold a priory by the measurement of the SEMG at maximum voluntary contraction can be considered, but for the young children this measurement is most likely not successful as long as they are not capable of following the instructions.

9 Detection of Clonic events

For the detection of clonic events there is only one nocturnal recording of one patient available. In this recording there was only a single seizure that would have required intervention. Values for sensitivity and PPV are not meaningful. In this chapter a strategy is proposed to detect this type of seizures.

The description of clonic muscle contraction suggests that single compound muscle action potentials should be recognised in the surface EMG readings (see chapter 5.1.1 for a description). Simulated readings of a single MUAP show a tri-phasic transient waveform (see Figure 10). The CMAP is a summation of MUAPs. The EMG bursts are supposed to occur simultaneously in an antagonist–agonist pair. After the burst there should be a relatively silent period in the EMG. A first approach to distinguish between these specific waveforms and normal muscle contractions is made.

This chapter will start with some examples of waveforms recorded at our clinic that are associated with clonic muscle contractions. The examples are compared to the description given before. Then a first attempt will be made to detect single CMAPs. With the insights that are obtained from this pilot study a second proposal based on the repetitive occurrence of the clonic muscle contractions is presented.

9.1 Subject RB65

The only subject in the dataset who showed clonic muscle contractions and where the SEMG recordings were of sufficient quality is RB65 (male, age 12 years and 3 months). He spent 10 hour and 44 minutes in his bedroom from 20:32 to 7: 16 the next day. It took 11 minutes before the first sleep was noticed. He was awake 5 minutes before he left his bedroom. About 20 epileptic isolated clonic movements where marked by the expert. Three episodes with repetitive myoclonic movements, are marked. At one of these episodes consciousness is lost and intervention was necessary. This episode took place in his bedroom and would have been the domain of an automated seizure detection system, the other two where during breakfast.

EMG electrode impedances as measured earlier on the registration day where 139, 84, 35 and 57 kΩ, the first two values for the biceps and the second two for the triceps of the same arm. It is likely that the impedances have been improved by the technician but not measured again because the recording shows little artefacts.

9.2 Example signal

To explore the features of the surface EMG signal observed during clonic muscle contraction some example signals are presented. We start to represent the signals in the way they are seen by the expert. The presented signals are compared with the descriptions found in the literature (as described in section 5.1.1).

Figure 37 shows a section with a seizure marked as clonic in it. There are about 17 comparable segments marked during the night. Both muscles are not always involved in these brief seizures. In this example both muscles are activated, but the amplitude is relatively

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low compared to other voluntarily muscle contractions of the same patient. A peak to peak difference of about 800 μV is measured compared to approximately 2.5 mV in normal contractions. The EMG of the deltoideus was also recorded, but this recording shows only motion artefacts during the short movements and thus has been left out.

The CMAP follows the sharp wave in the EEG within the prescribed time frame of 17 – 50 ms. The EMG burst length supposed to be beneath 50 ms, but 50 – 100 ms is also accepted [13,14,40]. This burst is about 95 ms long. The synchronisation between the antagonist and agonist as shown in Figure 12 can be assumed present; the maximum and minimum of the EMG of both channels occur approximately simultaneously in Figure 37. This observation does not hold for all the other clonic marked events of this subject. Counter phase and other phase differences has also been observed. We observed that the onset of the muscle contraction is always synchronic when both muscles do participate, i.e. at our time resolution of 5 ms the EMG signal of both muscles starts to change at the same time, but not always in the same direction.
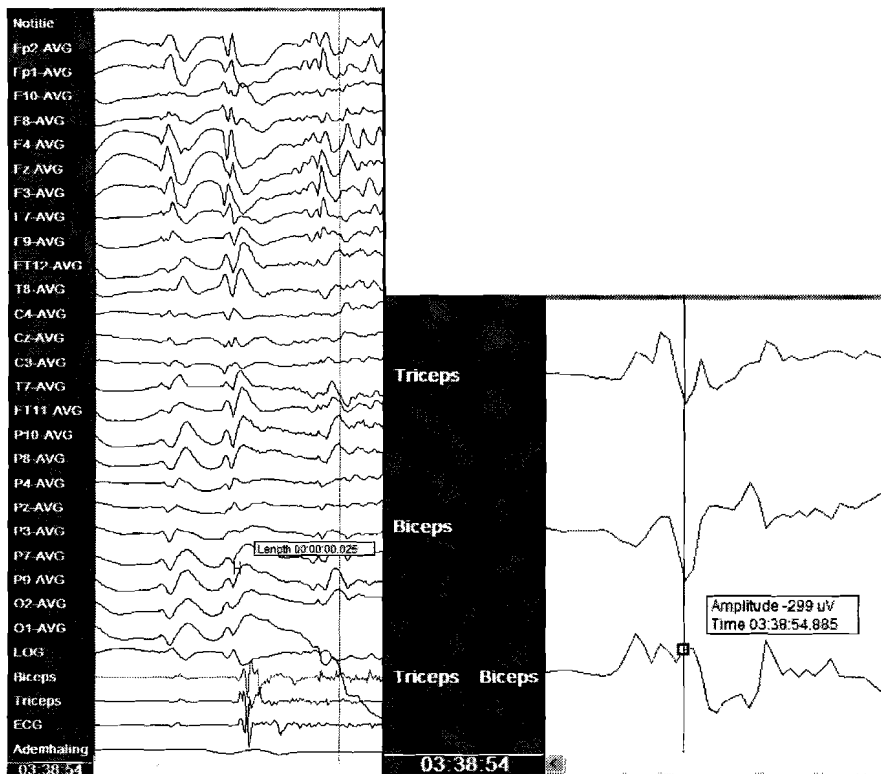
Figure 37 This section of subject RB65 is marked as clonic by the expert. The patient does show a shock like movement on the simultaneously recorded video and wakes up immediately after this seizure. Latency of 25 ms is within the margin of 17 – 50 ms. Some form of synchronization may be imagined in the right picture. The burst length is about 95 ms and the peak to peak voltage difference about 800 μV. A relatively silent period is observed during the slow wave.

