MECHANISMS OF FATIGUE

IN THE JAW-CLOSING MUSCLES OF MAN.

MERVYN FREDERICK LYONS,

BDS (Otago), MSc (Lond), FDSRCPS (Glasg)

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in the Faculty of Medicine, University of Glasgow.

Department of Prosthodontics

Glasgow Dental Hospital and School

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TABLE OF CONTENTS

CHAPTER 5. **PAGE**

FATIGUE AND ELECTROMYOGRAM CHANGES DURING SUSTAINED ISOMETRIC CONTRACTIONS IN HEALTHY VOLUNTEERS

CHAPTER 6.

MASSETER MUSCLE RELAXATION RATE IN VOLUNTEERS WITH A MYOGENOUS CRANIOMANDIBULAR DISORDER

INDEX OF FIGURES

INDEX OF TABLES

TABLES | PAGE

TABLES PAGE

INDEX OF APPENDICES

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This thesis is the original work of the author.

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SUMMARY

The jaw-closing muscles generally are more resistant to fatigue than the limb muscles. The specific process of fatigue referred to here is localized fatigue proximal to the neuromuscular junction. In view of this resistance to fatigue and the notion that muscle fatigue leads to the muscle pain experienced in craniomandibular disorders, it was considered that this process required further investigation.

The jaw-closing muscle system presents difficulties for fatigue studies because of the complex inter-relationship of the muscles. It is not possible to isolate the force output of the individual muscles and it is not practical to gain access to the nerve supply of these muscles.

The first experiment was carried out to investigate the endurance and susceptibility to fatigue of the masseter and anterior temporalis muscles of a selected group of bruxists. The state of fatigue was assessed by measuring the percentage change in EMG signal amplitude during a sustained isometric contraction and a large variability was found in this parameter. It was found that bruxists have greater endurance and a larger maximum bite force than the age-matched controls. The differences between the bruxists and the controls were not statistically significant.

It was found that the bite force transducer introduced problems into this first experiment, particularly inducing contra-lateral pain. The thickness of the transducer (7 mm) was thought to be a problem and therefore a commercial system of measuring bite force (T-Scan system) using piezoelectric foil (thickness 80 μ) was investigated. It was found that this

system was so inaccurate that it was discarded as a means of monitoring sustained biting force.

Subjective perception of fatigue was then studied in a group of normal healthy volunteers. Subjective perception was assessed by the use of visual analogue scales and compared to objective measures of fatigue. Median frequencies of the EMG power spectra and percentage change in amplitude were recorded. It was found that these objective measures were closely correlated to the subjective perception of fatigue. Spectral changes were more closely correlated to subjective perception than amplitude changes.

Finally, relaxation rate, one of the muscle processes affected by localized fatigue, was investigated in the masseter muscles of a group of patients with a myogenous craniomandibular disorder, a group of age-matched controls and an additional separate healthy group. This was measured at 10-second intervals during a sustained contraction, and again during a 3-minute recovery period; the median frequency of the power spectra was measured at the beginning and the end of the sustained contractions. It was found that the patients, compared with the other two groups, became less fatigued during the sustained contractions but recovered less quickly on completion.

ABBREVIATIONS

AC	Alternating Current
ADP	Adenosine Diphosphate
ATP	Adenosine Triphosphate
CMD	Craniomandibular Disorder
CNS	Central Nervous System
CrP	Creatine Phosphate
DC	Direct Current
EMG	Electromyography
FFT	Fast Fourier Transform
FM	Frequency Modulated
MPD	Myophosphorylase Deficiency
MVC	Maximum Voluntary Contraction
RMS	Root Mean Square
RPE	Ratings for Perceived Exertion
SDT	Sensory Decision Theory
TMJ	Temporomandibular Joint
TTL	Transistor-transistor Logic
VAS	Visual Analogue Scale

GENERAL INTRODUCTION

The relevance of the process of fatigue in the jaw-closing muscles lies in the fact that it is considered to be of significance in the aetiology of the craniomandibular disorders i.e. temporomandibular joint pain dysfunction (myofascial pain dysfunction), facial pain of muscle origin and certain types of headache (Ramfjord, 1961; Laskin, 1969; Miles, 1978; Laskin & Block, 1986; Hansson, 1988).

