Pattern Recognition using Surface Electromyography of the Anterior Temporalis and Masseter muscles.

by

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Abstract

Many factors are thought to be involved in the dynamic interplay, or equilibrium between the different components of the masticatory system. Studies have attempted to analyse the normal functional, and parafunctional behaviour of the masticatory muscles. The most widely used treatment mode for parafunctional behaviours is an intra-oral occlusal apppliance (or splint), and the mechanism of action of intra-oral splints remains controversial. There has been no attempt to link muscle activity pattern recognition with the jaw movements produced, or for that matter with the resultant forces developed. Neither has a satisfactory method for pattern recognition been proposed to analyse jaw movement patterns.

The aim of this study was to develop a pattern recognition system capable of predicting forceful movements of the jaw using an occlusal appliance, and to develop an analytical methodology for discriminating the features of EMG recordings of the 4 muscles relative to specified intra-oral tasks.

The experiments were divided into three main studies:

A reproducibility study , in which a subject, using an occlusal splint and performing a series of prescribed movements was recorded using EMG of the anterior temporalis, and masseter muscles bilaterally. This showed that it was possible to identify patterns on a daily basis, and that it was possible to discriminate between different movement directions more reliably than different movement speeds. A pattern recognition study was performed utilizing the previous results, and showed that for the same subject it was possible to predict the movements 98.2% of the time for the 5 day period. The final study involved the pattern recognition for a sample group of 10 subjects, this resulted in a 95.7% success rate overall for movement prediction.

This study has shown that using a relatively simple computer algorithm, the smoothed and filtered EMG waveform, and discriminant analysis, it is possible to discriminate between different simulated bruxist-like movements

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1.1 Introduction

Many factors are thought to be involved in the dynamic interplay, or equilibrium between the different components of the masticatory system. Loss of structural integrity, altered function, or biomechanical overloading can compromise adaptability, and increase the likelihood of dysfunction by disrupting this equilibrium (Parker 1990, Mcneill 1991).

In order to gain a greater understanding of the masticatory system, many studies have attempted to analyse the normal functional, and parafunctional behaviour of the masticatory muscles. Parafunctional habits refer to oral behaviours that do not serve the common functions of swallowing, chewing, incising and speaking, and occur in both children and young adults. These parafunctional habits may overload the jaw joints and masticatory muscles, and contribute to the signs and symptoms of dysfunction. They may include lip and cheek biting, jutting the jaw forward, or eccentrically, atypical chewing, chronic gum chewing, unilateral chewing, and bruxism.

1.2 Bruxism

Bruxism has been defined as an oral parafunctional activity that can occur when an individual is asleep or awake (American academy of orofacial pain 1996). More recently however, bruxism has been classified into primary (idiopathic), and secondary (iatrogenic) forms. In the absence of a medical cause, primary forms of bruxism include daytime clenching and Sleep Bruxism. Secondary forms of bruxism are associated with either neurologic, psychiatric or sleep disorders, or with the administration, or withdrawal of drugs. (Lavigne 2000)

Bruxism occurring during wakefulness should be differentiated from Sleep Bruxism, because the two conditions occur under different circumstances and have been considered different entities (Rugh 1989)

1.3 Sleep Bruxism

The American Academy of Sleep Medicine has classified Sleep Bruxism as a parasomnia (a sleep disorder which is not an abnormality of the processes for sleep and

awake states per se, but rather as an undesirable physical phenomenon that occurs during sleep) . Sleep Bruxism has also been defined as an oral parafunctional activity during sleep, and is considered an involuntary oromandibular movement with tooth grinding or clenching during sleep, regardless of cause (Thorpy 1997). Reports of current tooth-grinding are essential elements in the diagnosis of this condition, whereas the appearance of tooth wear and reports of muscle tightness are less reliable (Bader and Lavigne 2000, Lavigne and Manzini 2000).

It is currently thought that the jaw elevator muscles commonly exhibit three basic patterns of activity during sleep bruxism: rhythmic, chewinglike movements, that are repetitive and phasic (three or more bursts of muscle contractions at a frequency of 1 Hz), prolonged, strong, isotonic contractions of the jaw closing muscles (contractions lasting more than 2 secs), or a mixture of both types (Ware and Rugh 1988, Lavigne et al 1996). An anlaysis of electromyographic studies (EMG), shows that 88% of sleep bruxism episodes are either phasic, or of the mixed type, 60% of these occur during light sleep, and the mean frequency of episodes per hour is 5.4 to 5.8 (Lavigne et al 1996, Macaluso 1998, Saber 2002). In cases of severe and frequent sleep bruxism, the variation of the number of oro-motor episodes per hour of sleep is 25%, and the variation of tooth-grinding frequency is 53.5% (Lavigne et al 2001).

In normal subjects during sleep, nearly 60% show rhythmic masticatory muscle activity (RMMA), which occurs at a frequency of 1.8 episodes per hour of sleep. This is three times lower than in sleep bruxism patients, the muscle contractions are of lower amplitude, and no tooth-grinding sound is reported (Lavigne et al 2001).

1.4 Sleep events

Other activities that need to be identified as other than sleep bruxism are swallowing , coughing, sleep-talking, sighing , and myoclonus. These can all be recognized when subjects are monitored with polygraphic and audiovisual recording systems in a laboratory setting (polysomnography) but currently EMG recordings alone are insufficient (Kato et al 1999, Lavigne and Manzini 2000).

Oro-mandibular myoclonus is defined as a sudden , brief (<0.25 sec) jerk of a limb, neck or jaw muscle. Oro-mandibular myoclonus occurs across all stages of sleep, is

characterized by briefer muscle contractions, and occurs in 10% of patients with a history of tooth-grinding (Kato et al 1999)

1.5 Incidence

The total duration of bruxism per night is approximately 10 minutes in patients with clinically obvious signs of bruxism, e.g. attrition (Kydd 1985). The frequency of sleep bruxism can be variable in a given subject over time; some patients grind once a month whereas others grind "every" night . Most bruxism episodes appear frequently during partial sleep arousal (when sleep moves from deeper to lighter stage) (Satoh 1973) and appear during stage 1 and stage 2 sleep (Rugh 1988,). Some bruxism episodes have been reported to be accompanied with increased heart and respiratory rates (Kydd 1985, Satoh 1973,Robinson 1969), and a more recent study has shown that sleep bruxism episodes are associated with powerful arousal activity during NREM sleep ; these are characterized by an oscillation in autonomic, respiratory, and motor activity that has been termed a cyclic alternating pattern of sleep (Macaluso 1998).

The prevalence of sleep bruxism reports, and awareness in the general population, ranges from 6-8%, and decreases rapidly with age, down to 3% in patients over 60 years of age; there is no gender predilection.(Lavigne and Montplaisir 1994) .

It has also been estimated that 20% of sleep bruxers report concomitant orofacial pain (Goulet 1993, Dao 1994).

Historically it was thought that occlusal discrepancies, and emotional stress were major causes of sleep bruxism, these are now no longer considered as serious etiological factors. A recent study failed to show any relation between awake stress and EMG changes in sleep (Pierce et al 1995), however several studies agree that sleep bruxism patients may have an anxious personality (not a disorder), and may be more task-oriented in comparison with normal individuals (Bader et al 1997, Kampe et al 1997, Major et al 1999). In a recent review of the literature, and assessment of the evidence for occlusal adjustment as a treatment for nonacute temporomandibular disorder, bruxism , and headache, the evidence was neither powerful enough, nor convincing enough to support the use of occlusal therapy as a general treatment modality (Tsukiyama 2001).

Currently, although the exact mechanism is unknown, many studies suggest that sleep bruxism is a centrally driven phenomenon, with autonomic –cardiac nervous system processes related to oromotor functions and sleep-wake regulation (Kato 2001).The current literature on the genesis of sleep bruxism supports the view that tooth-grinding and and sleep bruxism are among the last events in the sequence of sudden brain and cardiac activations termed "micro-arousal during sleep" (Macaluso et al 1998, Kato et al 2001).

1.6 Risk Factors

Several risk factors for sleep bruxism have been reported; for example, it is 1.9 times more prevalent in smokers (Lavigne 1997), while obstructive sleep apnea syndrome, caffeine, alcohol, stressful life events , and anxiety have all been cited in the literature (Hartman 1994, Ohayon 2001). Age represents an important factor as the incidence of sleep bruxism declines from childhood to old age (Lavigne and Montplaisir 1994, Laberge et al 2000).There is no gender difference for sleep bruxism , however a familial predisposition has been recently supported in studies with twins, although no genetic inheritance pattern has so far been demonstrated (Lindqvist 1974, Hublin et al 1998). Historically, bruxism (daytime or sleep) has been associated with the signs and symptoms of masticatory system dysfunction, as a causative or contributing factor. Bruxism has also been thought to have played a role in the etiology of temporomandibular disorders (TMDS).

1.7 Temporomandibular Disorders

These include a number of musculoskeletal problems of the masticatory system (Okeson 1996). TMDS are characterized by pain and tenderness of the masticatory muscles and/or temporomandibular joints, and are often associated with temporomandibular joint sounds, and a restricted range of movements (Merskey 1994) In the long term, there may be deterioration of the TM joint disc, and articular surfaces of the condylar head and fossa, possibly associated with arthritides. Many epidemiologic surveys indicate positive correlations between bruxism and TMD, however , causality is extremely difficult to establish. In a recent 20 year follow up study it was shown that some signs and symptoms may act as risk factors, and predict TMD in a long term

perspective. The most notable of these were oral parafunction, tooth wear, TMJ clicking, and deep bite in childhood (Carlsson 2002). Conversely , other authors suggest only a mutual co-existence between bruxism and TMD (Lund 1992).

1.8 Clinical Management

Currently there is no definitive, or specific treatments for bruxism and TMD. In the majority of cases, a specific diagnosis of the source of the pain is difficult for the clinician to elicit, and a specific treatment modality at a muscular level is rarely employed. Rather, a multi-disciplinary approach is aimed at symptomatic relief of the various complaints of TMJ pain, masticatory muscle pain and spasm, limitation of opening, neck pain, tooth wear, head-aches, and periodontal problems.

The multi-disciplinary approach frequently involves medications such as analgesics, anti-inflammatories, and muscle relaxants, while physiotherapeutic techniques include muscle training exercises, and ultra-sound. Attempts aimed at "stress reduction" in the subject's general lifestyle, counseling and psychological guidance may also play an important part in the attempts to reduce the level of distressing symptoms.

1.9 Occlusal splints

The most widely used treatment mode is an intra-oral occlusal apppliance (or splint). This has been utilized for not only masticatory dysfunction (Ramfjord , Ash 1994), but also for motor disorders (e.g. Parkinsons disease, oral tardive dyskinesia), sleep disorders (e.g. Sleep apnoea, and snoring), sensitive teeth related to chronic sinusitis, head-aches, ranging from "tension-type" to Migraines, and all sub-groups of TMD. (Dao & Lavigne 1998). A survey of the treatment of TMD and Bruxism for the American Dental Association, showed that Oral Splints were by far the most commonly used treatment by both general practitioners and specialists (Glass 1993).

It is estimated that over 3 million splints are provided to the American population each year, at an estimated cost of $990 million /year, or 2.9% of US dental care dollars in 1990 (Pearce 1995).

(Dao & Lavigne 1998) have stated however that the mechanism of action of intra-oral splints remains controversial. They reported the results of a clinical trial that lent

support to their effectiveness (i.e. the patient's perception of positive changes), but not to their efficacy (i.e. true therapeutic value). These authors recommended that oral splints should be used as an adjunct for pain and behaviour management, rather than a definitive treatment.

The proposed mechanisms of the action of oral splints variously include changing in the vertical dimension of occlusion, repositioning the TM joints, decreasing the level of muscle activity, reducing bruxism, removing occlusal interferences, enhancing the patient's cognitive awareness, "recapturing" the TM disc, and "unloading" the TM joints (Dao & Lavigne 1998).

Many of these proposed mechanisms have relied on electromyographic studies (EMG), as part, or all of the measurements of the efficacy of the outcomes. Many of the concepts have involved a belief in an "abnormal muscle activity" or "muscle imbalance", that may or may not be associated with repositioning of the TM joint, and a more "therapeutic" or "concentric" position of the condylar head in the fossa in three dimensions. The apparent effect of oral splints was initially assumed to be related to a decrease in muscle activity, and this was shown in many of the early studies, with a stronger effect in the temporalis than in the masseter muscles (Lobbezoo 1993). Conversely, some studies have shown increased EMG activity (Wood 1984), and other studies have shown a variation in response with EMG levels decreased in 52%, increased in 20%, and unchanged in 28%, of the patients(Clark 1979). These effects may also be transitory, as reports of similar values of temporalis muscle activity 2-4 weeks after treatment, were comparable to those measured without the splint, while the masseter muscle did not display any significant changes (Naeije 1992). As with many of the early studies, some of the experimental data were not collected under blinded conditions, and there was also variation in the sample selection with regard to inclusion of both symptomatic and asymptomatic subjects. However, a decrease in EMG activity in the elevator muscles has been reported repeatedly in the majority of studies involving splints. It can be concluded that the overall response to oral splint treatment, the remission of TMD symptoms, and also the physiological significance of changes in EMG activity are not fully understood, and require further study. As seen from the previous references, the evaluation of

masticatory muscle activity has been most commonly studied by means of electromyography (EMG).

1.10 Electromyography

The use of surface electromyography for recording and analyzing muscle function, has been an important, and sometimes controversial issue in dentistry. EMG allows the qualitative, and to a certain extent the quantitive analysis of muscle function. (Hannam 1977, Yemm 1985). It has also been used to study muscle hyperactivity (Ramfjord 1961), muscle fatigue (Naeije 1986), the relationships between masticatory muscle activity and malocclusion , craniomandibular disorders (e.g. associations between muscle overuse , oral habits , myoarthropathies of the masticatory system, and associations between the nocturnal level of masticatory muscle activity and facial pain (Rugh and Harlan 1988). The history of surface electromyography in musculoskeletal biomechanics generally is exhaustive, and a technical comprehensive review of the subject is beyond the scope of this introduction, however , some of its more important features will be discussed , including some of the technique's limitations.

Electrical activity within a muscle arises due to transient ionic potentials in activated motor units(MU's), which are the smallest functional grouping in muscles. Each MU consist of a single motor neuron and several associated muscle fibres. Surface EMG is measured from the skin overlying the muscle, and is a spatial and temporal interference pattern of multiple active motor units located near the detection surfaces. Surface EMG can therefore be used as an indicator of muscle activation, and the signals can provide the timing sequence of one, or more muscles performing a task. Surface EMG's relationships to the force produced by a single muscle, and its ability to provide information (non-invasively) about the force contribution of groups of muscles are of considerable importance when biomechanical models are being considered. Surface EMG can also serve as an index of the fatigue processes occurring within a muscle, thus having the potential to predict the onset of contractile fatigue.

1.11 EMG limitations

General concerns regarding the surface EMG technique's limitations generally focus on the fidelity of the signal, specifically the "signal-to-noise" ratio, and the distortion of the signal. The noise is defined as the part of the electrical signal that is not part of the wanted EMG signal, while the distortion of the signal refers to relative frequencies in the EMG signal that can be altered.

Another factor is susceptibility to cross–talk i.e. the possible sampling of electrical activity from adjacent muscles. This inaccuracy may be reduced by reducing the size of the electrodes, accurate electrode placement , and the fact that such are unwanted signals at a lower frequency (originating from further away), since they are subject to additional filtering due to spatial filtering effects.

Electrical noise may be inherent in the electronics components in the recording equipment. Ambient noise arises from electromagnetic radiation eg. radio waves, TV, lamps, bulbs, and power sources. Also, there may be motion artifacts arising from the interface between electrode and skin, and also from the skin to muscle, in that the skin is non-contractile. There may be movement of the cables connecting the electrodes to the amplifier, creating noise. There is also an inherent instability of the signal, since EMG is quasi-random in nature, due to random firing of the motor units (0-20 Hz) which can be considered a component of unwanted noise.

The electrodes used should thus provide minimal distortion, and good signal-to-noise ratio. Electrodes function by the formation of a layer of charge at the electrode - electrolyte interface. This creates a potential difference that can be measured . The impedance of the skin - electrode interface can be reduced by rubbing the skin with alcohol prior to placement, and by using a conductive gel. Silver chloride electrodes are stable, and widely used as surface electrodes, and the placement of the electrode is also important. Criteria for their use should include that the long axis of the electrode is aligned parallel to the long axis of the muscle fibres, the electrode is placed in the mid-line of the muscle group (away from the motor point, or innervation zone), away from the tendinous insertion, and away from the edges of the muscle, and that reference electrodes are placed relatively far away, and on electrically neutral tissue such as, bone.

The signal is detected at two electrical sites and electronic circuitry subtracts one signal from the other and amplifies the difference, i.e. differential amplification. This results in amplification of the signals generated in the vicinity of the electrode. For safety purposes, the amplifiers are either optically isolated (or use isolation transformers) to ensure that a power surge cannot be transmitted to the subject during the experiment. The amplifiers are individually grounded, and can also be battery powered (3-15volts) ensuring safety, and further reducing unwanted noise.