Figure 38 shows the seizure that has to be detected. It is marked as a clonic seizure but does not exactly match the description that was found in literature and adopted as

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guideline for this project. The EMG bursts are far too long. Synchronism between biceps and triceps is not observed in the way it is described in 5.1.1.1.
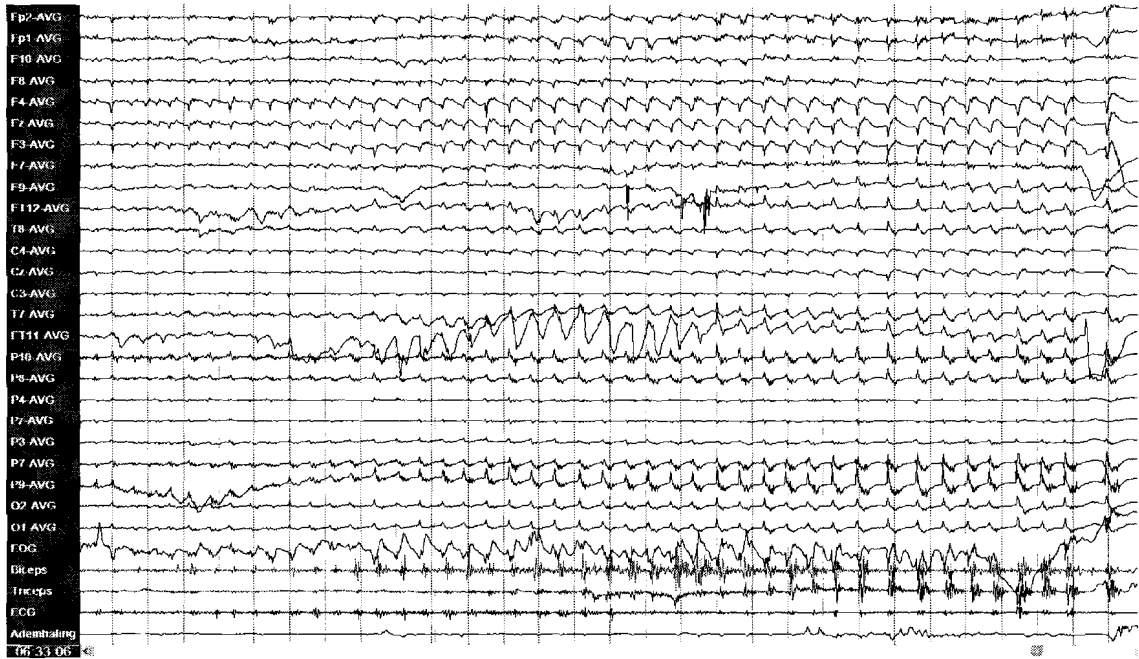
Figure 38 This section is marked as a clonic seizure. In this picture the end of the ictal period is shown. The subject looses consciousness during this seizure. This is marked as a seizure that would potentially require intervention.