It has been shown that the jaw-closing muscles are more resistant to fatigue than limb muscles (van Steenberghe, de Vries & Hollander, 1978; Clark & Carter, 1985) and yet the craniomandibular disorders are common problems in clinical practice. It is clear that a greater understanding of the mechanisms of this process is required to help in understanding the aetiology of these various disorders. The jaw-closing muscles present special difficulties for the investigation of fatigue because it is not possible to measure their individual force output. There are four muscles (the superior head of the lateral pterygoid muscle has been shown by Gibbs *et al* [1984] to be active on jaw-closing) on each side of the mandible which moves in a complex fashion.

Muscle fatigue is a process which takes place over a period of time rather than being an instantaneous event (Basmajian & De Luca, 1985). Localized muscle fatigue is characterized by changes in physiological processes occurring in a muscle or group of synergist muscles performing the contraction. It is seen as either a reduction in peak force output or as a necessity to increase applied effort in order to sustain a constant sub-maximal force. The processes occurring are either a transmission block at the neuromuscular junction, in which case the EMG level and force output both decrease, or failures distal to the neuromuscular junction, in which case only the force output will be reduced. There is also a decrease of the conduction velocity of the action potential along the muscle fibres (Lindstrom, Kadefors & Petersen, 1977).

It has been shown in many muscles that as fatigue progresses the rectified-integrated EMG signal increases in amplitude in order to maintain a given force level in a sustained isometric contraction (Edwards & Lippold, 1956). This increase is partly due to recruitment of additional motor units. However, some workers have found this increase to occur to a lesser extent in the masseter muscle, even though this muscle was apparently in a state of fatigue (Clark & Carter, 1985). The reasons for this require further investigation.

The shift of the frequency spectrum of the surface-derived EMG signal to lower frequencies as fatigue progresses has been shown to be a reliable and sensitive indicator of fatigue in limb muscles (Lindstrom *et al*, 1970; Mills, 1982). There are still varying opinions on why the shift occurs, but it is widely agreed that the shift does occur (Mills & Edwards, 1984). Power spectrum analysis has been applied to the masseter muscle, and would appear to be a useful technique in the investigation of fatigue (Palla & Ash, 1981; Naeije & Zorn, 1981; Lindstrom & Hellsing, 1983). This is particularly so in view of the small increase in rectified-integrated EMG to maintain a constant bite force, as mentioned earlier.

The rate of relaxation from an isometric contraction has long been known to decrease as fatigue occurs (Jones, 1981). This slowing of relaxation is one of the characteristic changes which may be seen, although the reasons for this slowing are still not completely understood.

A further complicating factor of particular relevance to the jaw-closing muscles is the contribution of rotation of synergist muscle activity to fatigue resistance (Hellsing & Lindstrom, 1983). This becomes of particular importance in the interpretation of the results of studies of fatigue and bite force (collective jaw-closing muscle force).

The positioning of any bite force transducer within the dental arch is also worthy of consideration. As the jaw-closing muscles on the left and right sides are not totally independent in their action, the effects of any asymmetry of force application require investigation. There is also undoubtedly some effect on force limitation from the periodontal mechanoreceptors (Hannam & Matthews, 1969; Bessette, Mohl & Bishop, 1974; Kloprogge, 1975; Cash & Linden, 1982), and this also requires consideration.

CHAPTER 1.

REVIEW OF LITERATURE

1.1 SKELETAL MUSCLE FATIGUE

1.1.1 Definitions

The concept of muscle fatigue invokes a certain degree of confusion, as different descriptions exist and the term may hold different connotations in different branches of science (Edwards, 1984). It was pointed out by Basmajian & De Luca (1985) that fatigue is a time-dependent process and so does not occur at a particular point in time or during a specific time interval. This implies that changes are taking place within the muscle before an observable reduction in force output occurs.

Fatigue has been defined as *"the inability of a skeletal muscle to produce, on either natural or artificial stimulation, a pre-existing level of tension subsequent to dynamic or static contractile activity of the muscle"* (Christensen, 1981). Fatigue has also been defined as *"a failure to maintain the required or expected force"* (Edwards, 1981). However, this latter definition does not acknowledge the fact that fatigue changes have already taken place before this failure occurs. A more comprehensive definition is *"any reduction in the force-generating capacity of the entire neuromuscular system, regardless of the force expected"* (Bigland-Ritchie & Woods, 1984). Vollestad *et al* (1988) make a distinction between fatigue and exhaustion, defining exhaustion as *"an inability to sustain contractions / exercise at the target force / intensity"*.