It is well established that the amplitude of the EMG signal is random(stochastic) in nature and that it can reasonably be represented by a Gaussian distribution function. The usable energy of the signal is limited to the 0-500 Hz frequency, with the dominant energy being in the 50-150 Hz range.

1.12 EMG Signal processing

Historically the preferred manner for processing the EMG signal was to rectify it over a specified time period, thereby forming a time series of the integrated values. Other options include the calculation of the "root mean square" value of the EMG signal .The rms value is often preferred as it is a measure of the power of the signal, and has a clear physical meaning.

The signal can be further processed for storage, and "off-line " analysis by conversion by an analogue-to-digital (A/D) converter. In order for complete recovery of information, the signal must be sampled at a rate that is twice that of the highest frequency in the sample (the "Nyquist theorem"). The A/D conversion resolution is determined by the number of bits per sample, or the number of discrete levels in to which the signal can be converted .The EMG signal is occasionally contaminated by other bio-signals. The most common of these is the ECG (electrocardiogram), which can be removed by High pass filtering at ~20-30Hz, with minimal impact on the power of the EMG (Redfern 1993).

Today, EMG amplitude can be estimated by a cascade of procedures, including noise rejection /filtering, whitening, multiple channel combination (gain scaling), demodulation, smoothing and relinearization. "Whitening", or decorrelation makes the samples statistically uncorrelated; it increases the statistical bandwidth (a measure of the

statistical degrees of freedom in the data), and reduces the variance of the amplitude estimation. Multiple channel combination can be used for multiple electrode placements on a single muscle group, and may provide a more complete measurement of the underlying physiological activity (Hogg and Mann 1980). Demodulation (power 2, or rms) gives the best maximum likelihood estimate of the EMG amplitude for constant-force, constant-posture, non-fatiguing contractions (assuming a Gaussian distribution). More recently a "Laplacian" concept has been proposed (Clancy and Hogan 1999); this allows for greater grouping of the signals closer to zero, however ,many experiments have shown the Gaussian model is still probably the better fit. Currently either process can be used, and experimentally there is actually very little difference between them. "Smoothing", filters the signal aiming to increase the signal to noise ratio. Several different techniques are proposed, and have been reviewed by Clancy et al 2001. Relinearization converts the signal back to units of EMG amplitude after the demodulation phase. A complete summary of the applications and techniques used in EMG recording can be found in de Luca (1997.)

1.13 Jaw Muscles

The Jaw muscles used most for recording surface EMG signals are the masseter, and anterior temporalis muscles. Their locations make them readily accessible and a non-invasive approach possible. These are important jaw elevator muscles involved in both functional, and parafunctional activities. They have been used in many previous EMG studies.

Masseter muscle

The masseter muscle is most commonly described as having 3 heads of origin arising from the zygomatic arch (Ebert 1939, Schumacher 1961, Last 1966). It is assumed to have 3 different layers: a superficial layer, which arises from the anterior 2/3 of the of the lower border of the zygomatic process, as far anteriorly as the zygomatic process, and that inserts into from the angle of the mandible anteriorly to the ascending ramus; an intermediate layer that arises from the central , medial 1/3 of the zygomatic arch and the lower border of of its posterior 1/3 ; and a deep part arising from the deep surface of the arch.

The deep and intermediate parts of the muscle insert into the central and upper parts of the ascending ramus to the level of the coronoid process. The masseteric artery separates the superficial and intermediate parts, whilst the masseteric nerve separates the deep and intermediate heads. The muscle has complex internal 3-D arrangements with internal aponeuroses, and interleaving septa in the posterior parts of the muscle. There is a variety of muscle fibre orientation, oblique, and multipennate in nature; most of these insert into the interleaved aponeuroses. Functional partitioning of activity is possible in at least 3 regions of the muscle, (deep posterior, deep anterior, and superficial), and possibly 4 (Blanksma 1992). Studies have indicated that the more obliquely - oriented, superficial fibres contribute strongly to jaw elevation , elevation with protrusion , or movement on or towards the side contralateral to the muscle. The deep fibres contribute strongly to jaw elevation, and jaw retrusion on the ipsilateral side to the muscle. Isometric contractions follow a similar trend to this pattern with graded activity, indicating that the masseter muscle is capable of a degree of selective activity when the need arises (Blanksma 1992).

Other studies have also shown that the distribution of tension across the muscle cannot be uniform, and the magnitude and orientations of muscle force vectors will alter according to function (van Eijden & Raadsheer 1992). Studies show that the superficial masseter activity starts earlier on the balancing side than the working side, thus allowing the ramus to move medially, and develop occlusal forces on the bolus on the working side (Miller 1991). The masseter has also been shown to have greatest activity on the ipsilateral side when chewing is carried out , generating force on the ipsilateral side, but in this case does not produce movement of the ramus.The purpose of many of these studies has been to show that there is a complex and functional compartmentalization of muscle function, and also to show co-activation between different muscle groups, and selective activation of fibres in the same muscle.

Temporalis muscle

The temporalis muscle has a broad origin from the temporal fossa (inferior temporal line to the infratemporal crest), the majority of the fibres are in a "fan shape" and converge into a flat tendon that inserts into the anterior, medial , and posterior aspects of the coronoid process, as well as the anterior border of the ascending ramus. Occasionally

some fibres insert into mandibular crest as far as the 3rd molar. The tendon extends superiorly as an internal aponeurosis, and divides the muscle into superficial , and deep part. This is particularly noticeable in the anterior region, where the muscle has its greatest cross sectional size, and where it is definitely bipennate when viewed frontally. A few fibres from the posterior part also insert into the articular disc.

The complexity of the muscle structure would allow for behavioural flexibility, with the tendon pull capable of being directed anteriorly, vertically, posteriorly, and a limited amount of mediolateral movement. Graded, task-sensitive activation occurs in the anterior, middle, and posterior fibres (Moller 1966, Miller 1991). Alterations of muscle force activity with different bite force direction are less apparent in the anterior part of the muscle (Blanksma and van Eijden 1990).Selective activation may also occur in the mediolateral movement i.e. superficial and deep fibres either side of the aponeurosis may be activated differently (Wood 1986). The large anterior cross section of muscle, compared to the small posterior group, also imply differential muscle use, or even different roles for the different parts of the muscle, and the maximum tensions developed must be greater in a vertical direction than posterior.

Human jaw muscles contain predominantly Type 1 fibres in the anterior and deeper regions, with more equal proportions of type 1 and 2 fibres posteriorly and superficially (Miller 1991). The predominance of a particular fibre type in a specific region does not necessarily infer functional compartmentalization, although this is likely. It is also related to the motor unit(MU) organization. Human masseter MU territories appear to be restricted and the muscle is capable of regional contraction (Mcmillan & Hannam 1992), however, the wide distribution of some MU territories in humans suggests that muscle compartments may not be defined entirely by internal anatomical boundaries, but that "behavioural " regions may also have an effect.

MU recruitment and rate coding in the human jaw muscles appears to follow the general principles regarding "size", and common drive" found in the motoneuron pools of other skeletal muscles. Recruitment thresholds are not stable, and the order of recruitment can change. They may be influenced by the task, the approach, and its duration. Jaw muscle MU's are polymodal ie they can contribute to more than one task, and they are difficult to drive voluntarily at rates below 10 Hz. Most are recruited early in the performance of

each task, and the trigeminal system seems to rely mainly on rate coding thereafter to reach a muscle's maximum voluntary contraction.

This complex anatomical structure, fiber make-up , territorial dispersion , and functional properties of the MU's provides a template for sophisticated motor control that is constantly adjusted by the cortico-bulbar drive from the CNS, and various intra- and perioral sites.

A more detailed review of the internal organization of the human jaw muscles can be found in Hannam and Mcmillan (1994).

1.14 Contraction Pattern Recognition

The shape and firing rates of MU action potentials in an EMG signal can provide information on the normal and abnormal functioning of the muscle, and are used to diagnose various neuromuscular disorders. This information has also been utilized in attempts to control artificial prostheses for amputees. Important elements of this area of research are attempts at pattern recognition of the EMG signal , or its constituents. Pattern recognition has been utilized since the 1950-60's in the USSR, and then more widely in the 1970's in the US and Canada. Initially, it was only the power of the signal that was able to be used as a control parameter , rather than the complete EMG signal. It frequently involved multiple electrodes, relatively basic electronics, leading to limited interpretation, and limited functioning of the prosthesis. With the advent of faster and more reliable microcomputers, it has become possible to consider more than just the power of the EMG signal, and it is now possible to consider the temporal EMG pattern , and to decompose the signal into its constituent parts.

There are now many applications for pattern recognition techniques in the biomechanical, and medical fields. Diagnostic differentiation between upper motor neuron disorders, assessment and diagnosis of low back pain sufferers, myo-electric signals used to augment speech recognition systems, and increasingly complex prosthetic limb controls, are all examples.

Advances in computer technology have made automated EMG analysis feasible. Some algorithms have become commercially available ,however none of them have gained wide acceptance for routine clinical use. A relatively, simple, robust pattern recognition

system for EMG that could be used for long time samples would be useful, since it would enable relatively rapid analysis, and possibly the diagnosis of functional, and parafunctional activity during disorders such as sleep bruxism, and in areas of research where many hours of EMG activity need to be analysed and broken down into recognizable tasks. Currently the use of Cepstral coefficients the maximum likelihood method, weighted distance measure, co-efficient of cross correlation comparisons, and artificial neural network techniques based on unsupervised learning, have all been discussed in the literature with regard to EMG pattern recognition (Li and Caldwell 1999, and Christodoulos 1999).

There are many problems that need to be solved when using the EMG signal alone when attempting to discriminate between different oro-motor activites. This is related to the fact that the EMG signal reflects only the amplitude and duration of the muscle contractions.

2 Statement of the Problem

In order to gain a greater understanding of the masticatory system, many studies have attempted to analyse the functional and parafunctional behaviour of the jaw muscles. Excessive forces produced by both functional and parafunctional behaviours may contribute to the signs and symptoms of masticatory system dysfunction, including biomechanical overloading, altered function, and loss of structural integrity.

There has been no attempt in previous studies to classify bruxism by specific intra-oral movements, or to analyse the actual movements performed by individual subjects with bruxism or other parafunctional habits. Consequently a diagnosis that is related to the specific movements, or actions performed by the subject is not possible.

Currently a significant part of dental health financial resources is apportioned to a particular treatment modality, the occlusal splint, that has undoubted effectiveness, but has questionable efficacy. The splint is not considered as a definitive treatment so much as an effective tool for management of symptoms such as tooth wear. A more specific diagnosis of what actions are responsible for this may help in the development of more targeted treatment whether or not this involves splint use.

There are very few studies which have simultaneously recorded the 4 major muscles (masseter, and anterior temporalis bilaterally), involved in bruxing actions.
There has been no attempt to link muscle activity pattern recognition with the movements or tasks produced, or for that matter with the resultant force. These are important consequences of muscle activity, since they relate to possible damage to the teeth and supporting structures of the masticatory system.

There is a need to develop a method for linking nocturnal or involuntary muscle contraction patterns with actions specific to an individual. This would be an important first step in creating an analytical approach that could be later modified for longer term studies of sleep bruxism.

3 Aims of the study

1. To develop a pattern recognition system capable of predicting forceful movements of the jaw on a conventional occlusal appliance.
2. To utilize 4 muscles (masseter and anterior temoralis bilaterally) to improve the sensitivity of the records used for movement prediction.
3. To control the occlusal guiding surfaces and the movement involved as a means for increasing the predictability of the pattern recognition system.
4. To develop an analytical methodology for discriminating the features of the EMG recordings of the 4 muscles relative to specified intra-oral tasks.
5. To attempt to identify which of the variables used by the analysis are the most reliable predictors of the specified tasks.
6. To measure the success of the predictability of the variables produced by the method by means of a commonly used statistical program.
7. To estimate in 10 subjects the success of the pattern recognition system in discriminating among the movements performed by them .

4 Materials and Methods

The experiments were divided into three main studies. These studies were carried out with ethics approval from UBC's Clinical Ethics Board. They included:

1. A Reproducibility study , involving the same subject and experimental procedure on 5 consecutive days in order to test for experimental error, i.e. to see if the performance on different days was consistent.
2. A Pattern recognition study in a single subject.
3. A Pattern recognition study for a sample group, in which 10 subjects took part. These data were used to train a computer program to recognize the EMG recordings and tasks carried out by each subject.

4.1 Reproducibility Study

The subject in this analysis was a 43 yr old male, with no history of TMD , an otherwise healthy dentition, and no relevant medical history.
Alginate impressions were taken of the dentition, and a "centric relation" wax bite record was made in order to construct a hard acrylic bite plane. The impressions were cast immediately, with dental stone , and trimmed models were sent, along with the occlusal record to a commercial laboratory. The models were articulated, and a minimum of 2mm splint thickness in the posterior region was prescribed.

Splint design

This was a hard acrylic, maxillary flat plane splint of horse-shoe design, with retention determined by the buccal embrasures, and the height of contour of the teeth. A canine rise was prescribed so that the mesial incline of the mandibular canine contacted the disto-palatal aspect of the canine ramp to achieve immediate posterior disclusion in lateral, and protrusive excursions.

The splint was adjusted so that there was a comfortable, even occlusal contact in centric relation, and there was immediate posterior disclusion during any lateral excursion and protrusive movement. The splint was also adjusted so that in lateral excursive movements there was a "guidance pathway", to help the subject make reproducible movements during the experimental tasks. The pathway was not restrictive so there would be no muscular exertion against resistance to movement.

Recording technique

Electrode placement

Electromyograms of the anterior (and superficial) portion of the left and right masseter muscles, and the anterior portion of the temporalis muscles were recorded using "Duo-trode" Ag/ AgCl surface electrodes (Myo-tronics, Inc. Tukwila WA 98188). These electrodes had a center-to-center distance of two centimeters, and an active area with a diameter of one centimeter.

After palpation of the main band of muscle fibres, the electrodes were placed away from the anterior edge, running parallel to the main direction of the muscle fibres and as centrally as possible, while ensuring no hair impeded the contact. Prior to electrode fixation the skin was prepared by vigorously rubbing with 70% Propyl alcohol on a gauze pad. The electrode contact included conductive electrode gel (Grass medical instruments EC2 electrode cream, Quincy, Mass 02169).

The "earth", or reference electrode was placed at the bony prominence(spinous process) at the base of the cervical spine.

Figure 1. Example of occlusal splint used in study. Even contact in centric occlusion is seen , with guidance in protrusive and lateral excursive movements on the canine ramp.

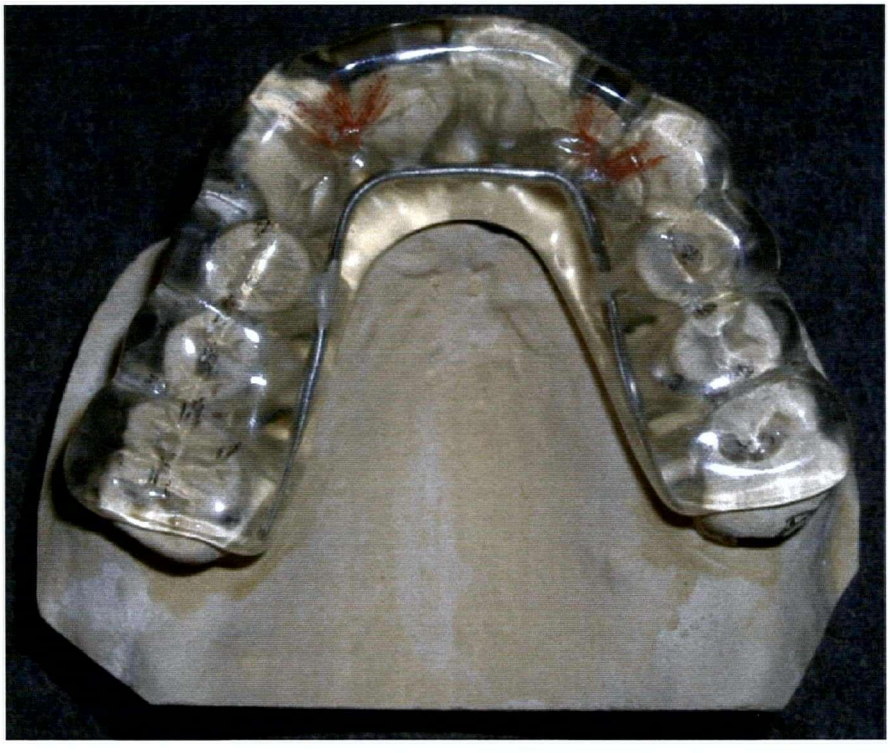
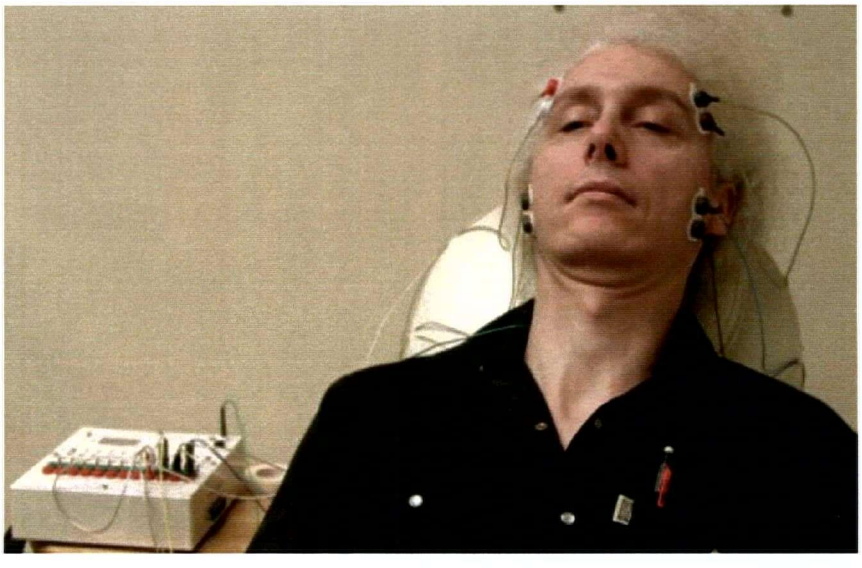


Figure 2. Example of typical EMG recording set up showing pre-amplifier, and electrodes connected bilaterally. Subject is observing the oscillosclope target.