9.3 Straightforward approaches

Straightforward approaches in both time- and frequency domains turn out not to be adequate because the lack of specificity in clonic seizure-related activity when compared to other EMG activity. For the frequency domain, this is illustrated in Figure 39. The power spectral density of clonic EMG bursts do not differ from other muscle contractions, at least not in our recordings sampled at 200 Hz. The plot shows a summation of FFTs to show that there are no specific frequency peaks detectable in the clonic EMG readings.
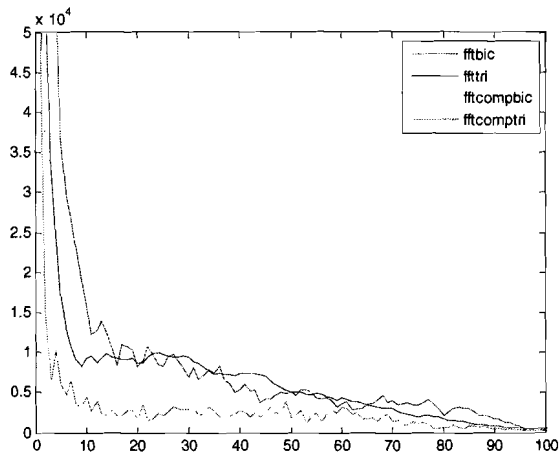
Figure 39 Summation of the FFT of 13 clonic segments of subject RB65 compared with the sum of 13 random selected segments. The power spectrum does not show a useful peak.

9.4 Wavelets

In the assumption that individual CMAPs would have to be detected and because wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series, the use of wavelets is explored.

The choice of a wavelet function is a somewhat arbitrary choice. However it should be noted that the same arbitrary choice is made in using one of the more traditional transforms such as the Fourier, Bessel, Legendre, etc. In choosing the wavelet function, there are several factors which should be considered. This includes orthogonal or nonorthogonal, complex or real, width and shape. All these factors are explained in short below.

9.4.1   Orthogonal or nonorthogonal

A nonorthogonal analysis is highly redundant at large scales. This type of transformation is useful for signals with smooth, continuous variations in amplitude. For the detection of muscle activity an orthogonal wavelet function will be appropriate.

9.4.2   Complex or real

A complex wavelet function gives information about amplitude and phase and is better adapted for capturing oscillatory behaviour. A real wavelet function provides only a single component and can be used to isolate peaks or discontinuities. To detect clonic muscle activity a real wavelet function will be sufficient. In case of tonic contraction we will consider a complex wavelet.

9.4.3   Width

The width of the wavelet function is a trade-off between frequency resolution and time resolution. A broader function in time will have better resolution in frequency, but worse in time. For our application the exact frequency is not important. The same holds for the exact location in time as long as the reaction time is within the seconds range. The most

important property is to discriminate between seizure related muscle activity and all other signals. This will probably require more resolution in frequency domain than in time domain.

9.4.4 Shape

The wavelet function should reflect the type of features present in the time series. For time series with sharp jumps or steps, one would choose a boxcar-like function, such as the Haar wavelet, while for smoothly varying time series one would choose a smooth function such as a damped cosine. If one is primarily interested in wavelet power spectra, then the choice of wavelet function is not critical, and one function will give the same qualitative results as another [43].

9.4.5 Discrete wavelet transform

The discrete wavelet transform (DWT) of a sampled signal x[k] is calculated by passing it through a series of filters. First the samples are passed through a low pass filter with impulse response g. The signal is also decomposed simultaneously using a high-pass filter h. The outputs giving the detail coefficients (from the high-pass filter) and approximation coefficients (from the low-pass).

However, since half the frequencies of the signal have now been removed, half the samples can be discarded according to Nyquist's rule. The filter outputs are then down sampled by 2:

$$y_{low}[n] = \sum_{k=-\infty}^{\infty} x[k]g[2n-k]$$

$$y_{high}[n] = \sum_{k=-\infty}^{\infty} x[k]h[2n-k]$$
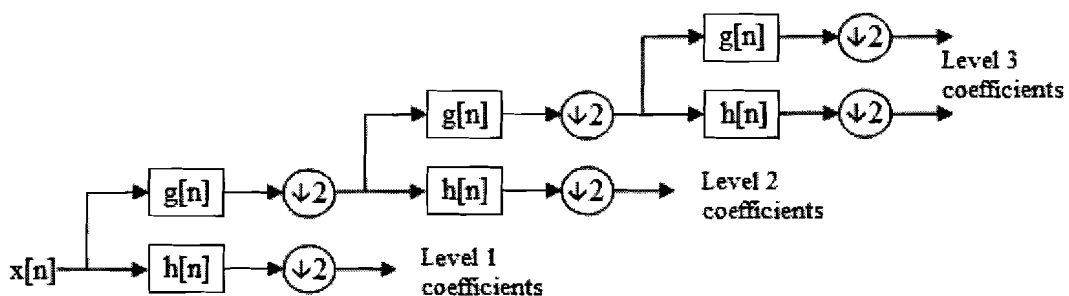
Figure 40 Filter structure used by MATLAB to calculate the DWT [33].