1.1.2 Central and Peripheral Fatigue

The term localized muscular fatigue was explained by Chaffin (1973) and defined as *"an inability to maintain a desired force output, augmented muscular tremor and localized pain"*. This term differentiates between fatigue which occurs peripherally (in the muscle tissue or neuromuscular junction) from that which may occur centrally (in the brain and spinal cord). Localized muscle fatigue is characterized by changes in physiological processes occurring in a muscle or group of synergist muscles performing the contraction. It is seen as either a reduction in peak force output or as a necessity to increase applied effort in order to sustain a constant sub-maximal force. The sites at which fatigue may occur are the central nervous system (CNS), the motor end-plate, the cell membrane, the transverse tubular system and in the energy supply to the muscle. The energy source for brief contractions is muscle adenosine triphosphate (ATP) and creatine phosphate (CrP), while for longer contractions (more than five seconds) local glycogen stores are utilized with a resulting intra-muscular accumulation of lactic acid (Edwards, 1984).

Current evidence suggests that in prolonged intermittent submaximal contractions muscle activation by the CNS is fully maintained, i.e. central fatigue does not occur, and that force output is not limited by failure of neuromuscular transmission (Bigland-Ritchie *et al*, 1978; Bigland-Ritchie, Furbush & Woods, 1986a; Bigland-Ritchie, Furbush & Woods, 1986b). The presence of central fatigue can be tested by comparing the force of a maximal voluntary contraction with that obtained by supramaximal tetanic stimulation of the motor nerve. This can be painful, however, and muscle tendon damage can result. In order to avoid these problems the technique of twitch interpolation (Denny-Brown, 1928; Merton, 1954) is commonly used (Belanger & McComas, 1981; Bigland-Ritchie *et al*, 1978, 1986a, 1986b). This technique involves the application of single maximal stimuli to the appropriate motor nerve (transcutaneously) during a voluntary sub-maximal contraction. A detectable twitch response may be seen from any motor units which have not been recruited or from any units which are discharging at less than the tetanic frequencies for maximum force output. There is an approximately linear negative relationship between the strength of the voluntary contraction and the size of the superimposed twitch response (Figure 1). Thus, if the volunteer has claimed to perform a maximum voluntary contraction and a superimposed twitch can be seen, then either it was not a true maximum effort or central fatigue has occurred.

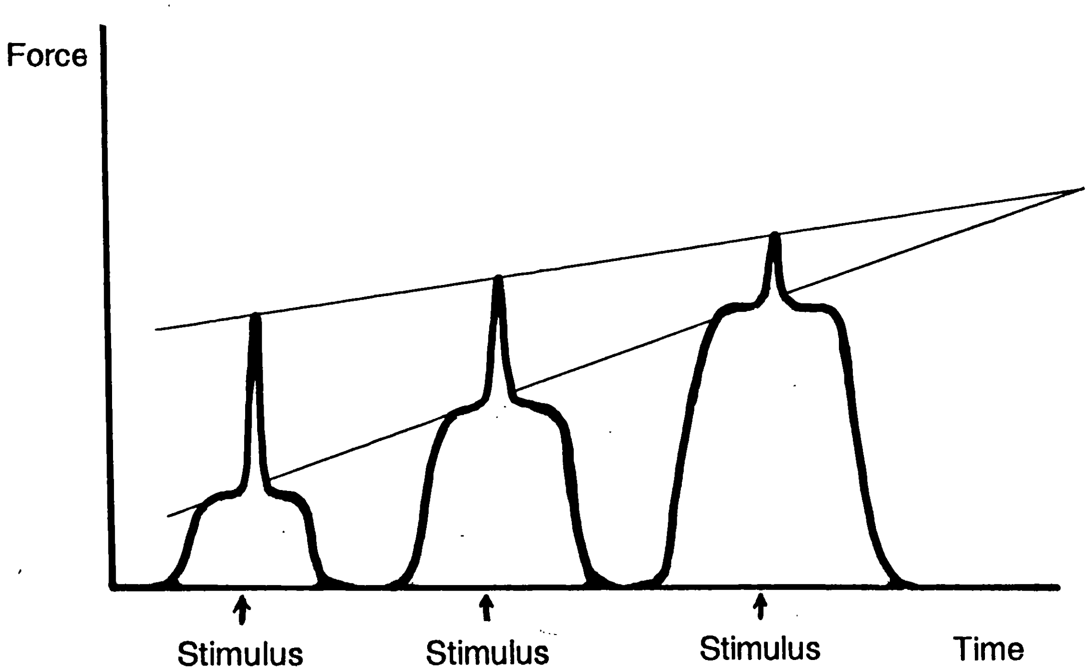


Figure 1. Diagramatic representation of the twitch interpolation technique.