Electrode placement template;

In order to accurately record the position of the electrode placement, an acetate sheet with permanent markers was used, and overlaid on the patient. It was referenced to the outer canthus of the eye, the tragus of the outer ear, and the corner of the mouth, along with the outline, and central position of the electrodes. Left and right templates were used and the same ones were used every day during the reproducibility study. This ensured as accurately as possible, correct repositioning of the electrodes. Also, the same operator placed the electrodes each day.

The electrodes were connected to the pre-amplifiers and channel control switch.

The pre-amplifiers were in turn connected to a Bioamplifier away from any AC power cords to eliminate unwanted noise, and to ensure good connections from the electrode leads.

Bioamplifier;

This was a 16 channel Isolated Bioelectric amplifier system Model CP-12/24BA #41310 (SA instrumentation Co. San Diego CA US). The Bioamplifier was isolated with optical and magnetic isolation barriers. The bioamplifier had a rechargeable battery for added safety. Four channels were utilized. These employed high pass filters (0.5-2-100-500Hz; 2 pole response -12dB/oct;-3dB Butterworth type),

low pass filters (0.5-1-5-10 Hz 2 pole response, -24 dB/oct; -3 dBpoints) and had selectable gains of 2x, 5x,10x, and 20x. The unit included noise level reduction features and cross talk reduction (10000:1).

Experimental Protocol

The subject was seated upright in a standard dental chair. He was asked to ensure that he was comfortable, and told not to move his head and neck from the support offered by the chair's headrest. The electrode leads were taped to the chair to prevent any movement of the wire connectors. Prior to the MVC recording the subject was asked to practice maximal voluntary clenches. Between 5-10 MVC tracings were recorded and shown to the subject. After this brief training period, 3 MVC's were recorded before the series of tasks, and 3 more were recorded at the end of the experiment. There were rest periods

between each of the MVC practices, and between the sets of task recordings.The highest value overall for the 6 MVC's was used to normalize all later EMG recordings.
The subject was asked to have his teeth lightly touching the appliance prior to the commencement of the task. In order that the task duration was standardized as closely as possible, the subject was asked to visually follow an oscilloscope target. This had a zero "lead in period", followed by an inclined ramp to a maximum value, which remained as a plateau until the end of the task. The oscilloscope screen had 10 divisions, each division representing 0.5 seconds for a total of 5 seconds. The subject was asked to keep his teeth lightly touching during the "lead in" period, and to commence the designated task only after the tracing started up the ramp portion of the tracing.

Experimental tasks

The tasks to be performed were a right lateral excursion, a left lateral excursion, and a protrusive movement. These tasks were performed during a ramp time of 1 second for the "slow" designation, and 0.5 second for the "fast " designation. Thus, a total of 6 tasks were performed. As the oscilloscope trace started to rise on the ramp portion of the tracing, the subject was asked to grind his teeth on the appliance and to slide to the designated side, so that the task was completed during the plateau portion of the tracing, and to hold that position. He was then asked to simply relax from the clench, rather than to actively open the mouth. The subject was allowed 1 or 2 "practice" movements for each of the "slow" and "fast" task designations, to ensure as much reproducibility as possible without actually "training" him.
Each of the 6 tasks was performed 15 times. The order was right lateral slow/ left lateral slow/ protrusive slow/ right lateral fast/left lateral fast/ protrusive fast. This sequence was maintained throughout the study. Thus, a total of 90 tasks was recorded.

Data Processing

The EMG signal was processed via an analogue-to-digital converter and sampled by a PC-based "virtual interface" software program(Agilent Vee Pro, (Agilent Technologies Inc). This was a graphical programming environment optimized for use with electronic instruments. It enabled rapid construction of a program which processed each signal, by controlling all measurements, filtering , rectifying (rms), MATLAB functions , and storing the processed data. The amplifiers were set to a gain of 2. The high-pass filter was set above 20 Hz, and the low-pass filter below 1KHz.

The EMG raw data were first rectified , then filtered using a Butterworth digital filter at 4Hz. The Butterworth filter sacrificed rolloff steepness for monotonicity in the pass- and stopbands. It thus provided smoothing, and was used because it suited applications requiring preservation of amplitude linearity in the passband region. It was this feature that made the filter an ideal candidate for conditioning the EMG signal. The filter level gave a consistently smoothed representation of the changes in the original EMG data, while revealing frequency components likely to be reflected in changes in jaw movements and bite forces.

The filtered data were stored as a text file with task names, muscles, repetition numbers, and filter values.

Figure 3. Example of EMG raw data output with rectified, smoothed, and filtered waveform for Maximum Voluntary Clench (MVC) for 4 muscles LM,LT,RM,RT.

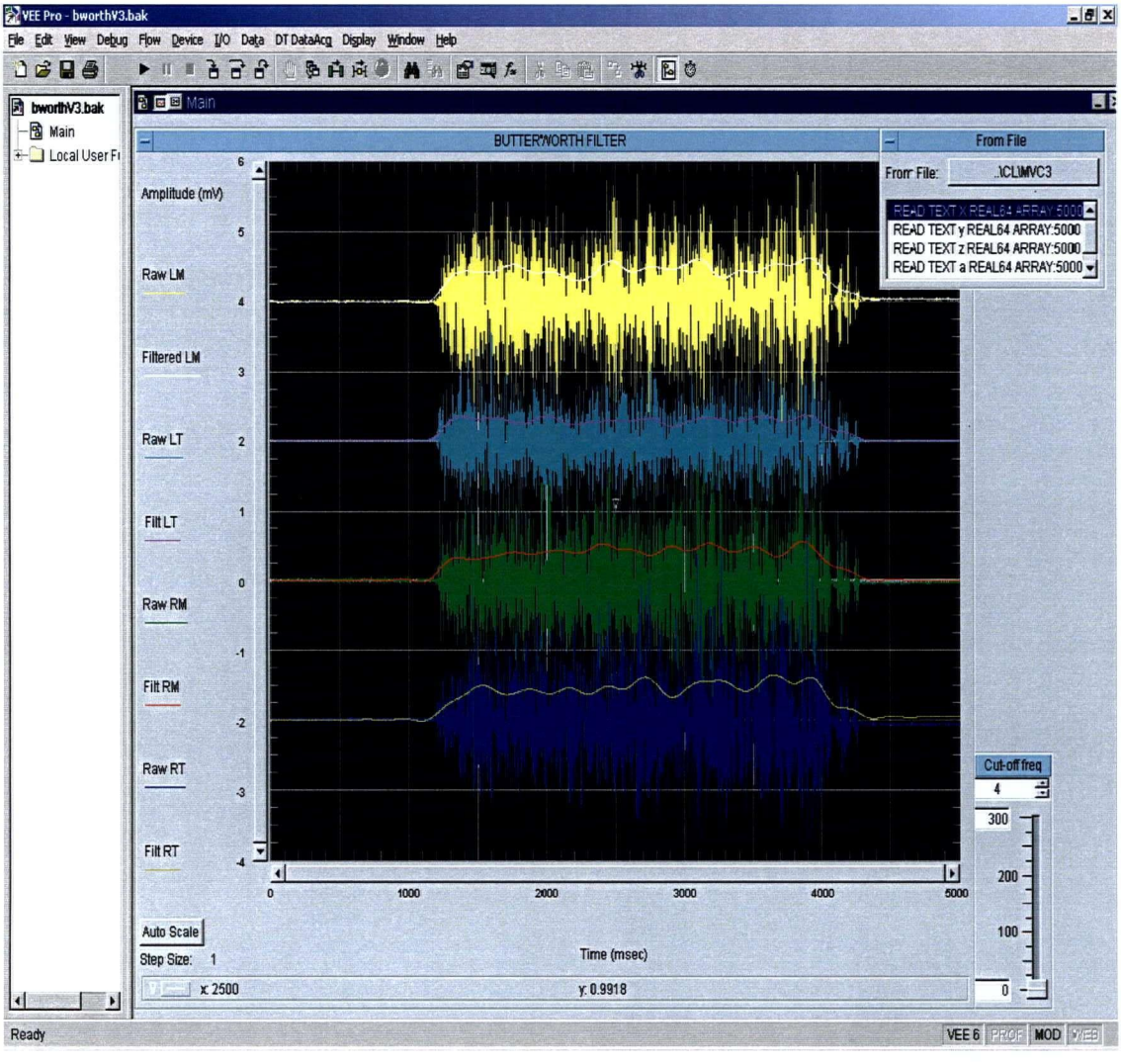


Figure 4. Example of EMG raw data for left lateral movement with rectified, smoothed and filtered waveform superimposed. Data set shows 4 muscles LM,LT,RM,RT

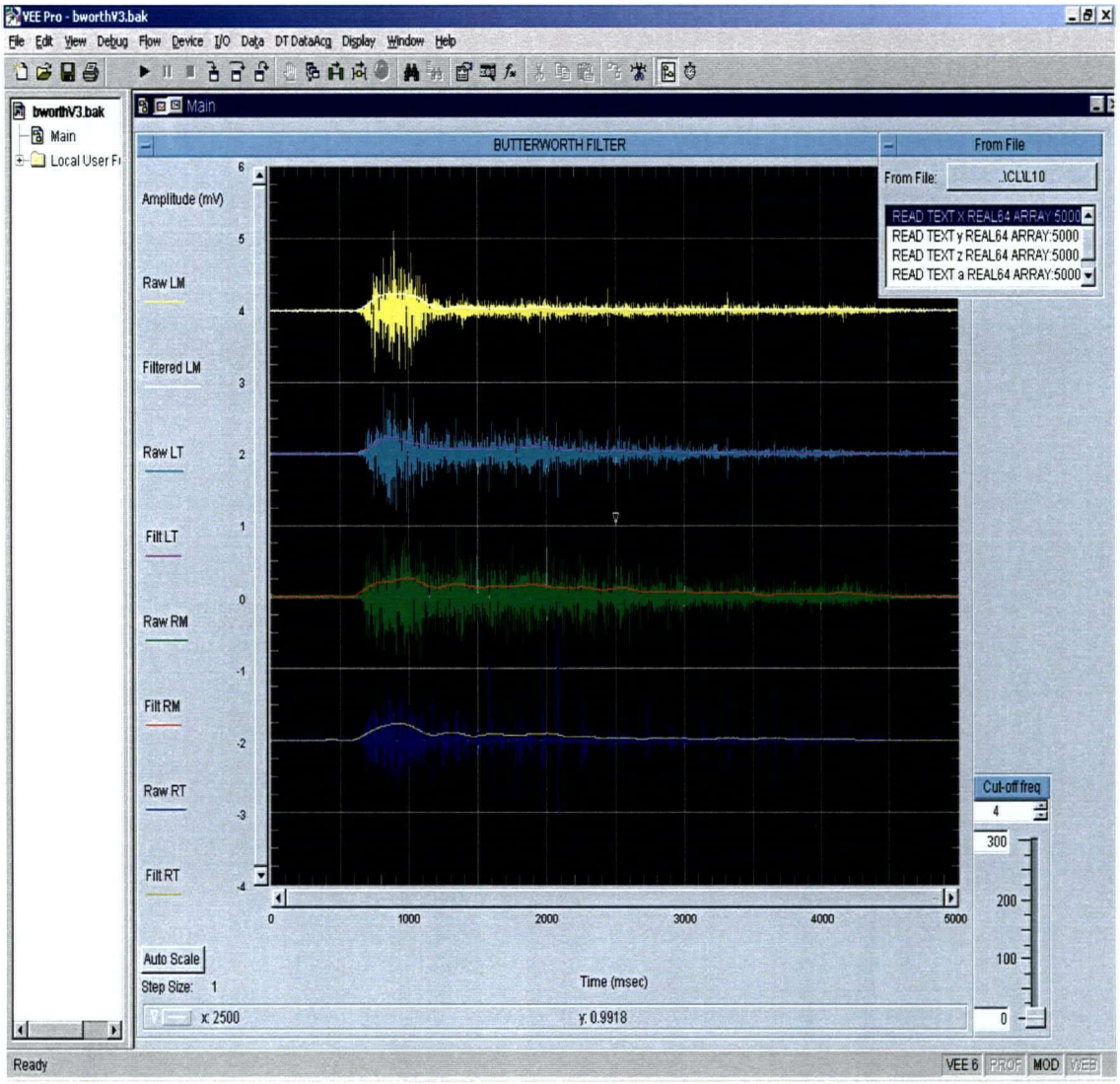
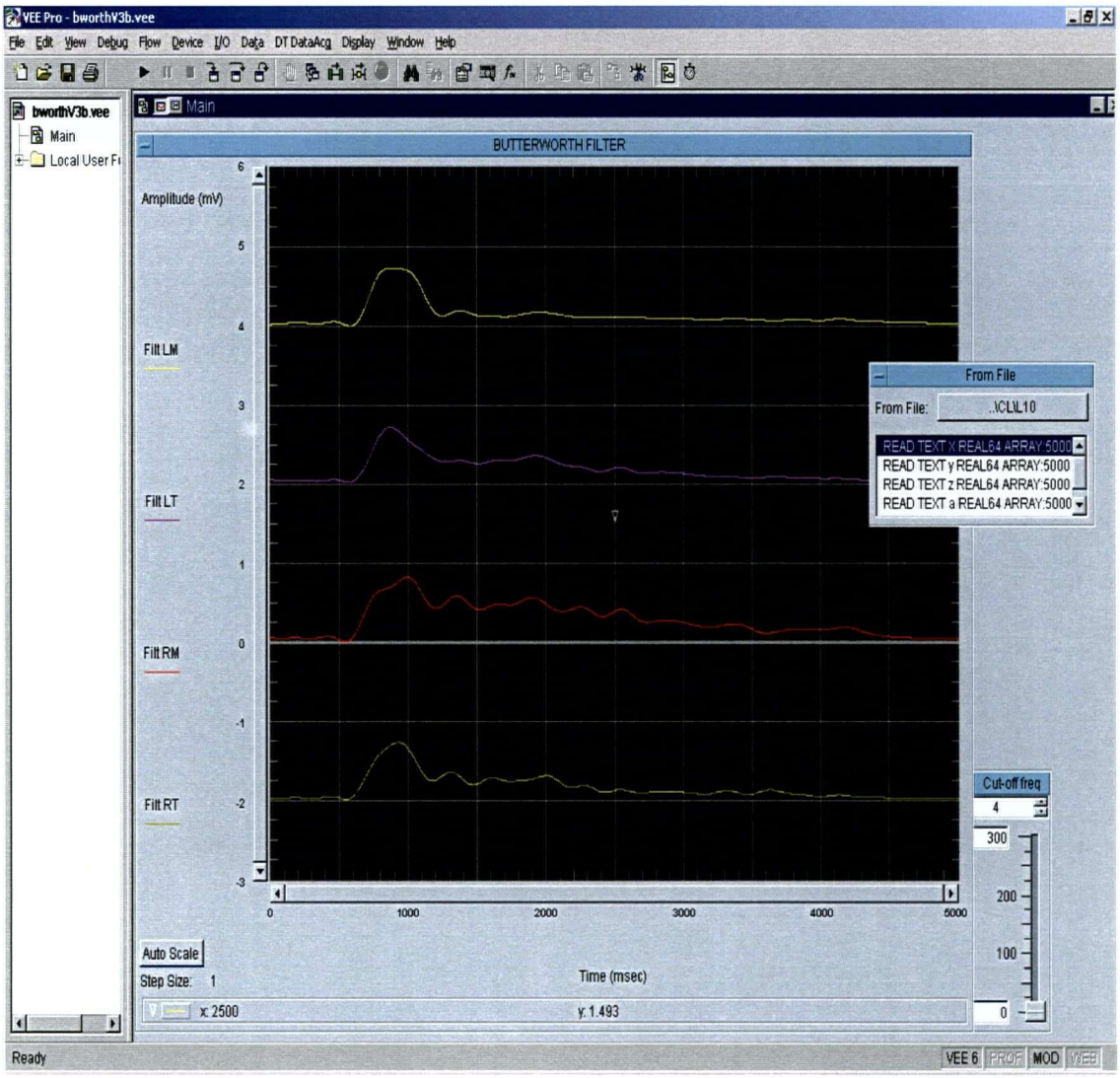


Figure 5. An example of the rectified, smoothed, filtered data set. Display shows output for 4 muscles: LM,LT,RM,RT.