9.4.6 Continuous Wavelet Transform

The wavelet transform of a signal s(t) is the family C(a,b), which depends on two indices a and b. The set to which a and b belong differs for the continuous wavelet transform (CWT) compared to the DWT. For the CWT the coefficients are chosen using a redundant representation close to the so-called continuous analysis, instead of a non-redundant discrete time-scale representation of the DWT.

$$C(a,b) = \int_R s(t) \frac{1}{\sqrt{a}} \Psi\left(\frac{t-b}{a}\right) dt$$

In case of CWT: $a \in R^+ - \{0\}, b \in R$ (where R denotes the real valued numbers)

For the CWT the mother wavelet Ψ is stretched in a continuous way

While in case of DWT $a = 2^j, b = k2^j, (j,k) \in Z^2$ (where Z denotes integers) the wavelet Ψ is stretched in discrete steps [24].

9.5 Selected wavelet family

Wavelets commonly used for de-noising biomedical signals include the Daubechies (db2, db6 and db8) wavelets and orthogonal Meyer wavelet. The wavelets are generally chosen whose shapes are similar to those of the MUAP [45]. After comparing these wavelets with each other, the Daubechies 6 wavelets was selected for this project. It is a real valued orthogonal wavelet that is suitable for the discrete wavelet transform.
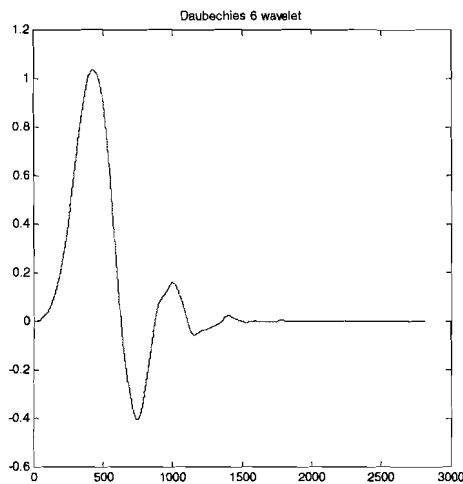
Figure 41 Waveform of the Daubechies 6 mother wavelet.

9.6 Wavelet transform applied

To evaluate the potential value of the wavelet transform the segments of the surface EMG recordings of subject RB65 where analyzed. The scale and level that showed the most power during epileptic muscle contractions where selected. For this subject scale 11 of the CWT and level 3 and 4 of the DWT where selected for further analyses. Selection is done by calculating the total power of each scale and each level for al clonic marked EMG within a 30 minutes segment. This distribution of the energy over the scales and levels is compared with the distribution during the rest of the, not as clonic marked, EMG. The scale and level where the difference between those distributions was maximal was selected. Level 3 of the DWT contained more difference in power, but with marginal difference with level 4 so both are selected.

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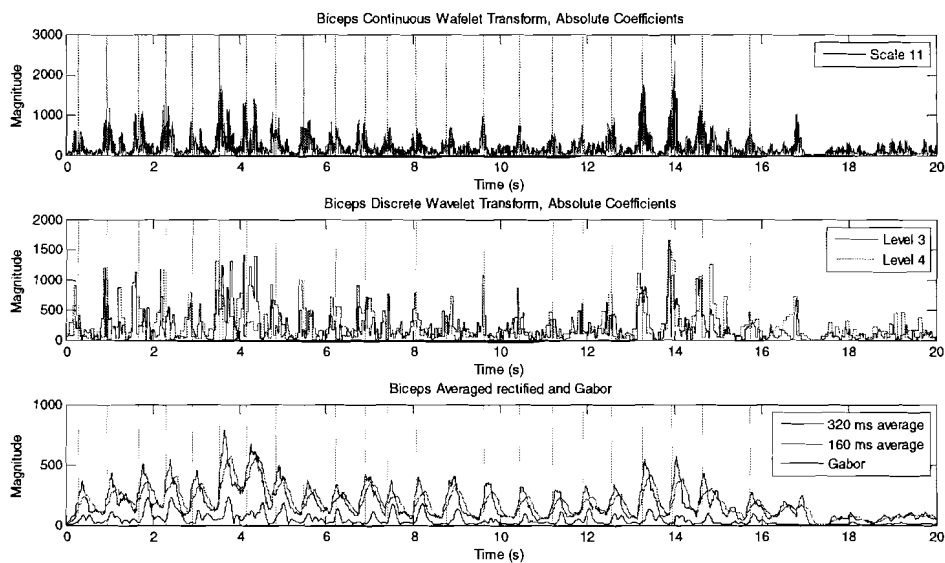
Figure 42 Example of extracted signal using scale 11 of the db6 continuous wavelet transform and level 3 and 4 of the discrete version. The selected scale and levels showed the highest energy during clonic muscle contraction. Clonic muscle contraction is marked with a green line by the expert.