Vollestad *et al* (1988) added evidence to the conclusion that fatigue occurs due to impairment of the excitation/ contraction process and not to impairment of central motor drive. They also found that the subjects inability to continue contractions (which they define as exhaustion) was strongly related to creatine phosphate and glycogen depletion but unrelated to muscle lactate levels. These conclusions were reached after a study involving various types of exercise and repeated muscle biopsies of the quadriceps muscle in human subjects. Mills & Edwards (1984) also pointed out that fatigue was unrelated to lactacidosis in patients suffering from myophosphorylase deficiency (McArdle's disease), as these patients do not produce lactic acid and yet suffer excessive fatigue. These patients were all confirmed as being myophosphorylase deficient after histochemical examination of muscle biopsies.

1.1.3 The Gamma Loop System

A comprehensive discussion of this system was provided by Hagbarth *et al* (1986). This is a functionally and anatomically distinct system consisting of intrafusal fibres connected to muscle spindle organs. This system allows the CNS to achieve varying degrees of tension and movement sensitivity. The sensitivity of the spindle organs to the muscle's tension and length states can be varied by the contraction of the intrafusal fibres which are under the control of the CNS by the gamma efferent fibres. Chaffin (1973) proposed a theory to explain the neuromuscular changes associated with fatigue, saying that muscle spindles are stretched as the fatigued muscle stretches in an attempt to produce the required force. This increased stretch results in increased stimulation of the spindles, increased facilitatory feedback to the CNS, and increased extra-fusal motor-unit recruitment at the period of every 100 msec. This periodic recruitment produces both low frequency shift in the power spectrum and increased tremor. Chaffin further claimed that the increased facilitation also accounts for the tendency to perceive light forces as being heavier.

An alternative explanation, and one which is more generally accepted, is that this sensation of a load becoming heavier is due to the increased efferent barrage of voluntarily generated signals which are required in order to maintain a contraction with progressively fatiguing muscles (McCloskey, 1985).

1.1.4 High and Low Frequency Fatigue

Peripheral fatigue may be usefully divided into high frequency and low frequency categories, i.e. stimulation frequencies around 80 Hz lead to high frequency fatigue and around 20 Hz to low frequency fatigue (Edwards *et al*, 1977). Thus low frequency fatigue is a selective loss of force at low stimulation frequencies, and is thought to be a result of impaired excitation-contraction coupling. It is generally long lasting, and is also more pronounced following eccentric contractions i.e. those made when the muscle is stretched during a contraction (Newham *et al*, 1983). The activities of everyday life are mostly the result of submaximal contractions induced by low frequency stimulation i.e. 10 to 30Hz (Grimby & Hannerz, 1977).

High frequency fatigue is the selective loss of force at high stimulation frequencies, and is considered to be due to impaired transmission at the neuromuscular junction (Stephens & Taylor, 1972) and/or impaired propagation of muscle action potential (Jones, Bigland-Ritchie & Edwards, 1979; Bigland-Ritchie, Jones & Woods, 1979). High frequency fatigue can occur as a result of cooling of muscle and of experimentally produced ischaemic fatigue (Edwards, 1984). The effect of high frequency fatigue is that it reduces the maximum force output of the muscle, whether by voluntary effort or by electrical stimulation.

One of the practical problems that occur in the investigation of fatigue is knowing whether or not the subject is really exerting a maximal voluntary contraction. One answer to this problem in the jaw-closing muscles is to make sure that there is a good level of reproducibility between the contractions, which would not occur if they were sub-maximal (van Steenberghe, de Vries & Hollander, 1978). The other approach is to apply the technique of twitch interpolation, which has already been discussed.

1.2 RELAXATION RATE

A slowing of relaxation is one of three predominant changes seen in localised muscle fatigue, the other two being the response to high frequency stimulation (high frequency fatigue), and changes in twitch amplitude and shape (Jones, 1981). The rate of relaxation from an isometric contraction has long been known to decrease with fatigue. The half-time of the latter part of the time course of relaxation, the exponential phase, may increase by a factor of two or three. In addition, there is no recovery of the relaxation rate under anaerobic conditions (Edwards et al, 1972). The reasons for these phenomena are still not completely understood.