Offline Processing

The next stage of data processing involved a program specifically adapted for the study. "Curvematch" (developed in collaboration with F.Zhang, The University of British Columbia), extracted a series of variables that described the smoothed filtered data.

Normalization

Normalization of the EMG signal with reference to the maximum values is a common method of correlating the EMG values to the force, torque, or energy related to the EMG signal, (see The Standards for reporting EMG data, Merletti 1999).

In order for the data to be compared between days/sessions, the value of the EMG recording for the task was scaled to a "maximum voluntary clench (MVC)" value recorded before and after the series of tasks performed each day. In this way the EMG value for the task was compared to the value of MVC for that day. "Curvematch" also normalized the variables for amplitude with reference to the peak values.
The data were also normalized so that the results could be compared among muscle groups. For a specified muscle, the time of task duration was also normalized with respect to the total duration (ie the time between the onset time of the first muscle to contract, and the offset value of the last muscle to cease contracting).

Definitions

In each record the base line was defined as the mean of a series of continuous points which met the following criteria

Base line

a. the mean of a minimum of 300 data points.
b. The mean value must be less than or equal to the maximum mean set at 0.03
c. The variation expressed as CV (coefficient of variability) of the sample points must be less than or equal to Maximum CV=10.

Onset was described as the time where the signal began to rise. There were 2 variables at each onset

x- the time (the number of the data point in the array).

y-the magnitude, (the pure signal minus the baseline value) expressed as a % of MVC.

If the onset referred to the % of time, only the y value was calculated, since the x value was predetermined.

Offset was defined as the point where the signal began to decrease. There were 2 variables at each offset;

x- the time (the number of the data point in the array).

y- the magnitude (the pure signal minus baseline) expressed as a % of MVC. If the offset referred to % of time, only the y value was calculated.

Curvematch Axes;

The x-axis consisted of 5000 data points over 5 seconds, each point representing a millisecond.

The y-axis was expressed as the ratio of the signal amplitude to the MVC value.

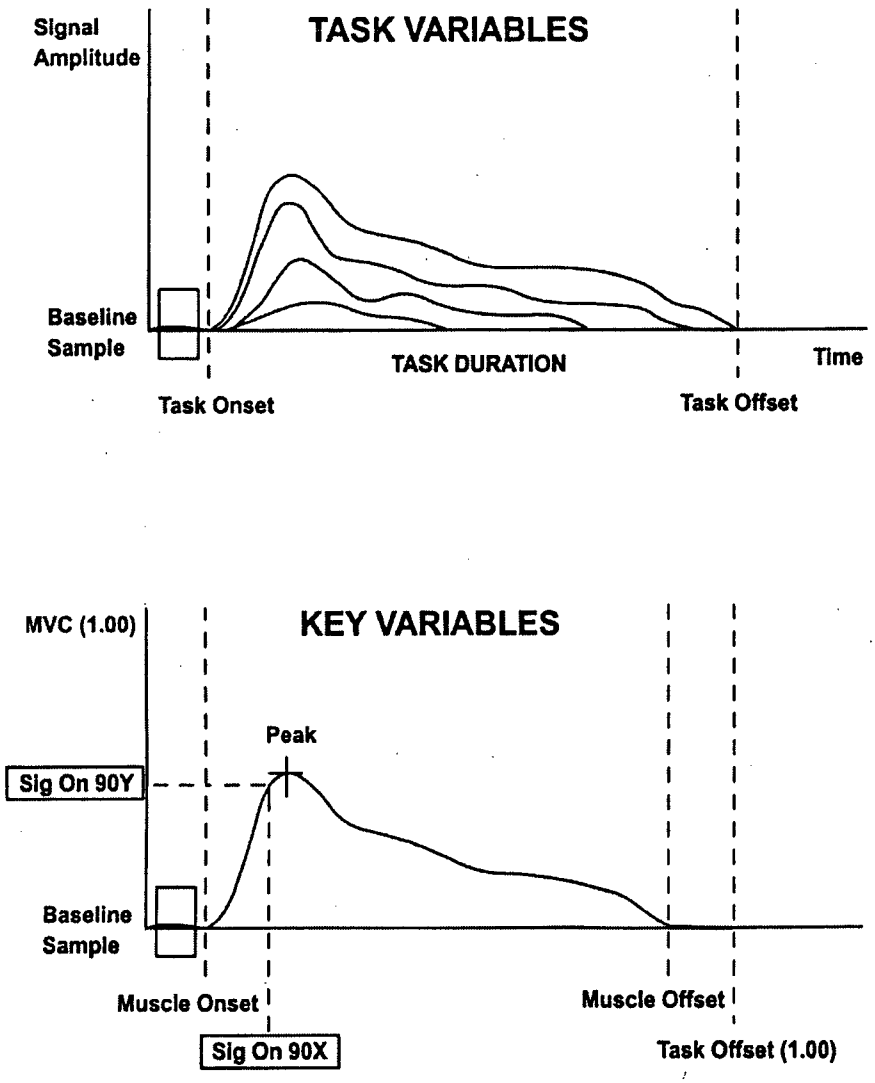
Curvematch variables

The program was designed to extract key features of the smoothed, rectified, waveform. (see Fig X).

'Signal on X'- this described time values expressed as percentages of the total task duration, when the signal reached 10% increments of the peak amplitude (up to 100% of peak). These values are designated by muscle prefixes eg LMSigon90X.

'Signal on Y'- this described the amplitudes, expressed as percentages of the MVC (for that session), at the corresponding values of time. These values were designated by muscle prefixes eg RMSigon90Y.

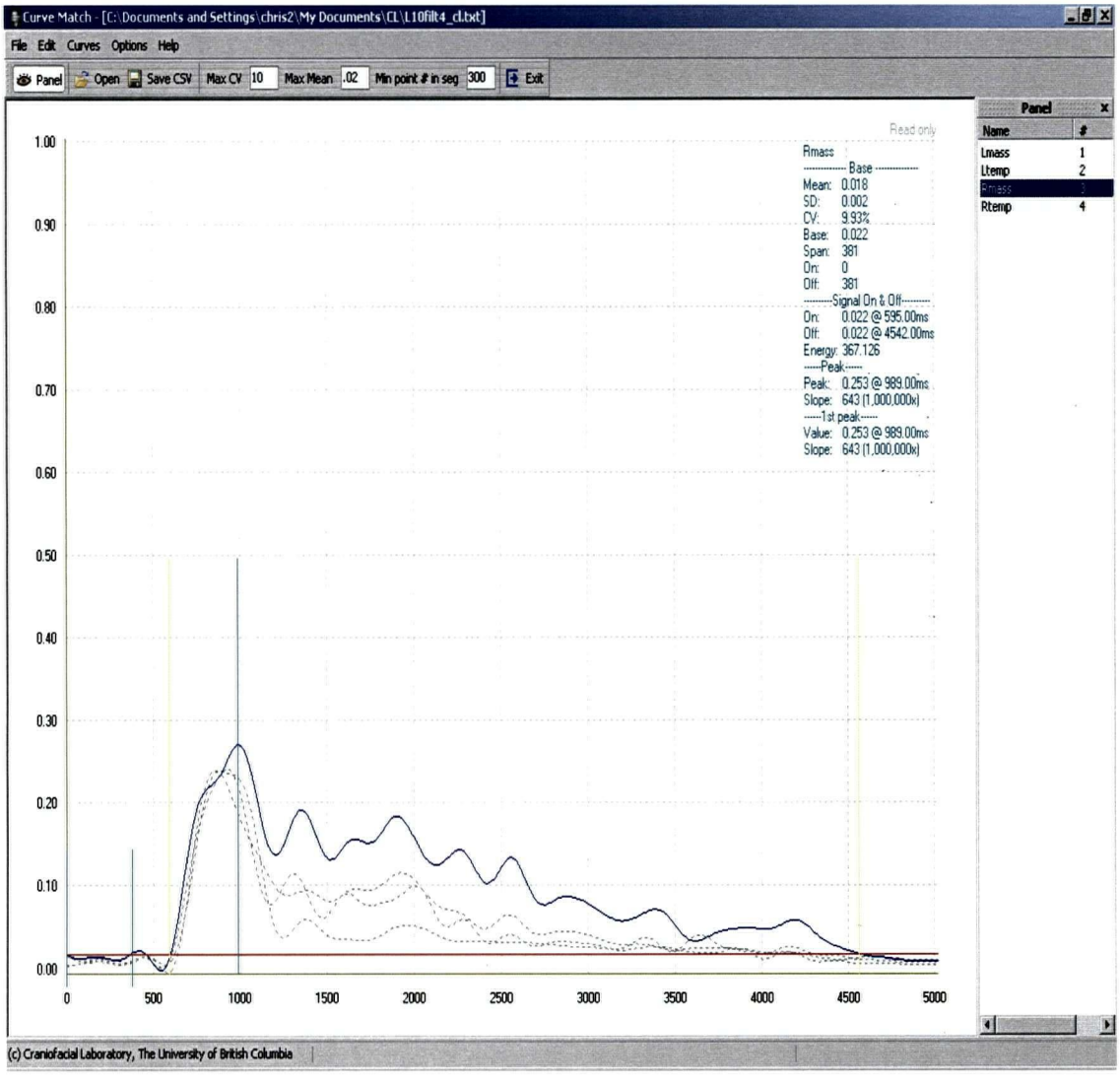
Figure 6. Diagram showing the derivation of the key variables from the rectified, smoothed and filtered waveform.



The "Curvematch" program could therefore derive up to 64 variables for each task for each muscle. The total number of variables available for all muscles (244), was too large for a "Windows Excel" program to load. So each data set was converted into a "Notepad text" file and exported to an SPSS statistical package program (SPSS Inc. 233 South Whacker drive , 11th floor, Chicago , IL 60606-6412). In order for this program to process large numbers of task files, the data were first "batch processed" by "Curvematch", to automate the process.

"Curvematch" produced a graphical display of the 4 muscles for each 'task file', and generated a peak value for the individual muscles. The units were expressed as numerical ratios for "y" values, and as milliseconds for "x" values. This step was useful in that it allowed initial visualization of the data, including overt variations in the visual pattern recognition, and the overall ability to screen the results.

Figure 7. An example of "Curvematch" batch output data for 4 muscles LM,LT,RM,RT, in this case RM is solid line.



4.2 Pattern recognition for a Single Subject

This part of the study utilized the data from the subject taking part in the Reproducibility Study. In order to improve discrimination, the number of variables that the "curvematch" program produced was increased to account for recognition of a variety of increasingly complex waveforms. The statistical test used for this part of the study was discriminant analysis.

Curvematch variables

'Signal off X'- this described the time, expressed as a % of the total task duration, when the signal decreased at 10% increments of the peak amplitude.(decreasing from 100% of peak). These values were designated by muscle prefixes eg LMSigoff90X

'Signal off Y'- this described the amplitude, expressed as percentages of the MVC (for that session), at the corresponding values of time when the amplitude began to fall (expressed as 10% increments of the peak amplitude.) These were designated by muscle prefixes eg LMSigoff90Y.

'Signal time Y' - is the value of amplitude, expressed as percentages of the MVC at 10% increments (up to 100%) of the total duration of the task.These were designated by muscle prefixes eg RMst10y

Duration of activation- This was the duration of the activation for each muscle from 'onset' time to 'offset' time. It was designated by muscle prefixes eg LMDur.

'Energy ', was calculated as that area under the curve between the 10% increments of the onset , and offset values. It was designated by muscle prefixes eg RME20 .

'Onset ranking'- The numerical sequence of the muscle activation timings for each task.

4.3 Pattern Recognition for a Sample Group

This part of the study involved 10 subjects most of whom were either residents or staff of the Graduate Periodontics program, and included one UBC alumnus. The same enhanced number of "Curvematch" variables as before was used for the sample group. The statistical test used for this phase of the study was discriminant analysis.

Subjects

The 10 subjects included 2 males aged between 24 and 33 years, and 8 females aged between 28 and 38 years. There were no relevant medical histories, and all subjects had complete healthy dentitions. No attempt was made to divide the group according to a history of bruxism, since the purpose of the study was to devise a technique for recognizing EMG patterns whether they were a bruxist subjects or not.

Procedure

The Splints, experimental protocol, recording techniques , and offline processing were identical to the protocol described in the Reproducibility Study.

5 Results

5.1 Reproducibility Study.

Although "Curvematch" derived 64 variables for each muscle, two primary variables for each muscle (making a total of 8) were selected to demonstrate how the analysis was conducted.

The two key variables selected were:

Signal On 90Y - (The amplitude of the signal).

Signal On 90X - (The activation time of the signal).

These examples were analysed in four different ways

1. Descriptive statistics
2. Q/Q plots of normal distribution.
3. Independent samples t tests
4. General linear model ; Repeated measures.

The reasons for selecting each of these forms of analysis are discussed below:

Descriptive statistics. Here , plots of the mean values and standard deviations were made for each muscle, for each day , and were divided by "task" or ID number. This permitted visual inspection of the key variables on a a day to day basis.

The Q/Q probability plot was a graphical technique for determining whether the data sets came from populations with normal distributions. Here the data sets were plotted against theoretical quantiles. This permitted decisions regarding which statistical tests (parametric, or non-parametric) were the most appropriate, and also the degree of precision with which the results could be interpreted.

The Independent-samples t test compared the means for any 2 tasks or movements performed. Significant differences could be shown between the mean values for different "tasks" performed, (denoted by ID number). The 2 samples t test was fairly

robust regarding departures from normality. The study assumed equal variance with independent samples from a normal distribution.

General Linear model;Repeated measures. The One-Way ANOVA procedure produced an analysis of variance for a quantitative dependent variable by a single factor (independent) variable. ANOVA was used to test the hypothesis that several means were equal, and was an extension of the 2 sample t-test.

Note:

Post hoc tests are used for determining the differences among means after an experiment has been conducted. When there are differences between the means, post hoc range tests and pairwise multiple comparisons can determine which means differ. Pairwise multiple comparisons test the difference between each pair of means, and yield a matrix where asterisks indicate the significantly different group means at an alpha level of 0.05.

The Bonferroni pairwise multiple comparisons uses t tests to perform pairwise comparisons between group means, but controls the overall error rate by setting the error rate for each test to the experiment wise error rate divided by the total number of tests. Hence, the observed significance level is adjusted for the fact that multiple comparisons are being made.