As can be seen in Figure 42 the extracted signals using wavelet analyses do show changes in energy during clonic muscle contractions. In the figure below can be seen that also a not seizure related EMG signal is detected by the CWT and DWT. To compare the wavelet transform with the filtering that was applied for detection of the tonic muscle contraction the filtered signals are also included in the previous and next plot.
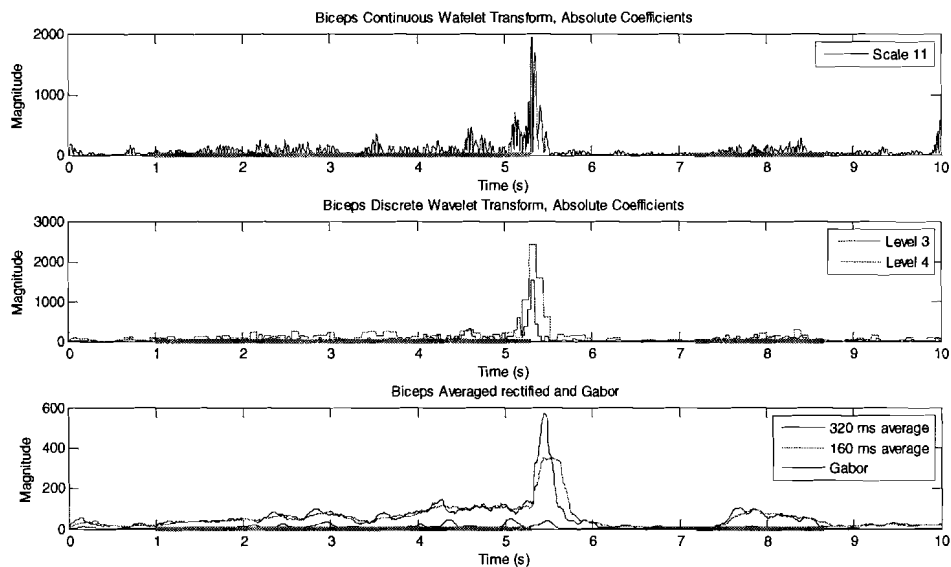
Figure 43 Same analyses as in the figure before, but this time a normal muscle contraction is shown, marked with a light blue line in the bottom of the plots.

Wavelet analyses, like expected after exploring the characteristics of the recorded signal at our clinic, do not extract more useful information than the averaged rectified signal does. A further attempt to extract the clonic simple motor events was discontinued. In the next section a proposal for the detection of recurrent clonic movements is presented based on the already explained averaged rectified SEMG signals which were used for the detection of tonic muscle contraction before (see section 8.2.2).

9.7 Further detection proposal

The clusters of clonic muscle contractions in a clonic seizure occur in a rhythmic manner (see Figure 38 and Figure 42). Repetitive clonic contraction are probably more important to detect than single contractions. The oscillatory behaviour could provide useful information about the presence of a clonic seizure. This idea is explored in more detail in the next section.

9.7.1 Spectrogram of extracted features

Here a strategy is proposed to detect repetitive clonic contractions. When the CMAPs occur repetitively the frequency of occurrence is typically 1.6 – 3.4 Hz [14]. The average frequency of the occurrence of the EMG bursts for our subject is about 1.38 Hz (10 burst in 7.24 seconds, see Figure 42).

To examine whatever the change in frequency can be noticed a spectrogram is drawn. Time is displayed in seconds from the bottom to the top and the band power is represented in color. Blue means that there is no energy present in that particular bans at that time, red means the opposite.