There are two main possibilities explaining the time course of relaxation (Cady *et al*, 1989):

- The reduced rate of re-accumulation of calcium by the sarcoplasmic reticulum.

- The reduced rate of dissociation of cross-bridges after the activating calcium has been removed (Edwards, Hill & Jones, 1975).

The dissociation of myosin cross-bridges is required for relaxation from an isometric contraction, and this dissociation requires the binding of ATP to the myosin molecule. It has been shown that the slower the relaxation, the slower the ATP turnover (Edwards, Hill & Jones, 1975). However, Edwards *et al* (1975) point out that it seems unlikely that a reduced amount of ATP as a substrate for actomyosin ATPase is the cause of slower relaxation, but rather that it has caused a change in regulatory subunits. Alternatively, this reduced concentration of ATP may possibly result in a reduced rate of calcium pumping by the sarcoplasmic reticulum (Dawson, Gadian & Wilkie, 1980; Jones, 1981).

There has been recent evidence to support the contention that slowing of relaxation is associated with reduced calcium uptake by the sarcoplasmic reticulum (Gollnick *et al*, 1991). Experiments were conducted on the quadriceps femoris muscle, and repeated muscle biopsies were taken. It was found that the half-time of relaxation was elongated on exhaustion, with full recovery after 30 minutes. At exhaustion the calcium uptake by the sarcoplasmic reticulum was reduced to 58% of the pre-exercise value. Gollnick *et al* (1991) suggest that some change to the sarcoplasmic reticulum occurs on exercise which depresses the Ca^+-activated ATPase and reduces Ca^+ uptake.

The concept of a reduced turnover of cross-bridges is supported by studies involving muscle heat production, where heat production falls as relaxation slows. It has been calculated that the reduced heat production might correspond to an approximately three-fold reduction in ATP turnover. These calculations are based on the heat produced from the splitting of phosphoryl creatine and from glycolysis (Edwards & Hill, 1975; Edwards, Hill & Jones, 1975b). With a reduction in relaxation rate there is a reduction in ATP and creatine phosphate, and in addition there is an accumulation of lactic acid and H^+. It has been shown in patients with myophosphorylase deficiency (MPD) that there is a slowing of relaxation with fatigue, even though these patients do not produce lactic acid, and so accumulation of lactic acid is unlikely to be a cause.

The classic reaction CrP + ADP $\rightarrow$ ATP + Cr is now considered to be important as a mechanism for eliminating ADP rather than producing ATP. ADP has a powerful negative effect on muscle force production, and muscles are rarely deficient in ATP.

A recent study investigated the relationship between slowing of relaxation and changes in intracellular pH and phosphorus metabolites in normal subjects and in those with MPD (Cady *et al*, 1989). Their experiments were performed on the first dorsal interosseous muscle under ischaemic conditions, and metabolite levels were measured using nuclear magnetic resonance spectroscopy. It was concluded that there are two processes involved, one due to H^+ accumulation (i.e. pH-dependent) and the other due to some other cause (i.e. pH-independent). The H^+ accumulation may inhibit Ca^+ uptake by the sarcoplasmic reticulum. The pH-independent cause might be accumulation of ADP, modification of Ca^+ pumping, or modification of the activity of actomyosin cross-bridges (Cady *et al*,1989).

1.3 HISTORY OF ELECTROMYOGRAPHY

An account of the history of electromyography was presented by Basmajian & De Luca (1985), where they state that the relationship between muscle contraction and electricity was first observed by Galvani in 1791. They continued by pointing out that the first detection of signals elicited voluntarily from muscle was reported in 1849 by Du Bois-Reymond. Methods of measuring electrical signals from human muscles were greatly simplified by the introduction of the metal surface electrode in 1907 by Piper. A significant advance for clinical electromyography was made by the introduction of the needle electrode in 1929 by Adrian & Bronk. The development of silver/silver chloride and fine-wire electrodes in the late 1950's resulted in an increase in the use of EMG for kinesiological studies.

The first use of EMG in dental research may be attributed to the orthodontist Moyers (1949). One of the first to use EMG for the investigation of patients with craniomandibular disorders was Jarabak in 1956. Ramfjord (1961a,b), Moller (1966), and Ahlgren (1966) were prominent in the use of EMG for dental research. Yemm (1969a,b,c; 1971) was one of the first to investigate the effects of emotional stress on masseter muscle function, and later established a technique for recording single motor unit potentials from the first dorsal interosseous muscle (Milner-Brown, Stein & Yemm, 1973a). This group (Milner-Brown, Stein & Yemm) studied contractile properties (1973a), recruitment (1973b), and changes in firing rate (1973c) of single motor units from the first dorsal interosseous muscle, and Yemm also investigated the orderly recruitment of motor units of the masseter and temporal muscles (Yemm, 1977).