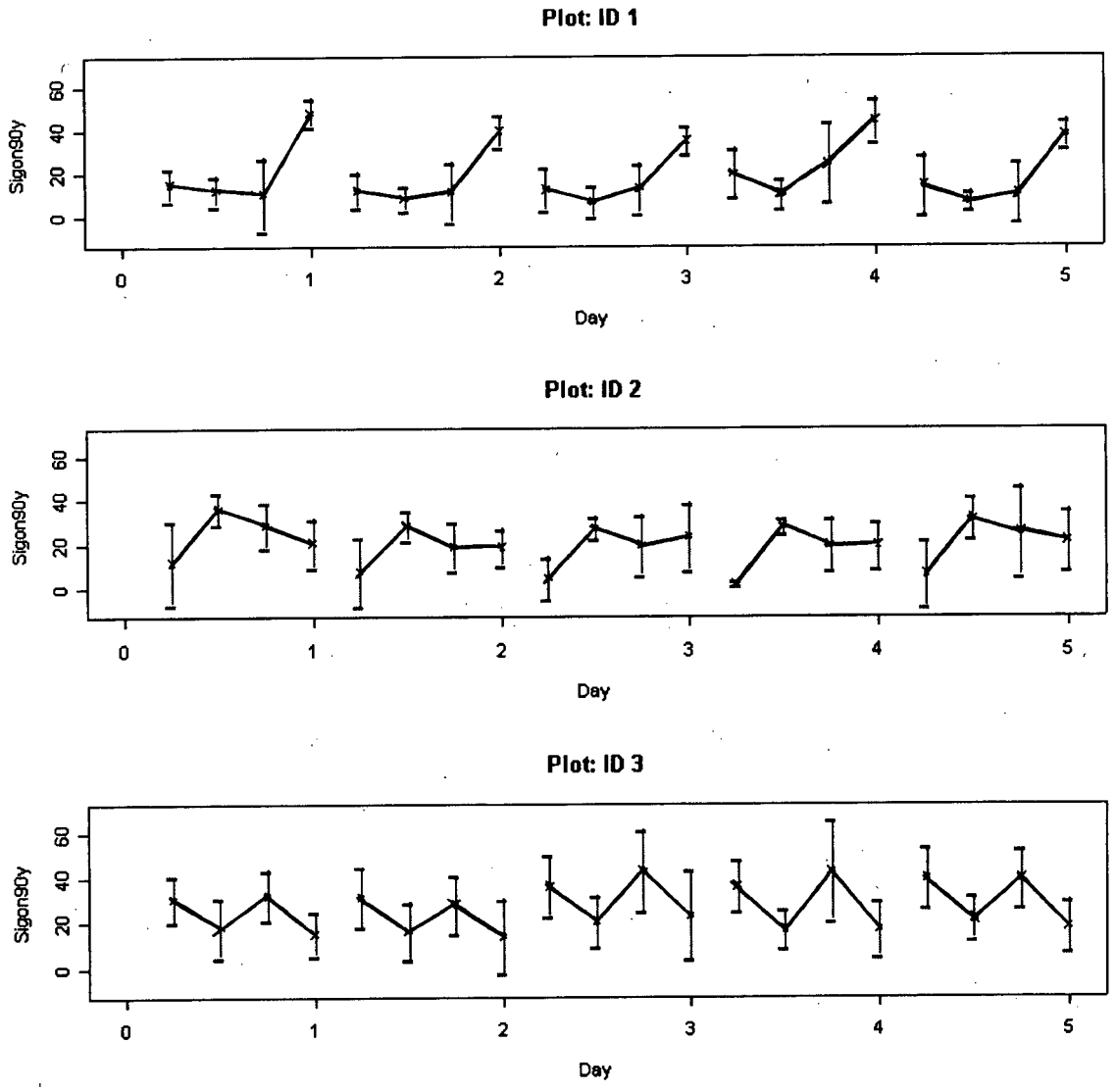
Key variable 1 Amplitude

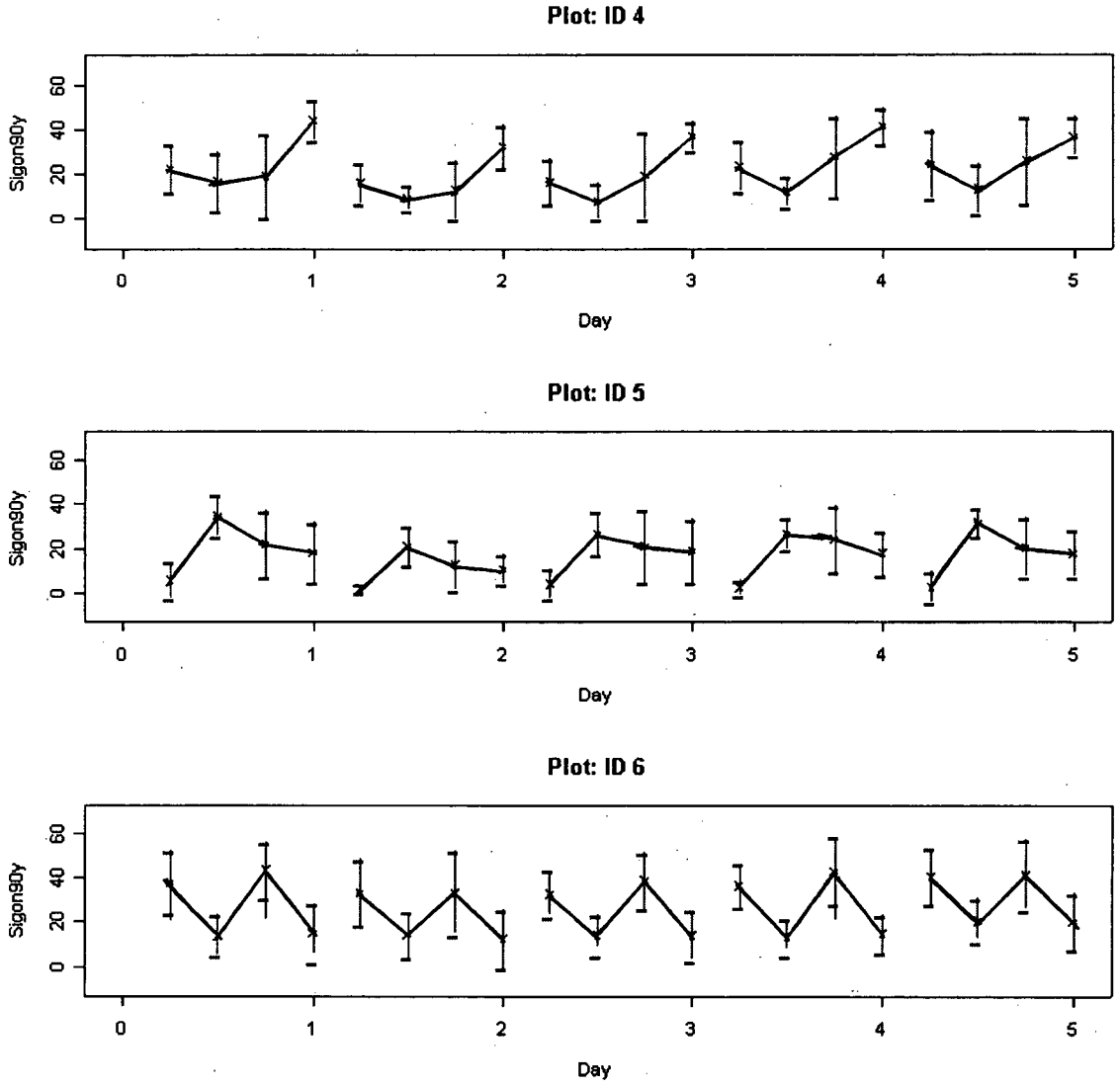
(90% of the Signal's Maximum amplitude SigOn90Y).

Descriptive analysis

This variable was chosen since it represented the greatest amplitude of the signal, whilst still in the rising section of the EMG onset curve. It was apparent on observing the batch processing of the EMG by "Curvematch", that when the curve was complex, or bimodal, on some occasions the actual peak (ie Signal On 100Y) occurred late in the data set. This may have been due to variation in subject compliance , difficulty performing the task, lack of understanding, or loss of concentration when performing the task.

Figure 8. Reproducibility study. Key variable 1. (90%of the amplitude) SigOn90y : Mean amplitude and standard deviation for 4 muscles: Left masseter,left temporalis,right masseter,right temporalis (henceforward convention LM,LT,RM,RT) from day 1 to day 5 with respect to different movements/ tasks (ID numbers).The panels Plot ID1-6 illustrate the data over 5 days.In each panel sets of 4 muscles are shown for each day.The muscles in each set are ordered from left to right in the sequence LM,LT,RM,RT. The black lines have been added to aid pattern recognition and do not represent continuous data.





Analysis

From the descriptive statistics it is clear that from day to day , the mean values and standard deviations for each muscle, were consistent for the prescribed tasks over the 5 day period.

The figures show that for the:

Right lateral slow movement (ID-1) the LM,LT,RM, were all similar in value. The LT having the least, and the RT having the highest values .

Left lateral slow movement (ID-2). a similar pattern emerged, LM showing the lowest mean value , whilst the LT consistently had the highest value.

Protrusive slow movement (ID-3). the LM and RM muscles showed consistently higher values than the LT, and RT means. Both sets of muscles had similar values.

Right lateral fast movement (ID-4). there is a similar distribution of mean values as in the ID-1 (slow) set, again with the RT being the consistently highest mean value. This strongly resembled the plot of ID-1.

Left lateral fast movement (ID-5), the LM is consistently the lowest value mean, followed by the LT being consistently the greatest value. The plotted values resemble the plot for ID-2

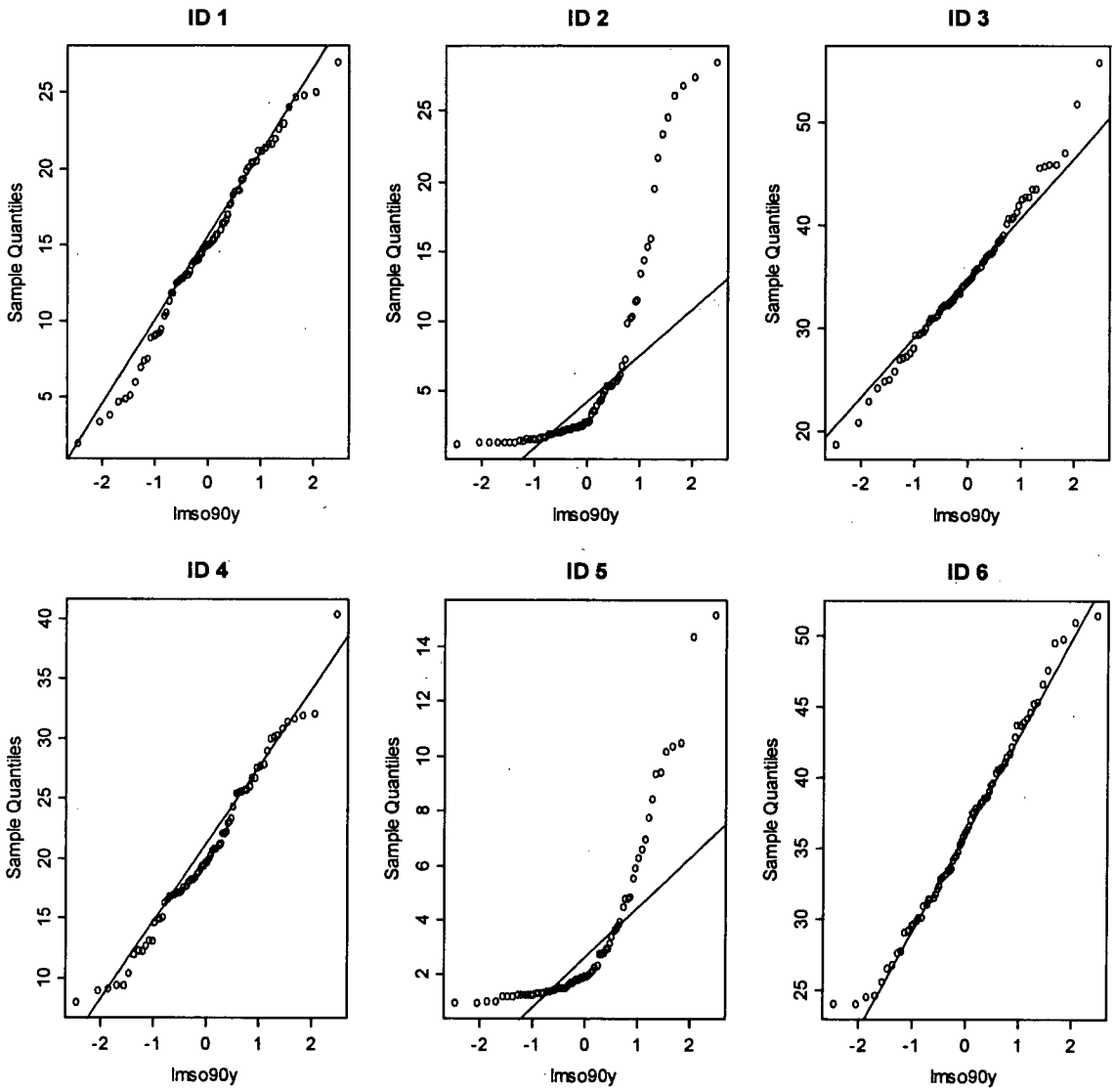
Protrusive fast (ID-6) the mean values of the RM are consistently the highest, and the difference between LM,and LT, were similar to the differences between RM, and RT. Again this resembles the ID-3 plot.

In summary, by grouping the muscle variables on a daily basis, and dividing them by task, although there were various standard deviations, there appeared to be similar mean values each day. The variation between muscles appeared to follow a similar pattern. Visual inspection suggested that on a day to day basis the results were consistent. (See Fig.8)

Q/Q Plots.

The data for the Sig On90Y (90%of the amplitude) were normally distributed. The greatest variation was seen in the ID-2, and ID-5 plots for the left masseter. Both were left lateral excursions,(ID-2 being slow, and ID-5 being fast). In both cases there was a "heavy tail". However for the majority of the plots, the distribution of the data was normal.

Figure 9. Reproducibility study: QQ plots for the left masseter muscle for key variable 1. 90% of the signal amplitude (SigOn 90Y)



Independent Samples T Tests;

These compared the same key muscle variables eg LM Signal On 90 Y (90% of the signal amplitude)for different movements /tasks, for the same day. They determined whether the difference between the variables could distinguish between a movement to the left, or the right, or between a fast and slow movement, for the specified muscle. This procedure was performed for all 5 days.

(See Tables 1-4. below).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	NS	P<0.029	P<0.001	P<0.003	NS
(4+1)	P<0.001	P<0.046	P<0.043	NS	P<0.001
(5+2)	P<0.027	P<0.014	NS	NS	NS
(5+4)	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001
(6+3)	P<0.005	NS	NS	NS	NS

Table 1 . Reproducibility study. : Key variable 1. Left Masseter Signal On90Y (90% of the amplitude) for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001
(4+1)	P<0.035	NS	NS	NS	P<0.001
(5+2)	NS	P<0.001	NS	NS	NS
(5+4)	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001
(6+3)	NS	NS	P<0.001	P<0.017	NS

Table 2. Reproducibility study Key variable 1. Left Temporalis Signal On 90Y (90% of amplitude) for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	P<0.001	P<0.003	P<0.009	NS	P<0.001
(4+1)	P<0.017	NS	P<0.043	NS	P<0.001
(5+2)	P<0.008	P<0.004	NS	NS	NS
(5+4)	NS	NS	NS	NS	NS
(6+3)	P<0.001	NS	NS	NS	NS

Table 3. Reproducibility study Key variable 1. Right Masseter Signal On 90Y (90% of amplitude) for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001
(4+1)	P<0.005	P<0.001	NS	NS	NS
(5+2)	NS	P<0.001	NS	NS	NS
(5+4)	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001
(6+3)	NS	NS	P<0.003	NS	NS

Table 4. Reproducibility study Key variable 1. Right Temporalis Signal On 90Y (90% of amplitude) for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

Analysis

The results of the 5 day study showed that there were significant differences between all the tasks (ID numbers). Ideally, one would like to have seen significant differences between all the tasks, all the time.

When the data were analyzed between movement or "task"(ID number):

For slow, right and left lateral exursion (ID-2+1), a significant difference was seen 17/20 times, making it the task most likely to show a significant difference.

For fast, right and left lateral excursion (ID-5+4), a significant difference was seen 15/20 times making it the next most likely task.

For right lateral, fast and slow excursions (ID-4+1), a significant difference was seen 9/20 times.

For left lateral , fast and slow excursions (ID-5+2), a significant difference was seen 6/20 times.

For protrusive, fast and slow (ID-6+3), a significant difference was seen 5/20 times.

These results show that the independent samples t test was best able to differentiate between tasks of different directions (e.g. between left and right) and that discrimination could be made for slow movements more often than for fast ones. There were fewer results with significant differences between different speeds of task for the same side. The right side was more often significantly different. The difference between the speed of task for protrusion was the least significant.

General Linear model; Repeated Measures.

This ANOVA procedure was performed to assess the variation in the means from day to day. Again, using key variable 1 Signal On 90Y (90% of the amplitude) as the muscle variable, the daily mean values of the 15 repeated tasks were compared using Multivariate tests. All pairwise comparisons were conducted by Bonferroni controlling for the error rate.

The results were divided by movement /task (ID number).

Left Masseter;

LM SigOn90Y and ID-1 (Right lateral slow) showed that there was a significant difference($p<0.05$) between Day 4, and Days 1,2,3, and approaching significance for Day 5 ($p<0.08$).Day 4 mean value was significantly greater.

LM Sig On90Y and ID-2 (left lateral slow) showed that there was a significant difference between Day 1, and Day 4 ($p<0.011$).However , for ID-2 the difference was that the mean was much less.

LM Sig On90Y and ID-3 (Protrusive slow) showed that there was a significant difference between Day 1, and Day 5 ($p<0.015$), and that Day 5 had the highest value.

LM Sig On90Y and ID-4(Right lateral fast) showed that there was significant difference between Day 2, and days 4 and 5 ($p<0.012$, <0.008) , and between Day 3, and days 4 and 5($p<0.001$).The Days 2, and 3 had significantly lower mean values.

LM Sig On90Y and ID-5 (Left lateral fast) showed that there was no significant difference between any of the days.

LM Sig On90Y and ID-6 (Protrusive fast) showed that there was no significant difference between any of the days.

Left Temporalis;

LT Sig On90Y and ID-1 (Right lateral slow) showed a significant difference between Day 1, and days 3, and day 5($p<0.001$, and <0.001), and between Day 4 and day 5 ($p<0.039$) Day 1 had the greatest mean value, and Days 3, and 5 the lowest.

LT Sig On90Y and ID-2 (Left lateral slow) showed a significant difference between Day 1, and days 2,3,4 ($p<0.00$), and between Days 3, and day5 ($p<0.031$). Generally the values for days 2,3 and 4 were considerably lower than days 1, and 5.

LT Sig On90Y and ID-3 (Protrusive slow) there was no significant differences between the days.

LT Sig On90Y and ID-4 (Right lateral fast) showed significant differences between Day 1, and day 3($p<0.037$), and between Day 3 and day 5 ($p<0.002$).Days 1 and 5 had the highest mean values , whilst days 2, and 3 were the lowest.

LT Sig On90Y and ID-5 (Left lateral fast) showed significant differences between Day1 and days 2,3, and 4($p<0.002$), between Day 2 ,and days 1,4,and 5 ($p<0.009$), and between Day 4 and day 5 ($p<0.00$).Days 1 ,and 5 had the greatest mean values, whilst day 2 had the lowest.

LT Sig On90Y and ID-6 (Protrusive fast) showed significant difference between Day 5 and all the other days. Day 5 had a significantly greater mean value than all other days.

Right Masseter;

RM Sig On90Y and ID-1, there were significant differences between Day 4, and all other days ($p<0.001$-0.004),Day 4 was significantly the greatest mean value.