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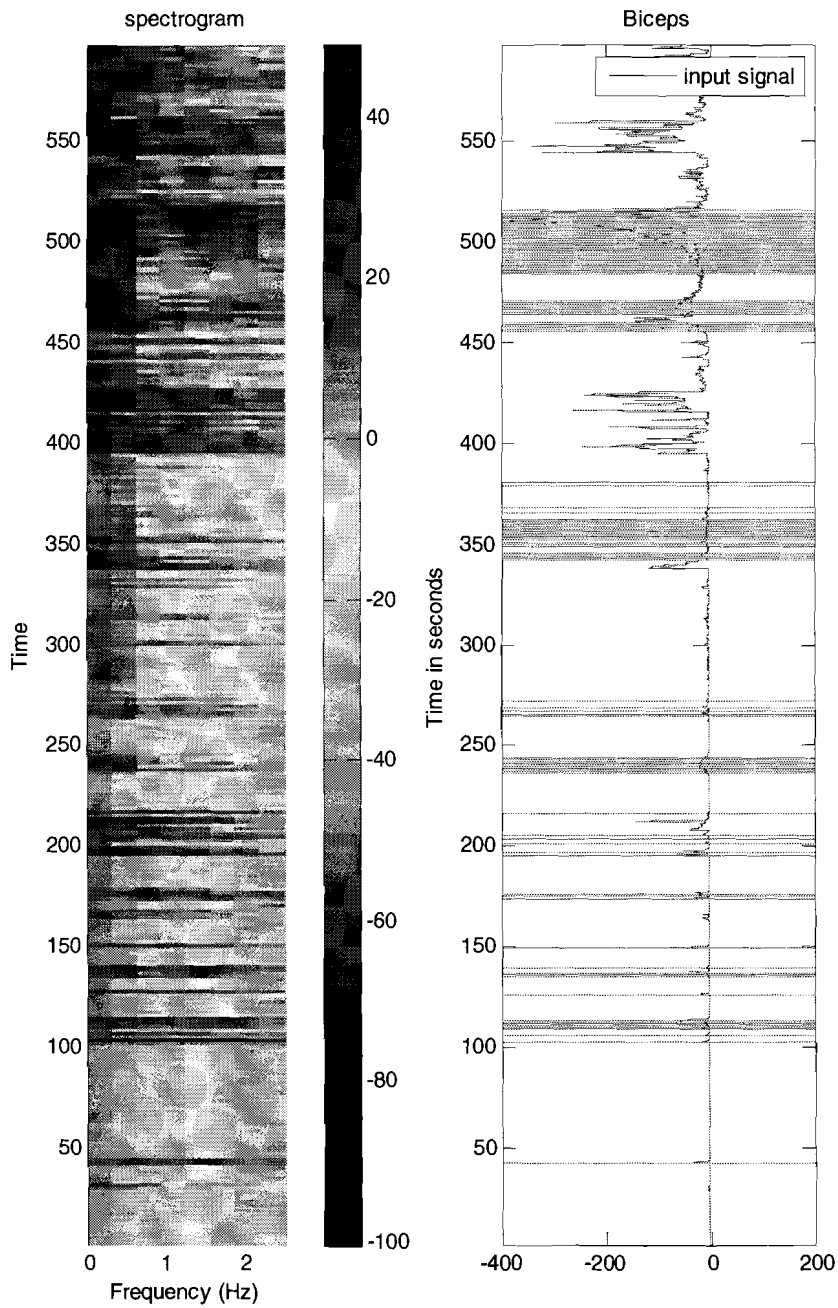
Figure 44 Spectrogram of a 10 minute segment including a seizure that should be detected around the 500ᵗʰ second. On the left the spectrogram is shown. On the right the filtered input signal is shown in red and the single clonic muscle contractions are marked in green. The isolated red spot around the 500ᵗʰ second and the 1.5 Hz represent the seizure.