1.4 ELECTROMYOGRAPHY AND FATIGUE

1.4.1 EMG to Force Relationship

It has been shown for many muscles that as fatigue occurs in a sustained sub-maximal isometric contraction, the rectified-integrated EMG signal increases in amplitude in order to maintain the same force output (Edwards & Lippold, 1956; Kadefors *et al*, 1968; Vredenbregt & Rau, 1973; Stulen & De Luca, 1978). This increase in amplitude is more pronounced near the end of a sustained contraction, and is a result of either recruitment (Edwards & Lippold, 1956), rate modulation (Lippold, Redfearn & Vuco, 1960) or synchronization (Milner-Brown, Stein & Lee, 1975).

The relationship between the amplitude of the EMG signal to the force output of the muscle in a non-fatigued state has been described by some to be linear (Stephens & Taylor, 1972; Milner-Brown & Stein, 1975), while others have described it as non-linear (Komi & Buskirk, 1970; Vrendenbregt & Rau, 1973). Haraldson *et al* (1985) found the relationship to be linear for the anterior temporalis muscle but not for the masseter muscle. As the EMG amplitude to muscle force relationship in a non-fatigued state has been considered by some to be linear, the EMG amplitude has been used as a direct measure of force. However the amplitude observed at a given force increases as fatigue occurs, and as it is difficult to know when one is observing a fatigue effect or simply an increase in force output it can be seen that problems exist with this approach.

Lawrence & De Luca (1983) found that the relationship varied between different muscles, although it generally tended to be close to linear and was independent of the state of training of the muscle and its force output. They suggested that some of the factors which may be responsible for these differences between muscles are:

- Motor unit recruitment and firing rate properties.

- The distribution and quantity of slow-twitch and fast-twitch fibres within the muscle.

- Cross-talk from adjacent muscles.

- Agonist-antagonist muscle interaction.

Increasing force output by means of an increase in firing rate (rate modulation) provides a linear relationship to the EMG amplitude, whereas recruitment does not (De Luca & Van Dyke, 1975). The balance of these two mechanisms depends on the muscle concerned. It is also thought that at low force levels (30-50% MVC) recruitment is dominant in small muscles (e.g. first dorsal interosseous muscle), and that rate modulation becomes more important with increasing force (Freund, 1983). However, as force increases it becomes more difficult to assess the relative roles of these two mechanisms, particularly because action potentials of different motor units begin to overlap as force increases (Weytjens & van Steenberghe, 1984). Weytjens & van Steenberghe (1984) also confirmed that recruitment is the dominant factor up to about 30% MVC in the masseter muscle, with rate modulation becoming important at higher force levels.

Lawrence & De Luca (1983) state that the amplitude of the action potential of a single fibre is proportional to its diameter. As fast twitch fibres are generally larger than slow twitch fibres, they will have higher amplitude action potentials and a higher amplitude root-mean-square (RMS) EMG signal. However, the amplitude contribution depends on the distance between the motor unit and the recording electrode and so fibre distribution becomes relevant. One must also take into consideration the "size principle" which says that larger motor units are preferentially recruited at higher force levels (Henneman & Olson, 1965).

The agonist-antagonist relationship in isometric contractions is of particular importance where joints must be stabilized (Lawrence & De Luca, 1983). It is possible that this relationship has some relevance to the temporomandibular joints, and may contribute to the pain often described in the lateral pterygoid muscle.

1.4.2 Rate of Change of Force

An additional factor which complicates the use of the EMG/force relationship when the force is changing is the rate of change. A delay between peak EMG and peak force of the order of 70 msec has been shown in the temporalis muscle (Hannam, Inkster & Scott, 1975), but it has been shown that this is not a simple lag and is related to rate of change (Kawazoe *et al*, 1981; Devlin & Wastell, 1985). These studies have shown that the relationship is not a simple linear relationship, and that peak EMG tends to occur when the rate of change of force is greatest.