RM Sig On90Y and ID-2, there were significant differences between Day 1 and days 2,3,and 4 ($p<0.001$-0.013), and between Day 2 and day 5, ($p<0.045$).Days 2,3,and 4 had significantly lower mean values.

RM Sig On90Y and ID-3, there were significant differences between Day 1 and day3, ($p<0.002$), Day 2 and days 3,4,and 5 ($p<0.00$-0.007).Days 3,4, and 5 had significantly higher mean values.

RM Sig On90Y and ID-4, there were significant differences between Day 2 and day4,and 5 ($p<0.00$). Between Day 3 and day4 ($p<0.019$).Days 4,and 5 had higher mean values.

RM Sig On90Y and ID-5, there were significant differences between Day 2 and days 1,3, and 4($p<0.00$-0.008). Day 2 had significantly lower mean values.

RM Sig On90Y and ID-6, there were no significant differences

Right Temporalis muscle;

RT Sig On 90Yand ID-1, there were significant differences between Day 1, and day 2,3,and 5 ($p<0.0.00$).Between Day 2,and day3 and 4 ($p<0.014$-0.047), also between Day 3 and day4 ($p<0.00$), and Day 4 and day 5 ($p<0.002$).Day 1 was significantly greater than other days , and day 3 was the lowest value of the mean.

RT Sig On90Y and ID-2, there were no significant differences between any of the days.

RT Sig On 90Y and ID-3, there was significant differences between Day 2 and day3 ($p<0.01$). Day 3 had the greatest mean value.

RT Sig On 90Y and ID-4, there were significant differences between Day 1 and days 2,3,and 5 ($p<0.00$-0.01). Between Day 2and days 4and 5 ($p<0.001$-0.029), and between Day 3 and day4 ($p<0.024$).Day 1 and day 4, had larger mean values,and Day 2 had the lowest.

RT Sig On 90Y and ID-5, there were significant differences between Day 2 and days 1,3,4,and 5 ($p<0.00$-0.01).Day 2 was significantly the lowest value of the mean.

RT Sig On 90Y and ID-6, there were no significant differences seen between days for this group.

Analysis

For the LM group of results, No Significant difference was found between days for ID-5 (left lateral fast), and ID-6 (protrusive fast).

For the LT group, No Significant differences was found between days for the ID-3 (protrusive slow).

For the RM group, No significant differences was found between days for ID-6 (protrusive fast).

For the RT group, No significant differences was found between the days for ID-2 (right lateral slow), and ID-6 (protrusive fast)

It should also be noted that whilst ideally one would like to see no significant differences between all the tasks for all of the days, for 7 of the remaining 18 results the difference was accounted for by one particular day in the data set, meaning that 13 out of a possible 24 data sets showed either no significant differences, or were affected by only 1 day out of the 5.

Key Variable 2 Activation time

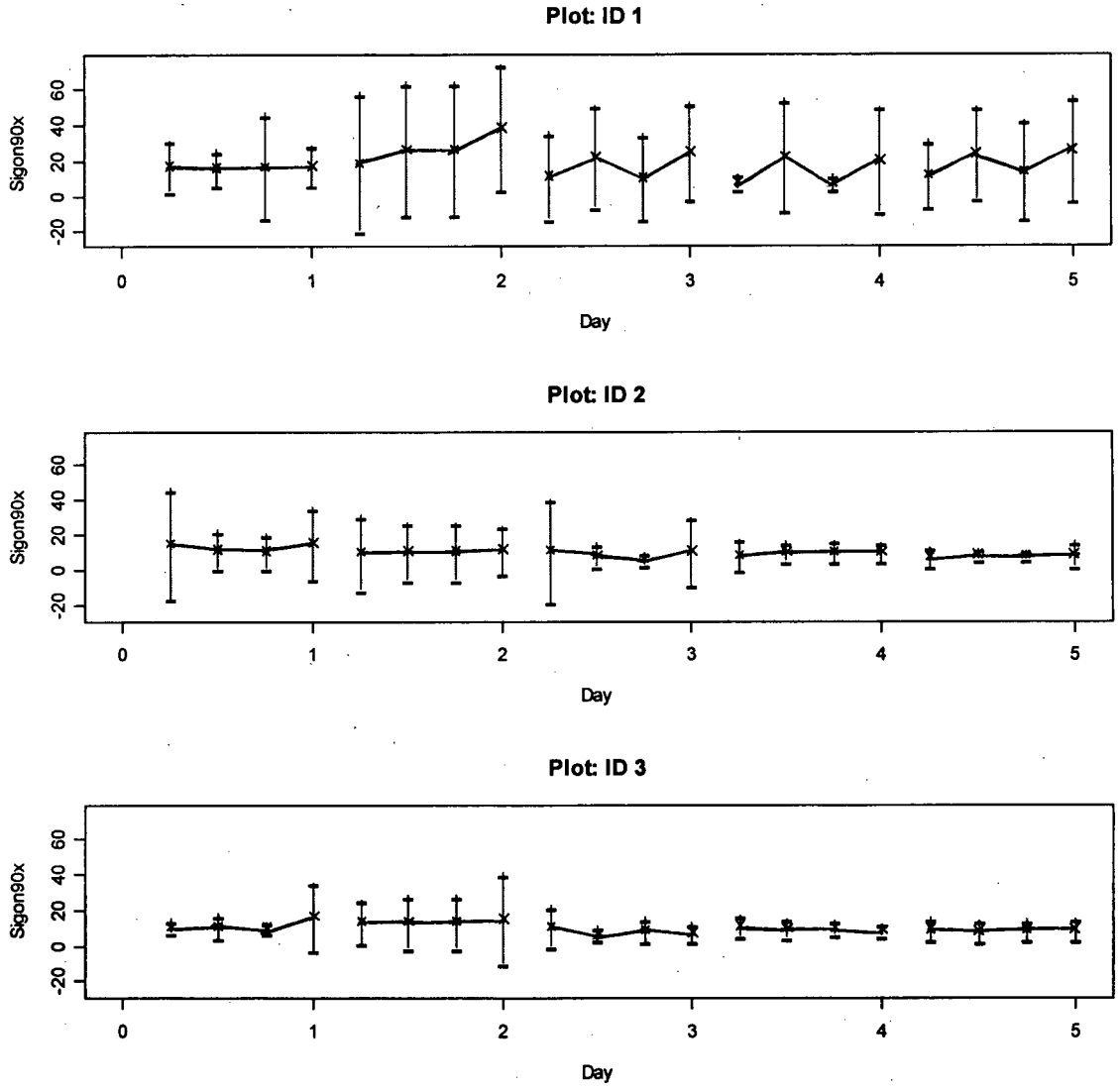
(time value where 90% of the peak amplitude occurs. SigOn90X).

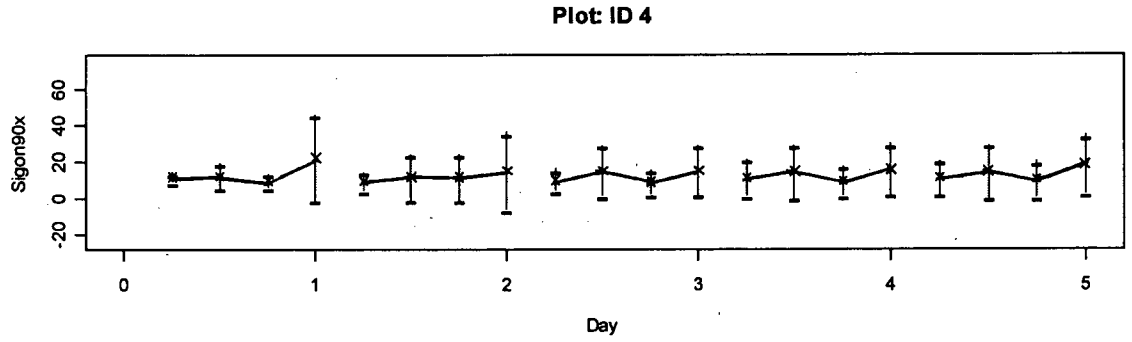
This variable was chosen as it represented the time variable for the corresponding value of amplitude that had been selected. Again, in order for comparisons to be made between different muscle groups, the time values were normalized using the total time of the task duration (onset time of the first muscle to come on, and the offset value of the last muscle to go off.)

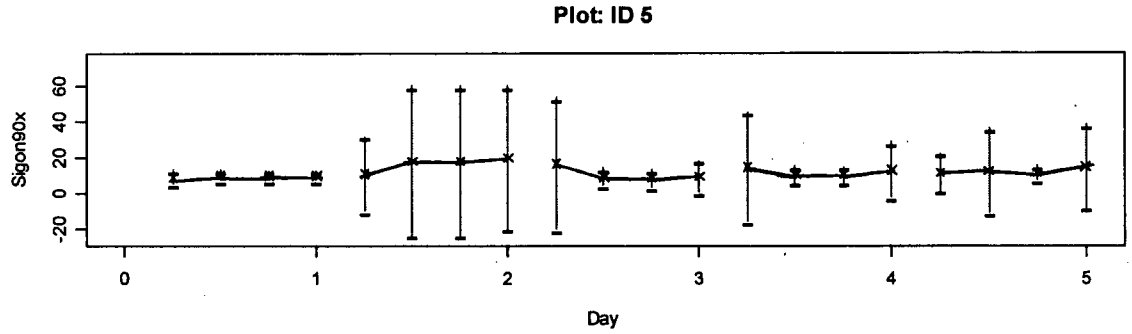
Descriptive analysis

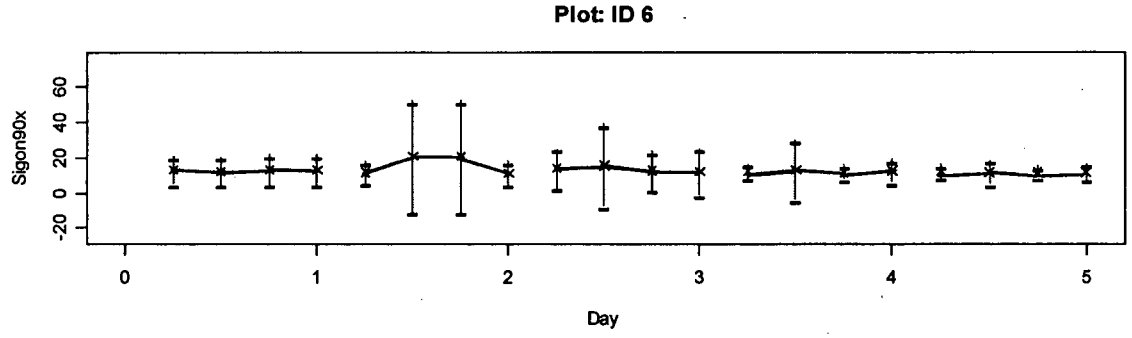
In this analysis, for each muscle , the mean values and standard deviations of the 15 repetitions were plotted , grouped by movement /task (ID number) for the 5 days of the study (see Fig 10).

Figure 10. Reproducibility Study Key Variable 2. Time value where 90% of the signals amplitude occurs (SigOn90X). Mean values and standard deviations for 4muscles LM,LT,RM,RT, for day1 to day5 with respect to different movements /tasks ie ID-number .









Analysis

The figures show that for the

For Right lateral slow (ID-1), Day 1 had similar mean values for the 4 muscles, day 2 had larger, and increasing values with greater standard deviations , and days 3,4,5 had a similar pattern between the masseter and temporalis muscles for means , and standard deviations.

For Left lateral slow (ID-2), similar mean values for the 5 day period, with large standard deviations for days 1,2,and 3, and less deviation for days 4,and 5.

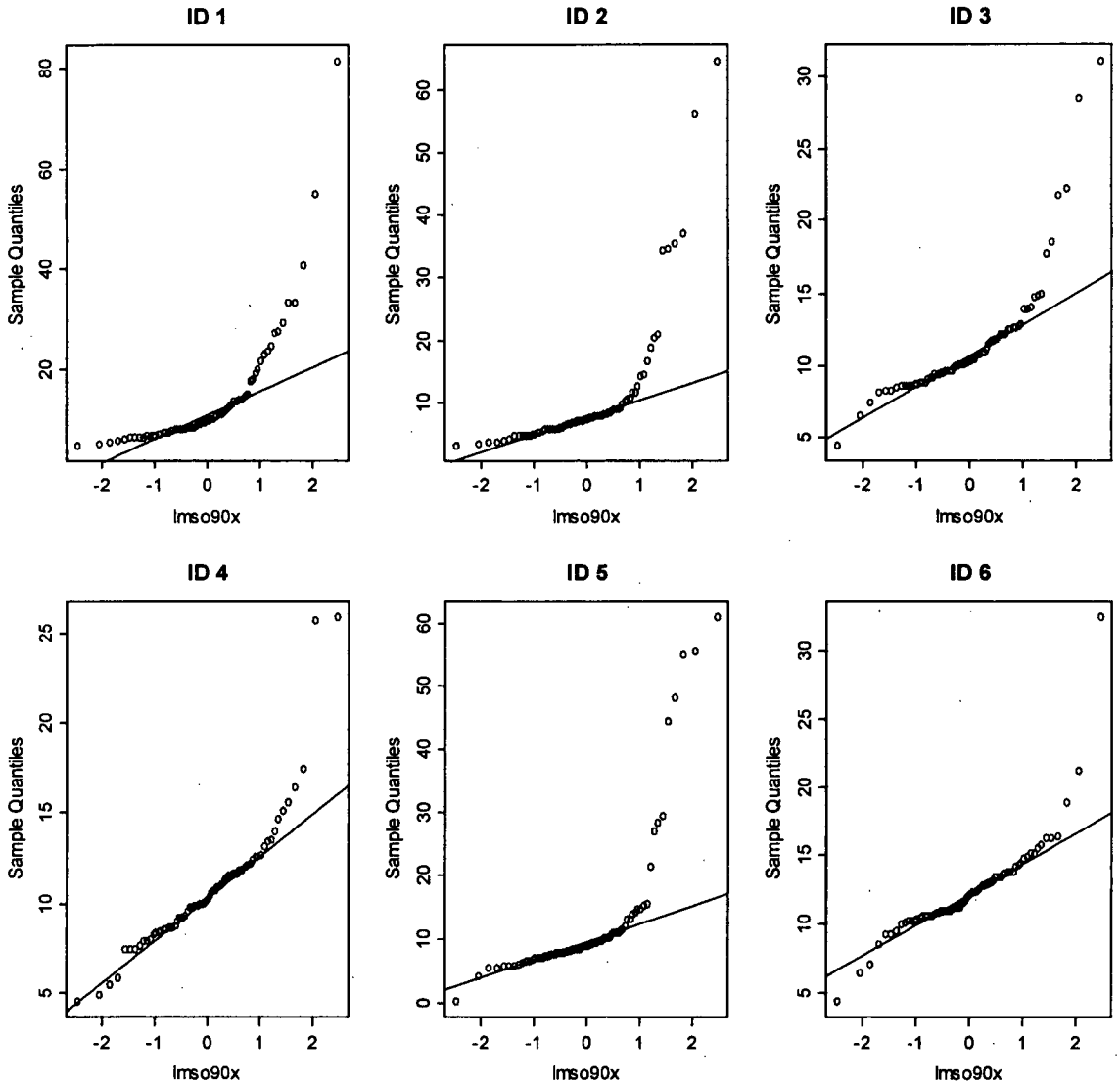
For Protrusive slow (ID-3), similar mean and standard deviation values for days 1,3,4,5 and greater deviations for day 2.
For Right lateral fast (ID-4); similar mean and standard deviations for all of the 5 day period.
For Left lateral fast (ID-5); similar mean values for the 5 day period, but the standard deviations were smallest on day1, largest on day 2, and moderate for the remainder.
For Protrusive fast (ID-6); similar mean values for days 1,3,4,and 5, with slightly higher values of mean and standard deviation on day 2.

In summary , the mean values for Signal On 90X were similar for all tasks over the 5 day period. The main variation was seen in the standard deviations , which were largest for the right lateral slow (ID-1) group, and also for left lateral fast (ID-4) day 2. No easily identifiable pattern was confirmed by visual inspection.

Q/Q Plots;

In most cases the Q/Q plots of the Signal On 90X variable showed , a tendency towards a normal distribution. However in several of the plots a noticeable 'heavy tail ' is seen. As the experiment was designed to control for time/speed variations , and as the data were expressed as a ratio compared to total duration of the task (with a ceiling towards which they tended), these results would not be expected to be normally distributed. However, the following Q/Q plots, and the fact that the Bonferroni pairwise comparisons test is quite robust with respect to violations of normality, providing there are enough data points, the analysis could be continued on the assumption there was a normal distribution.
(See Fig. 11).

Figure 11. Reproducibility study. Key variable 2. QQ plots for the left masseter muscle (Time value at which 90% of the amplitude occurs SigOn90X).



Independent Samples T test

These compared the time variable at which 90% of the amplitude occurred (SigOn90X), for the same muscle groups over the 5 day period, for different movements/ tasks. They determined whether the differences between the variables for muscle activation timing could distinguish between different movement /tasks, over the same five day period.