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Around the 500th second after the start of the depicted segment (in Figure 44) the seizure occurred. An isolated red spot at that time around 1.5 Hz is observed. This spot represents the seizure. Now we will take a closer look at the moment of the seizure.
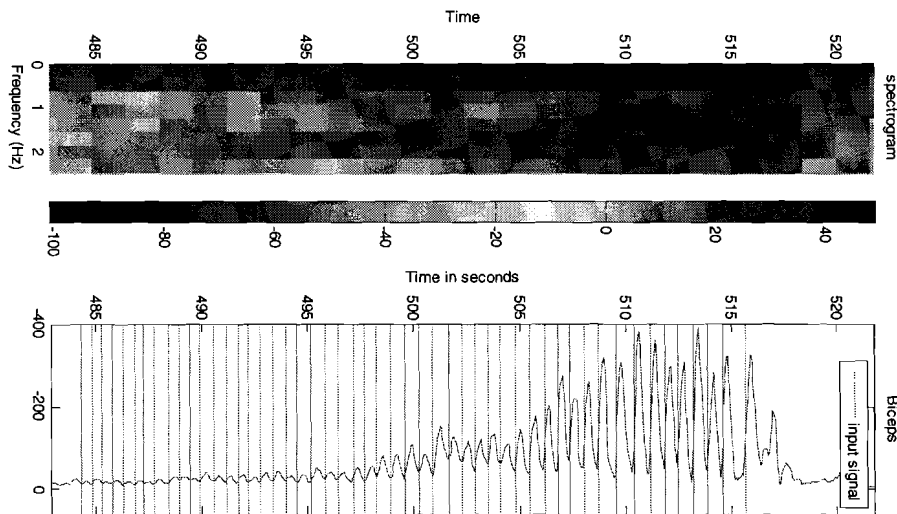
Figure 45 A closer view on the seizure that should be detected as depicted in Figure 44
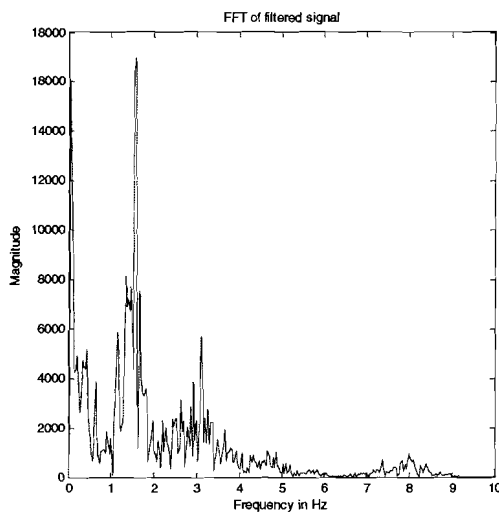
Figure 46 Fast Fourier Transform of the segment from second 485 till 515 of the above figure. The detected peak frequency is about 1.5 Hz.

At the moment of the seizure there is indeed a sharp peak witnessed in the FFT. If such sharp peaks always and only occur during seizures the detection of such isolated peaks in the range from 1.3 – 3.4 may provide useful information. Since we have only one seizure of this type available we can not guaranty that such peaks are always present in every severe

seizure. The other way around we can search for other oscillatory sources that could possibly interfere with this proposal.

One example of repetitive muscle contractions is found in the record. At 4:16 hrs in the night the subject is scratching his knee. The frequency of this movement is about 1 Hz and comes close to the frequency observed during the seizure (see Figure 47 and Figure 48). Fortunately the muscle contractions of scratching are in counter phase and those of a seizure in phase.
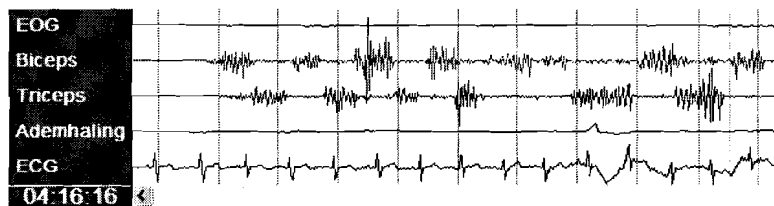
Figure 47 Non epileptic rhythmic muscle contraction. The subject is scratching his knee. The mean frequency of occurrence of the EMG bursts is around 1 Hz. jerk
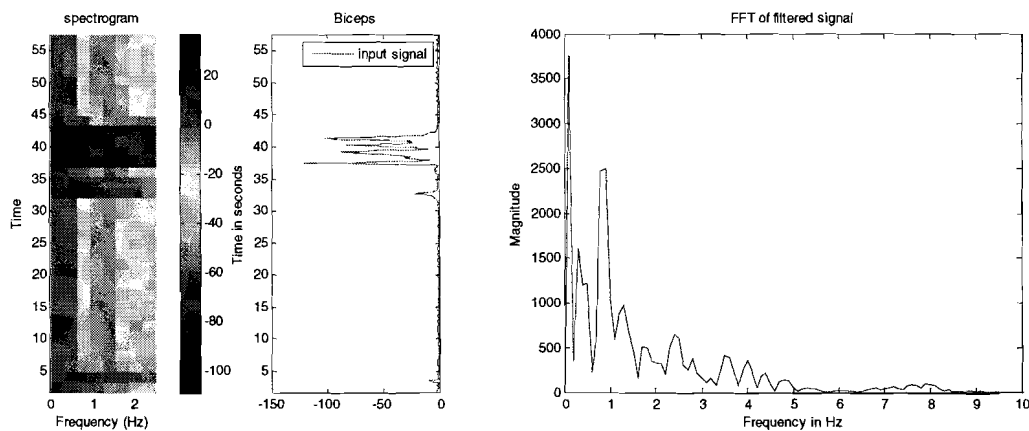
Figure 48 Spectrogram, filtered input signal from the biceps EMG and FFT of the segment containing the scratching as showed in Figure 47