1.4.3 Changes to the Power Spectrum

It is clear that as fatigue occurs there is a shift of the surface-derived EMG power spectrum towards lower frequencies i.e. an increase in the power of lower frequencies and a decrease in higher frequencies (Kadefors, Kaiser & Petersen, 1968; Kwatney, Thomas & Kwatney, 1970; Lindstrom, Kadefors & Petersen, 1977; Bigland-Ritchie, Donovan & Roussos, 1981; Palla & Ash, 1981; Lindstrom & Hellsing, 1983; Naeije & Zorn, 1981). This shift is most noticeable near the beginning of a sustained contraction.

Frequency decrease and amplitude increase have a common origin, as the local accumulation of metabolites results in a decrease in conduction velocity and hence a longer time duration of the motor unit waveforms (Basmajian & de Luca, 1985).

The use of the increase in amplitude as a measure of fatigue does not have the sensitivity of measuring the frequency shift, even though the amplitude increase is a measure of the frequency shift. The reason for this is that there is a decrease in firing rates in a constant-force contraction during fatigue (Bigland-Ritchie *et al*, 1982) and this will decrease the amplitude of the signal, thus offsetting the increase induced by the frequency shift. The low frequency part of the spectrum increases and the high frequency component decreases with the resultant power increase reflecting this change with reduced sensitivity.

The explanations that have been offered to account for the amplitude increase and the frequency decrease occurring during a sustained isometric contraction are:

- Recruitment (Edwards & Lippold, 1956; Vredenbregt & Rau, 1973). This is unlikely as an increase in the power of lower frequencies has been observed at force levels where recruitment does not occur.

- Synchronization (Chaffin, 1973; Palla & Ash, 1981; Bigland-Ritchie, Donovan & Roussos, 1981; Naeije & Zorn, 1982; Weytjens & van Steenberghe, 1984b). One of the problems with this idea is that synchronization increases as the duration of the contraction increases, whereas the frequency shift is greatest during the early part of a contraction.

- Conduction velocity decrease (Mills & Edwards, 1983; Lindstrom & Hellsing, 1983; Lindstrom, Kadefors & Petersen, 1977).

The two explanations most widely accepted are conduction (propagation) velocity decrease and synchronization. These explanations have been assessed by the use of mathematical models, and the two corresponding models are those of Lindstrom, Magnusson & Petersen (1970) and Lago & Jones (1977). Lindstrom *et al* (1977) believe that slowing of conduction velocity is the only explanation required, and other mechanisms such as synchronization are unnecessary in order to explain the phenomenon.

The conduction velocity of muscle fibres is related to fibre diameter and also to intramuscular pH. The intra-muscular pH depends upon the formation of lactic acid, pyruvic acid, and also on the rate of removal of hydrogen ions. Conduction velocity is directly related to membrane excitability, and it has been shown that membrane excitability decreases as the intracellular pH decreases (Orchardson, 1978). However, Mills & Edwards (1985) showed that hydrogen ion accumulation is not responsible for the power spectral shift seen in MPD subjects because acidosis does not occur (see Section 1.1.2). They postulated that accumulation of extracellular potassium ions may explain the spectral shift seen in fatigue of both normal muscle and the muscle of MPD patients.

It is clear that there is an increase in the power of the low frequency content of the power spectrum during a sustained isometric contraction, but the reasons for this increase are still the subject of discussion.

1.4.4 The EMG Fatigue Index

A method of expressing fatigue in quantitative terms was described by Lindstrom, Kadefors & Petersen (1977), whereby linear regression analysis is applied to the logarithmic form of the mean frequency of successive power spectra, to give a probability of fatigue. The fatigue index is the regression coefficient. The value of this index is zero for muscles unaffected by fatigue, and rises towards unity as fatigue occurs. A high value indicates progressive fatigue, not merely a state of fatigue.

1.4.5 Spectral Parameters

A single parameter is usually used to identify changes in the power density spectrum. The most useful of these are the median frequency (that at which the spectrum is divided into two regions of equal power) and the mean frequency (average frequency), both giving unbiased estimates of the spectrum (Stulen & de Luca, 1981). The mode frequency (peak frequency) has also been used to describe a spectrum, but provides a very poor estimate because the peak value is not always sharply defined. The median frequency has been shown to be a theoretically more reliable estimator than other convenient parameters, as it is less susceptible to noise (Stulen & De Luca, 1981).

The mean frequency has been used by Lindstrom, Kadefors & Petersen (1977), Naeije & Zorn (1981), Barker, Wastell & Duxbury (1989). The median frequency has been used by Palla & Ash (1981), Stulen & De Luca (1982) and others.