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	NS	NS	NS	NS	NS
(4+1)	P<0.03	NS	NS	P<0.037	NS
(5+2)	NS	NS	NS	NS	P<0.009
(5+4)	P<0.001	NS	NS	NS	NS
(6+3)	NS	NS	NS	NS	P<0.016

Table 5 . Reproducibility study. Key variable 2 Left masseter Signal On 90 X variable for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	P<0.029	P<0.007	P<0.001	P<0.08	P<0.001
(4+1)	P<0.014	P<0.006	NS	NS	P<0.016
(5+2)	NS	NS	NS	NS	NS
(5+4)	P<0.054	NS	P<0.004	NS	NS
(6+3)	NS	NS	P<0.01	NS	P<0.014

Table 6. Reproducibility study Key variable 2 Left Temporalis Signal On 90 X variable for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	NS	NS	NS	P<0.05	NS
(4+1)	NS	NS	NS	NS	NS
(5+2)	NS	NS	P<0.027	NS	P<0.001
(5+4)	NS	NS	NS	NS	NS
(6+3)	P<0.049	NS	NS	NS	P<0.004

Table 7 . Reproducibility study Key variable 2 Right Masseter Signal On 90 X variable for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

ID No.	Day 1	Day 2	Day 3	Day 4	Day 5
(2+1)	NS	P<0.001	P<0.002	P<0.017	P<0.001
(4+1)	NS	P<0.001	P<0.018	NS	NS
(5+2)	P<0.031	NS	NS	NS	NS
(5+4)	P<0.001	NS	NS	NS	NS
(6+3)	NS	NS	P<0.022	P<0.003	P<0.021

Table 8 . Reproducibility study Key variable 2 Right Temporalis Signal On 90 X variable for 5 days

The first column indicates comparisons between the two movements/ tasks denoted by ID-number. Right lateral slow(1), left lateral slow(2), protrusive slow (3), right lateral fast (4), left lateral fast (5), and protrusive fast (6).

Analysis

The results of the 5 day study showed that for the 4 muscle groups, and between the 6 movements / tasks (ID number), there were a total of 100 results over the 5 day period. In 67% there was no significant difference.

When the data were analysed between movements / task (ID number);

For slow, right and left lateral exursion (ID-2+1), no significant difference was seen 10/20 times

For fast, right and left lateral excursion (ID-5+4), no significant difference was seen 16/20 times .

For right lateral, fast and slow excursions (ID-4+1), no significant difference was seen 13/20 times.

For left lateral , fast and slow excursions (ID-5+2), no significant difference was seen 16/20 times.

For protrusive, fast and slow (ID-6+3), no significant difference was seen 12/20 times.

However, when we compare these results by muscle groups we can see that for the
LM group no significant differences were seen in 20/25 data sets.
LT group no significant differences were seen in 13/25 data sets.
RM group no significant differences were seen in 20/25 data sets.
RT group no significant differences were seen in 14/25 data sets.
This shows a difference between the 2 muscle groups with the Masseter group of muscles showing fewer significant differences in timing than the Temporalis group.

General linear model; Repeated measures.

This ANOVA procedure was performed to assess the variation in the means from day to day. Again, using Signal On 90 X as the muscle variable, the daily mean values of the 15 repeated tasks were compared using Multivariate tests and Bonferroni correcting for the error rate.

The results were divided by movement /task (ID number).

Left Masseter;

LM Signal On 90 X and right lateral slow (ID-1); shows a significant difference between Day 1 and day 4, ($p<0.003$), day 4 had the lowest mean value.

LM Signal On 90 X and left lateral slow (ID-2);shows no significant difference.

LM Signal On 90 X and protrusive slow (ID-3); no significant difference seen between days.

LM Signal On 90X and right lateral fast (ID-4); no significant difference seen between days.

LM Signal On 90X and left lateral fast (ID-5); no significant difference between days.
LM Signal On 90X and protrusive fast (ID-6); no significant difference seen between days.

Left Temporalis;

LT and Signal On 90X and right lateral slow (ID-1); no significant difference seen.
LT and Signal On 90X and left lateral slow (ID-2); no significance seen.
LT and Signal On 90X and protrusive slow (ID-3); significant differences seen between Days 1 , and 3 ($p<0.013$), Day 2 and day3 ($p<0.045$), and Day 3 and day4 ($p<0.048$). Day 3 had the lowest mean value.
LT and Signal On90X and right lateral fast (ID-4); no significant difference seen.
LT and Signal On 90X and left lateral fast (ID-5); no significant difference seen.
LT and Signal On 90X and protrusive fast (ID-6); no significant difference seen.

Right Masseter;

RM Signal On 90 X and right lateral slow (ID-1); significant differences between day 2 and day 4, ($p<0.016$), day 2 had a higher value than the other days.
RM Signal On 90 X and left lateral slow (ID-2); significant differences between day 3 and 4, and day 3 and 5. ($p<0.003$). Day 3 had a significantly lower mean value than other days.
RM Signal On 90 X and protrusive slow (ID-3); no significant difference seen between days.
RM Signal On 90X and right lateral fast (ID-4); no significant difference seen between days.
RM Signal On 90X and left lateral fast (ID-5); significant difference seen between day3 and day 5 ($p<0.03$).Day 3 had a significantly lower mean value than other days.
RM Signal On 90X and protrusive fast (ID-6); no significant difference seen.

Right Temporalis;

RT Signal On 90X and right lateral slow (ID-1); significant difference between Day 1 and day 2 ($p<0.005$). Day 2 had a significantly higher mean value than other days.
RT Signal On 90X and left lateral slow (ID-2); no significant difference seen.

RT Signal On 90X and protrusive slow (ID-3); significant difference between Day 1 and day3 ($p<0.024$).

RT Signal On 90X and right lateral fast (ID-4); no significant difference seen.

RT Signal On 90X and left lateral fast (ID-5); no significant difference seen.

RT Signal On 90X and protrusive fast (ID-6); no significant difference seen.

Analysis

For the LM group, only the ID-1 task, right lateral slow showed a significant difference over the 5 day period.

For the LT group, only the ID-3 task, protrusive slow showed a significant difference over the 5 days.

For the RM goup, ID-1,ID-2,and ID-5, right lateral slow, left lateral slow , and left lateral fast showed significant differences between the 5 days.

For the RT group, ID-1, and ID-3, right lateral slow, and protrusive slow, showed any significant differences over the 5 day period.

In Summary, the Reproducibility Study answered several important questions:

For the descriptive analysis of the amplitude variable (SigOn90Y), there were similar mean values for each day, and that visual inspection of the muscle activation pattern showed the results to be consistent on a day to day basis. The same was not true for the muscle activation timing variable (SigOn90X).

For the Q/Q plots, these were normally distributed, with a heavy tail being present in some cases.

The independent samples t test showed that for the amplitude variable (SigOn90Y), it was possible to discriminate best between tasks of different directions (eg left and right), and that discrimination could be made between slow task movements more frequently than faster movements. Protrusive tasks were least able to be distinguished.

The muscle activation time variable results (SigOn90X), t tests showed that there were nearly 70% of the movements /tasks showed no significant difference between the

movements. This indicates that the time variable was not the best indicator for discrimination between tasks.

The ANOVA tables results showed that for many of the tasks, for many of the days there was no significant difference between the days for the amplitude variable, there was also no consistent movement/ task, day, or muscle group that was consistently different. This implies that there was no repeatable, consistent experimental error. The ANOVA tables also showed that for the muscle activation time variable (SigOn90X), there were very few significant differences and there was no consistent pattern observed that might imply experimental error over the 5 day period.

5.2 Pattern recognition for a Single Subject

This first part utilized the data from the subject taking part in the "reproducibility" study. The statistical test used for this part of the study was discriminant analysis.

Discriminant analysis

Discriminant analysis is used for situations where one wishes to build a predictive model of group membership based on observed characteristics of each case. In this study we were trying to build a predictive model of the subject and tasks performed, based on the variables that were produced by the "curvematch" software program. The SPSS statistical package generates a discriminant function (or a set of functions), based on linear combinations of the predictor variables that provide the best discrimination between the groups. The discriminant functions that are generated from a known group , could then be applied to a new case to predict which group the case belongs to.

Results

The data set for the pattern recognition study for a single subject is divided into the 5 days of data acquisition and is labeled as "reproducibility 1-5"

An example of the data output is shown for the "Reproducibility 1". This is greatly reduced in detail as the full output can include: for each variable, means, standard deviations, ANOVA, and for each analysis: Box M's, within group correlation and covariance matrix, separate groups covariance, and total covariance matrix. For each canonical discriminant function: eigenvalue, %of variance, canonical correlation, Wilke's lambda, chi-square. For each step: prior probabilities, Fischers function coefficients, unstandardised function coefficients, and Wilke's lambda for each canonical function.

Table 9. Pattern Recognition for Single Subject. Day 1 . Predicted group membership of the prescribed task compared to movement /task (ID number).For all variables.

"Reproducibility Day 1"

Classification Results All Variables

			Predicted Group Membership						Total
		ID	1.00	2.00	3.00	4.00	5.00	6.00	
Original	Count	1.00	15	0	0	0	0	0	15
		2.00	0	15	0	0	0	0	15
		3.00	0	0	15	0	0	0	15
		4.00	0	0	0	15	0	0	15
		5.00	0	0	0	0	15	0	15
		6.00	0	0	0	0	0	15	15
	%	1.00	100.0	.0	.0	.0	.0	.0	100.0
		2.00	.0	100.0	.0	.0	.0	.0	100.0
		3.00	.0	.0	100.0	.0	.0	.0	100.0
		4.00	.0	.0	.0	100.0	.0	.0	100.0
		5.00	.0	.0	.0	.0	100.0	.0	100.0
		6.00	.0	.0	.0	.0	.0	100.0	100.0

a 100.0% of original grouped cases correctly classified.

This output shows that it was possible to identify group membership in 100% of the cases using all the variables provided by the curvematch program. The ID numbers 1-6 are shown , and the number of task repetitions are seen as well as the % of correct predictions.

Table 10.This table shows the Standardised canonical discriminant function coefficients that were selected to be the best for use in the analysis.

Standardized Canonical Discriminant Function Coefficients All Variables

	Function 1	2	3	4	5
LMSO10Y	.069	-.534	.077	-.889	-.185
LME10	-.901	-1.117	-.075	.989	.087
LTE0	-.367	.946	1.522	-1.083	-.219
LTSF10X	.519	.305	-.251	.600	.055
LTSO90X	.230	.219	.407	1.244	.201
LTST10Y	.424	.299	-.787	1.690	.440
LTST30Y	.396	.053	-1.276	.763	-.385
LTST100Y	.228	.380	-.089	-.286	.160
RME0	-.143	.817	-.198	-.575	-1.315
RMSO10Y	-.232	.079	.591	-.211	.931
RMSF10X	-.193	-.288	.791	.033	-.250
RMST30Y	-.949	-.195	.432	-.133	.745
RTSON0Y	.235	.174	.227	.112	.812
RTE10	1.613	-.505	-1.510	2.455	.527
RTE30	-.372	.329	1.956	-1.509	-.176
RTE90	.389	.122	.564	.577	-.042
RTST30Y	.568	-.244	-.309	-.559	-.380
RTST40Y	.059	.257	-.083	-.801	-.101
RTST60Y	-.284	-.372	-.354	-.651	-.050

Table 11. Pattern recognition for Single Subject Day 1 (reduced variable number).

Classification Results using variables Signal On X+Y,Energy,and Duration

			Predicted Group Membership						Total
		ID	1.00	2.00	3.00	4.00	5.00	6.00	
Original	Count	1.00	15	0	0	0	0	0	15
		2.00	0	15	0	0	0	0	15
		3.00	0	0	15	0	0	0	15
		4.00	0	0	0	15	0	0	15
		5.00	0	0	0	0	15	0	15
		6.00	0	0	1	0	0	14	15
	%	1.00	100.0	.0	.0	.0	.0	.0	100.0
		2.00	.0	100.0	.0	.0	.0	.0	100.0
		3.00	.0	.0	100.0	.0	.0	.0	100.0
		4.00	.0	.0	.0	100.0	.0	.0	100.0
		5.00	.0	.0	.0	.0	100.0	.0	100.0
		6.00	.0	.0	6.7	.0	.0	93.3	100.0

a 98.9% of original grouped cases correctly classified.

This table shows that it was possible to predict group membership 98.9% of the time using a greatly reduced number of the variables produced by curvematch (Signal On for the X , and Y variables, the energy, and the duration of activation).

Table 12. This shows the standardized canonical discriminant function coefficients

that were assessed as being the best coefficients to correctly predict group membership.

Standardized Canonical Discriminant Function Coefficients X+Y,E, DUR

	Function 1	2	3	4	5
LMSO10Y	.087	-.682	.440	-.915	-.211
LME10	-.583	-.967	-.486	1.137	.053
LTE10	-.122	1.045	.332	-.371	-.299
LTSO80Y	-.119	.191	-.237	.769	.117
RMDUR	-.087	.013	.599	.016	.211
RME10	-.634	.480	.539	-.725	-.197
RMSO90X	.128	-.278	.395	.318	-.172
RTDUR	.305	.089	.365	.089	1.073
RTE10	-.119	-1.420	-1.137	3.320	-3.154
RTSO20Y	.429	.371	-.523	-.805	1.152
RTE30	1.122	1.074	1.298	-2.972	2.266
RTE90	.409	.138	.340	.242	-.184

Table 13. Pattern recognition for Single Subject. Results table showing Reproducibility study days 1-5, with % of predicted group membership for all variables produced by curvematch program.

ID-No. (task) / Day	Predicted % Group Membership 1	2	3	4	5	6	Total % cases correctly predicted
1	100	100	100	100	100	100	100
2	100	100	93.3	100	100	100	98.9
3	93.3	100	100	100	93.3	100	97.8
4	100	93.3	100	100	80	93.3	94.4
5	100	100	100	100	100	100	100

Table 14. Pattern recognition for Single Subject. Results table showing Reproducibility study days 1-5 with % of predicted group membership using reduced variable numbers (Signal On for X, and Y, Energy and duration of activity).

ID-No. (task) / Day	Predicted % Group Membership 1	2	3	4	5	6	Total % cases correctly predicted
1	100	100	100	100	100	93.3	98.9
2	100	100	86.7	100	100	100	97.8
3	93.3	86.7	100	93.3	93.3	100	94.4
4	93.3	93.3	86.7	100	80	100	92.2
5	100	93.3	93.3	93.3	100	93.3	95.6

5.3 Pattern recognition for a Sample Group

This part of the study involved recording 10 subjects who were all either residents , or staff of the Graduate Periodontics department , and one UBC alumnus. The statistical test that was used for this phase of the study was discriminant analysis.

Table 15 . Pattern recognition for Sample Group. Results table showing Predicted % group membership(by task) for the 10 subjects using all variables produced by the curvematch program.

ID-No. (Task) / Subject	Predicted % Group Membership 1	2	3	4	5	6	Total % cases correctly predicted
1	100	100	100	100	100	100	100
2	100	100	93.3	93.3	100	100	97.8
3	100	100	93.3	93.3	100	93.3	96.7
4	86.7	80	73.3	100	73.3	86.7	83.3
5	100	100	100	93.3	100	86.7	96.6
6	100	100	100	100	100	100	100
7	93.3	86.7	93.3	100	93.3	93.3	93.3
8	100	86.7	100	100	100	100	97.8
9	93.3	93.3	93.3	100	100	80	93.3
10	100	93.3	100	100	100	100	98.9

Table 16. Pattern recognition for Sample Group. Results table showing Predicted % group membership using a reduced number of variables from the curvematch program (Signal On X and Y, energy, duration of task).

ID-No. (Task) / Subject	Predicted % Group Membership 1	2	3	4	5	6	Total % cases correctly predicted
1	100	93.3	100	100	100	100	98.9
2	100	100	93.3	93.3	100	86.7	95.6
3	80	93.3	86.7	93.3	100	93.3	91.1
4	80	73.3	66.7	100	66.7	66.7	75.6
5	93.3	93.3	100	93.3	93.3	93.3	94.4
6	93.3	100	100	80	100	100	95.6
7	93.3	80	66.7	100	93.3	93.3	87.6
8	100	86.7	100	100	93.3	93.3	95.6
9	80	80	86.7	93.3	86.7	80	84.4
10	93.3	93.3	100	93.3	100	100	96.7

In summary these results show that it is possible using the curvematch program, and discriminant analysis to predict group membership (ie for a specific movement / task) for an individual movement / task, to a significantly high recognition rate.

6 Discussion

This is the first study to attempt pattern discrimination between specific oral motor function tasks designed to simulate muscle activity during bruxism. Other studies have attempted to utilize algorithms to recognize a variety of different oral activities (Gallo et al 1998), to recognize oral function activities and to discriminate between these and parafunctional events (Gallo & Palla 1995). Efforts have also been made to discriminate between bruxism events defined as being above a suprathreshold EMG signal level or not (Gallo et al 1997).

In the present study a relatively simple computer algorithm was used to produce a number of variables that best describe features of smoothed and filtered EMG waveforms. In 10 subjects multivariate discriminant anlaysis then permitted the recognition of a variety of controlled tasks in an experimental environment, and the assessment of the recognition rate for each subject for each movement / task.