9.8 Discussion for the detection of clonic events

The SEMG of clonic muscle contractions as recorded in our clinic in one patient is explored and compared to the description that was found in the literature and adopted as guideline for the detection proposal using wavelet analyses. In an early stage it is discovered that a) detection of single clonic events is not likely to be successful and b) it does not provide clinical relevant information. A possible detection strategy is presented that needs further research.

10 Conclusion and discussion

The goal of this master's project was to develop an automatic detection algorithm to detect simple motor events in an accurate way and to evaluate the potential value of these detected events for automatic detection of seizures that require intervention. To reach this goal clonic and tonic SEMG signal of epileptic origin were analysed. The use of SEMG is new in the context of automatic seizure detection. Two detection proposals for simple tonic motor events are presented and evaluated. For the detection of clonic muscle contractions a separate detection proposal based on wavelet analyses is explored and a clonic seizure detection proposal is presented.

For the tonic seizures we tested a simple detection algorithm. The results of this trial are promising with a sensitivity of 75% and a PPV of 42% for the detection of the tonic simple motor events, but the initial target was set higher. When the same detection algorithm is used for the detection of marked seizures the performance decreases. We have to realize that this was a simple test and more research needs to be done before a complete automatic detection algorithm can be realized. The length and the distribution in time of the tonic muscle contractions can be a measure for the probability that the patient needs medical assistance. Our results suggest that SEMG is useful in the context of tonic seizure detection.

The SEMG of clonic muscle contractions as recorded in our clinic in one patient is explored and compared to the description that was found in the literature and adopted as guideline for the detection proposal using wavelet analyses. In an early stage it is discovered that a) detection of single clonic events is not likely to be successful and b) it does not provide clinically relevant information. A possible detection strategy for clonic seizures is presented but needs further research.

We believe that the detection of simple motor events can be used as building blocks for the development of more advanced seizure detection algorithms.

We believe that this thesis contains a basis for future research. We realize that much needs to be done in the future to approach the final goal of a reliable seizure detection system. A number of issues have to be investigated:

- The use of more than one module in a multi modal automated seizure detection system is only useful if the modules are complementary to each other. Different modules should produce FP and FN at different conditions otherwise there is no additional value. This should be analysed.

- The evaluation test we carried out included the data of only three patients. These patients suffer from clusters of tonic seizures. In the future we also have to test how well this approach works in other patients with seizures more even distributed in time.

- The sample frequency of the EEG equipment used for this study is too low to explore exact waveform, it is possible that there can be more information extracted when a higher time and spatial resolution is used.

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12 List of abbreviation

ACM accelerometry

CMAP Compound Muscle Action Potential

CWT Continuous Wavelet Transform

DWT Discrete Wavelet Transform

EEG ElectroEncephaloGraphic

EMG ElectroMyoGraphy

EPP End-Plate Potential

EOG Electrooculography

FFT Fast Fourier Transform

M1 primary motor cortex

RR Relative Risk

SEIN Stichting Epilepsie Instellingen Nederland

SEMG Surface ElectroMyoGraphy

SMA Supplementary Motor Area

SUDEP Sudden Unexpected Deaths in Epileptic Patients

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15 Appendix

15.1 Program code segment

15.1.1 Gabor2

This function returns the filter coefficients for the specified Gabor filter. freq determines the centre frequency in hertz, Fs is the sample frequency, windowl determines the length of the returned filter coefficients and alpha is a measure for the frequency resolution versus time resolution.

```
function [gab]=gabor2(freq, Fs, windowl, alpha)
v=freq;
t=linspace(-windowl/(2*Fs),windowl/(2*Fs),windowl);
if nargin < 4; alpha=1; end
gab = exp(-t*pi*i*v*2 - (v*pi/alpha)^2*(t.^2));
Nv=sum(abs(gab));
gab=gab/Nv;
```