Electromography

The use of EMG is an easy, non-invasive way of evaluating the physiological processes that allow muscles to generate forces and movements. Nevertheless, EMG has many limitations in its interpretation, and the precision of its results. In a comprehensive review of surface EMG, C.J.de Luca (1997), states that there are many factors relating to the ability of EMG signals to be related to force measurements. Many of these are technical and have been addressed in the introduction, but there are some which need comment here to facilitate interpretation of the study's results. The issue of "cross-talk', and the origin of the detected signal is important. The anterior temporalis, and the masseter muscles are relatively easy to palpate and to isolate, ensuring correct application of the electrodes. The possibility of cross-talk potential mainly concerns the buccinator muscle which has fibres that run horizontally, and run ninety degrees to the direction of the masseter. In this study (as perhaps opposed to a true bruxing environment), the majority of the subjects would not activate their buccinator muscle whilst performing the specified tasks. Also, the alignment of the differential electrode, means that any cross-talk would be proportional to the differential produced by the electrode diameter (i.e. relatively small), and is likely to have had very little effect on the EMG being produced

by the task. Another anatomical concern is related to the amount of fatty tissue between the electrode and the muscle surface. Providing the signal had a sufficiently good signal to noise ratio, and that there was a strong enough signal to measure, plus the fact that comparisons were not being made between subjects, this factor was constant for each subject.

There is also the issue of electrode movement relative to muscle fibres i.e. by virtue of the fact that there is a change in length of the muscle. The electrode however stays affixed to the skin which does not change dimension.

In this study the muscular contraction resulted in albeit a small jaw movement, (approximately between 6-10mm's),and would therefore be deemed to be near isometric. This has been shown to reduce the accuracy of any quantitative assessment of force production, however our experiment was the same bilaterally , and the protrusive movements also, would probably have produced a similar amount of electrode movement on each occasion. This observation , and the fact that our study was not attempting to quantitatively assess the resultant force produced may reduce the importance of any electrode movement. If it is necessary to process an EMG signal that is anisometric, de Luca suggests that every effort be made to analyse the near-isometric epoch of the task recording, it is for this reason also that the Signal On 90 X+Y variables in the rising phase of our EMG recordings was selected.

One of the dominant reasons for using surface EMG is its use as an indicator for the initiation of muscle activation. Since the signal can provide the timing sequence of one or more muscles performing the task, the initiation amplitude was one of the most important features of the EMG results used in this study.

The EMG signal was processed and filtered with a Butterworth filter set at 4 Hz. This might suggest a considerable loss of waveform sensitivity, (an "over smooth" waveform). However, the muscle activation sequence would not have been affected.

The relationship of the EMG signal to the resultant force produced by the muscle group is a complex problem. It can be said that the amplitude is qualitatively related to the force produced, but that an accurate quantitative assessment is more difficult to prove. Current literature suggests that for small muscles where the firing rate of the motor units has a great dynamic range and motor unit recruitment is limited to the lower end of the

force range , the force is linearly related to the EMG amplitude, whereas in larger muscles where motor unit recruitment continues into the upper end of the force range and the firing rate has a lower dynamic range, the relationship is relatively non-linear(de Luca 1997).

Tasks

The experimental design used 6 stereotyped sliding jaw movements including interocclusal force. These acts were not considered replicas of muscle activation patterns reported during bruxism which can be quite complex (Lavigne et al 2003). The timing of the tasks, and their separation into "fast" and "slow" categories, was an attempt to test the sensitivity of the analysis to be able to discriminate between different speeds of movement. Over 88% of sleep bruxism activity is defined as a mixture of phasic (3 or more bursts of contractions at frequency of 1 Hz) or mixed, including the tonic contraction lasting more than 2 seconds (Lavigne et al 2003). In future studies, it should be possible to modify the parameters used in the present study. The design should have included a group with a longer time limit to represent both short burst and longer tonic activites (see later, this section).

Normalization

To make comparisons between results from the same subject for a range of contractions, and to compare data among different subjects, it is common practice to "normalize" EMG signals, most commonly as a % of MVC. Obtaining the best estimates for MVC requires some preliminary training, otherwise the results can be up to 20-30% less than those achieved with training (Merletti 1999). The protocol adopted in the present study was similar to that by de Luca (1997), with the same experimental conditions as the "task" recordings, i.e. brief contractions (<5 seconds in duration and approximately 2 minutes between each contraction to allow recovery), and there was a training period of between 5-10 MVC's with feedback being provided to the subject viewing the recorded traces. Three consecutive MVC's were recorded before the "task" series, and 3 more at the end of the experiment. The greatest overall value was used for normalization.

For several variables the time axis was also normalized relative to the total time of task duration. This is a common approach in physiotherapy and kinesiology, where more complex, and longer time periods are frequently encountered (Falconer et al 1985). In the present study the results were relatively easily derived, although the program was designed to include more features than were ultimately used. This should make the approach to more complex acts (such as bruxism) feasible in the future.

Reproducibility study

Descriptive statistics

In the reproducibility study, the descriptive statistics revealed similar means and standard deviations for the muscle variables for the amplitude (SigOn90Y) over the 5 day period. However, similar statistics for the time variables showed less reproducibility. The means for the variables were within a similar range, and the standard deviations were generally reduced (except for noticeable exceptions on Day 2 for tasks ID-1,5 and 6, and generally, for the movement right lateral slow ID-1) over all 5 days. Thus the amplitude variations seen in the SigOn90Y produce a recognizable pattern on a daily basis whereas the time variables did not. This may be due to the control of the time variables with a target oscilloscope tracing. This approach did not guarantee subjects would copy the input target precisely on all occasions. In future experiments it would be useful to have an additional monitor of actual jaw movement, and to use this as a means for classifying fast or slow tasks rather than the a priori classification scheme used here. The fact that ID-1 had a generally higher standard deviations for all days may be explained by the fact that it was repeatedly the first task performed each session, and so this would be the task least trained for each day. The observation that the standard deviations were greatest for Day 2 and tasks ID-1,5,6, might mean that there was some anomaly peculiar to Day 2, as there did not appear to be any correlation between task or movement performed, or muscle group.

Quantile - quantile plots

The Quantile-quantile plots were constructed to see if the data were normally distributed.

In the plot for the Left masseter amplitude variable (SigOn90y) (Figure 9) the shape of the plot has a "heavy tail"for ID-2 and ID-5. These two tasks were both movements to the left, ID-2 being slow and ID-5 being fast. This may imply something specific for this subject with regard to a habit or persistent individual variation during the task.

T test results

The t test series of results was designed to assess whether the selected variables would be able to distinguish between different directions of movement and different speeds of movement. When selected for amplitude (SigOn90Y), by task (ID-No.) a significant difference was seen 17/20 times for the slow movement between left and right, and 15/20 for the fast movement between left and right. Thus with a simple t test the variables could accurately predict direction 85% of the time for slow movements, and 75% of the time for faster movements. When the speed of the movement rather than direction was specified, the success was less, only 45% for the right , and 30% for the left. Predictions for the protrusive movements were the least successful at 25% . Anatomically and biochemically, one would expect perhaps that different muscles would show greater amplitude variation in order to deflect the mandible to one side or another, i.e. to be direction specific. Notably, the slower movement was more predictable, so that in the present study design the specifications of a longer time period (> 1 second) might have yielded a higher success rate. This would also be more comparable with the 'tonic' or longer contractions found in sleep bruxism. The low degree of success found in detecting the speed of movement suggests this variable would be less able to discriminate between same side contractions since these were sampled at one location, making a 'rate' change difficult to see. It might reflect the experimental design, in that the differences between the two selected speeds (0.5 seconds v.1.0 seconds) may have been too small to differentiate between the two acts. As the time for the tasks was relatively "quick", the difference between similar muscle activation patterns would be more difficult to detect. The observation that the protrusive act was the least successfully discriminated could be due to the closeness of muscle group activation to that in bilateral tasks.

When we look at the results and compare them by muscle group, we note that for the masseters (left and right) there were a total of 25/50 (50%) significant differences seen

over the 5 day period, the temporalis group showed 29/50 (58%). For this series of tasks, we could say that the temporalis group is a more sensitive indicator than the masseter group. This has also been noted in a previous paper on activity recognition in long term EMG (Gallo & Palla '95).

For the time dependent variable SigOn90X, there were many more results of no significant difference. Again, as discussed earlier the experimental design may have affected the likelihood of finding fewer significant differences. However, muscle group analysis showed that the masseter group has 40/50 (80%) results with no significant difference, and the temporalis group had 27/50 (54%) results with no significant difference, again illustrating the increased sensitivity of the temporalis group in muscle activity recognition.

ANOVA

The results of the ANOVA tables and their subsequent analysis, are complex. Here the aim was to establish whether there was any significant variation over the 5 days of experimentation, and see whether it correlated to a specific task, or muscle group. That one would see no significant differences between the days for each task would be an "ideal" result. Even allowing for the experimental control and protocol adopted, the amplitude of the signals alone would result in some sample variation. For the amplitude variable SigOn90Y, the protrusive act was involved in the least number of significant differences between the days. When compared with t test results, these protrusive movements were also the least likely to be able to be predicted (~ 25%). It is possible that this movement required greater coactivation of all the muscle groups concerned to produce it rather than the specificity seen in the production of a unilateral movement. Also for the amplitude variable SigOn90Y, the analysis showed the fact that for the 4

muscle groups, and the 6 tasks, there were no significant differences seen between days for 6/24 tasks, and that for another 7 tasks the difference was accounted for by only 1 out of the 5 day's results in the data set. This suggests that 13/24 showed either no significance, or were affected by only one day of the results.

When the time variable results are considered (SigOn90X), the results were as we would expect. There were 17/24 occasions with no significant difference seen between the days for the 4 muscle groups, the majority of the other results show that only 1 day accounted for the difference. For the 4 muscle groups the ID-1 task (right lateral slow movement), was significantly different 3/4 times. Although there were many significant differences over the 5 day period, no clear pattern emerged, especially with regard to task performed, particular day, or specific muscle group. If there had been a greater "time" differential between the (fast and slow) tasks , there may have been fewer significant differences between the days, (i.e. the fast time period of 0.5 seconds may not have allowed for individual variation during the performance of the task).

Pattern recognition for Single Subject

This part of the study used the data from the reproducibility study. Since the curvematch program produced 244 variables, the larger the number of variables, the greater the potential for discrimination. A secondary goal of the experiment was to see if a high recognition rate could be maintained while reducing the number of variables. This could ultimately have clinical or experimental relevance, in that for a given subject fewer muscle groups might be required for recordings. Visual examination of the output for the canonical variables that the SPSS selected as the best determinants of the discriminant function did not produce any particular pattern with regard to muscle group or other curvematch variable set. The variable labelled "energy under the curve" was probably the most frequently seen, as this effectively represents the " power" of the signal and has a tangible meaning. The SPSS discriminant function program does actually "weight" the different functions used in the production of the output, but any patterns in this were difficult to discern.

From Results table 13 with all variables included, the ability to discriminate between the different tasks for two of the days was 100%, and fell to a lowest value of 94.4% on Day

4. This gave an overall result of 98.2% of cases correctly predicted for group membership over the 5 day period.

When the number of variables involved in the discriminant analysis was reduced to include only the Signal On variables for X and Y, the Energy , and the duration of activation, the recognition rate decreased, but the overall success rate was 95.7%, and even the lowest result on day 4 was 92.2% successful.

Pattern recognition for the sample group

This part of the study involved data sets from the 10 subjects recorded using all the same experimental protocol previously discussed. When all the variables were included, the number of cases correctly predicted varied from 100%, (in two subjects), to 83.3%. (Table 15). This resulted in an overall successful prediction rate of 95.7%. If the results from subject number 4 are excluded the result would be 97%. Again when the number of variables involved in the discriminant analysis was reduced (SigOn90 X and Y, Energy, duration of activity), the recognition rate decreased to 91% overall, (excluding number 4 the result would be 93%).

When we compare the two pattern recognition studies, there are several features worth noting. The single subject pattern recognition study used the same subject over a 5 day period. This would have resulted in an increasingly effective training period with feedback involved, possible wear of the appliance (leading to a less reproducible pathway, or an improved "habitual" task pathway) and a more relaxed approach to the experimental environment. However large numbers of task repetitions could be counterproductive to the required level of concentration. Thus high levels of predictability here of 98.2% and 95.7% should be tempered with the knowledge that a considerable amount of "training" may have been built into the results.

The converse is true for the sample group pattern recognition study. The subjects followed the protocol discussed for the recording of MVC, with feedback. They were allowed to practice each task several times before the recordings started(~10) with suitable rest periods between, and also to practice between the slow series and the fast series of task recordings, to attempt to allow them to adjust to the faster oscilloscope tracing recording. Three of these subjects had used an appliance before. Only one of the

group was a regular night guard wearer. The group included two subjects who claimed to be "night grinders". There were no reports of TMD, and at no time did any of the subjects complain of pain prior to the recording session. The subjects were all medically and dentally fit. There was no attempt to control the subject sample, as the purpose of the study was to devise a technique for pattern recognition rather than to assess the subjects themselves. However it should be noted that all the subjects were either residents or assisting staff of the Graduate Periodontics department (except subject number 4). All other subjects had a very high level of dental awareness, and considerable technical understanding of the tasks involved and the experimental procedure in which they were involved. Subject number 4 was an UBC alumnus, though not dentally trained. For this reason I have made a note of the success rates of the discriminant functions including , and excluding, subject number 4. Although the dentally trained group did not receive any extra training, it could be presumed that they were better able to perform the prescribed tasks by virtue of their greater dental knowledge. It is this area of the study that shows some weakness, since there was not an independent monitor of what the subjects were actually doing intra-orally. Another improvement that could be undertaken would be to perform similar "reproducibility" studies for all of the individuals involved in the sample group. In this case the limitations of availability of the individuals for time consuming EMG recordings was the major constraint. In future studies, it may be possible to incorporate jaw tracking in conjunction with the EMG recordings so as to be able to better assess the subjects actual movements.

Gallo and Palla '95, compared function and simulated parafunction using the signal mean value and a sliding window of 0.96 seconds duration to aid differentiation when processing long term EMG results. They concluded that temporal muscle recordings showed better discrimination, a fact also noted in our study, and also that signal mean level was 51% for clenching, and 21% for tooth grinding (%of MVC).They found that the sliding window duration of 0.96 seconds was the best in discriminating between chewing, grinding and clenching only. There were no other tasks reported. In 1997, Gallo et al continued their EMG observations and showed that portable EMG recorders are a reliable way of scoring bruxism episodes, and they had a 100% agreement with clinical evaluation in the recognition of bruxist events with portable recorders and

polysomnography. They also specified that an ideal time base for EMG signals to be integrated to allow for discrimination of bruxism patterns is 0.06 seconds. This study was based on the definition of bruxism purely as a suprathreshold EMG signal portion, and went on to compare the recognition results for the portable recorders and polysomnography. The agreement was 63%, significantly, polysomnography is considered the gold standard, they noted that in obtaining these results, the scorers had difficulty in discriminating between bruxist episodes that were tonic, phasic, or mixed, and that the scorers agreed upon only 62% of the episodes. In 1998 Gallo et al , reported on the development of an algorithm that had a success rate of discriminating between different oral motor activities, chewing, laughing, speaking, grinding and clenching. The overall recognition rate was 97%, and they noted that the signal features of clenching and grinding were more easily recognized (99%) as the rectified mean values were notably higher than for the other activities. They concluded that their algorithm was able to accurately differentiate between function and parafunction. A recently published report of an EMG based bruxism recording system (Haketa et al 2003) showed that 97% of simulated bruxism tasks , and 87% of non-bruxist signals were accurately recognized by scorers, and that there was a high level of intrascorer reproducibility , and intrascorer reliability. They were also able to complete a significant number of night recordings without any difficulty (317 night recordings and 56 subjects), and concluded that their system has a high utility with reasonable accuracy and precision.

None of the previously reported studies were involved in trying to distinguish between the different types of movement that were involved in the bruxist event, but rather to say whether a bruxist event had occurred or not, it is this feature that separates this study from the others.

7 Conclusion

This study has shown that using a relatively simple computer algorithm, the smoothed and filtered EMG waveform,and discriminant analysis, it is possible to discriminate between different simulated bruxist-like movements.

Future Directions

Future development of the approach could include its participation in polysomnography, sleep laboratory analysis, and in differentiation between movements in other long- term EMG studies. The next test for this approach would be to attempt to assess its predictive power with regard to more complex movements, involving bi-directional, or mediotrusive tasks. This would best be performed in conjunction with a jaw tracking apparatus to confirm the act actually performed when a complex task is specified, as one of the problems found in this study was the inability to ensure what the subject actually did intra-orally during the prescribed task.

Another way in which to increase the power in future experiments would be to incorporate some method of bite force measurement. In a study by Nishigawa et al 2001, the use of splints with strain gauge transducers showed that nocturnal bite forces during bruxism could exceed MVC values measured during the day. Piezoelectric film has been used by Baba et al 2003, though here it was used to detect bruxism , rather than to measure the actual forces concerned. Any way of incorporating force measurements would eliminate any of the supposed or theoretical assumptions regarding the use of EMG and its quantitative relationship to force in this instance.

Being able to make a specific diagnosis with regard to sleep bruxism, assess an individuals particular bruxist acts, and to then be able to design an appliance specifically to treat their problems is the logical extension of this aspect of research. A recent review paper by Dao and Lavigne (1998) concluded that specific treatments for this type of disorder were the ultimate goal .

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