The time taken for these parameters to return to normal after a sustained contraction has been reported to be four to five minutes (Mills, 1982).

1.5. ELECTRODES IN ELECTROMYOGRAPHY

1.5.1 Electrode Configuration

Electrodes are used to detect the current generated by muscle activity, i.e. ionic movement within the muscle. Electrodes may be used singly with a remotely placed reference electrode (monopolar configuration), or in pairs (bipolar configuration). The bipolar configuration has the advantage of recording less interference than monopolar, and may be used in conjunction with a differential amplifier. The higher the common mode rejection ratio of the amplifier, the better it will cancel out the effects of external interferences such as mains supply.

1.5.2 Subdermal Electrodes

Electrodes may be either surface (disc or subdermal hook) or in-dwelling (needle or fine wire). The subdermal hook electrode was first described by Ahlgren in 1967. It consists of 0.18 mm platinum wire bent over 5 mm from the end and bevelled. The performance of these was compared with the performance of surface disc electrodes by Ahlgren, Lewis & Yemm (1980). In a carefully planned experiment they placed the electrodes in an opposing diagonal arrangement, with a needle electrode in the middle, and found that averaged signals from the hook and the disc electrodes corresponded closely in both amplitude and duration. Both types of electrodes were able to sample units with small surface potentials equally effectively. They did not compare frequency response between the two types, however. They suggested that which of the two to use should really be a matter of convenience as neither had superiority in performance.

1.5.3 Disc Electrodes

The most widely used surface disc electrodes are of silver-silver chloride construction in order to provide a reversible chloride exchange interface with the metal of the electrode. This is to eliminate the AC component of the polarization potential, the DC component being dealt with by the use of differential amplifiers.

1.5.4 Motion Artifacts

A problem exists with the production of motion artifacts as a result of movement of the electrode wires which connect to the pre-amplifier. These artifacts can be substantial and therefore the wires should be kept as short as possible and the subject should keep still. An attempt to overcome this problem has been made (Fujisawa *et al*, 1990) with the use of built-in buffer amplifiers. The buffer amplifier has zero gain and acts by lowering the line impedance between the electrode and the amplifier and hence lowering the capacitance between the wire and earth. The description of the electronics was clear, but the method of testing the performance of these electrodes was not well presented and appeared to be inadequate. They simply compared the frequency response of these electrodes to that of a similar, but un-buffered, surface electrode pair as described by Yamaga, Yamada & Ishioka in 1982. An obvious concern is that the skin impedance of these self-adhesive electrode pairs could be unacceptably high. However, as pointed out by the authors, these self-adhesive buffered electrode pairs might be the answer for application by patients in biofeedback and sleep studies.

1.5.5 Ground Electrodes

It is necessary to ground, or earth, subjects when recording electromyograms in order to reduce unwanted signals or noise. In order to achieve this, it is necessary to reduce the skin-ground impedance to a lower level than the skin-electrode impedances. To reduce skin impedance the skin should be thoroughly prepared and an electrode with a larger active area than the other electrodes should be used. It is also desirable to locate the ground electrode as near to the active electrodes as possible, but not overlying muscle.

Various ground electrodes used include standard Ag/AgCl discs, ear-lobe clips, gauze wrist straps, and a lip-clip (Turker, Miles, & Hoanh, 1988).

1.6 THE REPRODUCIBILITY OF ELECTROMYOGRAPHY

1.6.1 Historical and General Factors

The problems of reproducibility and reliability of EMG were of particular concern before the wide availability of high-gain amplifiers with a high input impedance. In addition, experimental methods were not always standardised and it was difficult to make meaningful comparisons between different experiments.

An important paper was published in 1966 which set out some significant sources of error in electrophysiological research (Grossman & Weiner, 1966). Areas of concern, with recommendations, were:

- Frequency response characteristics: use amplifiers with a flat frequency response in the frequency range of interest, with high input impedance to prevent loading loss. The frequency range of interest in surface EMG of the jaw-closing muscles is 10-1000 Hz.

• Direct recording: beware of limitations in the amplitude and frequency response of ink-writers.

• Voltage integration: if a short time constant is used, only the average amplitude of the input signal voltage is displayed, and not an accurate instantaneous value at any particular point in time.

• Frequency spectrum of the muscle action potential: it is important that the equipment and the methods of analysis used take into consideration the whole of the frequency spectrum of the signal.

• Force of contraction and action potential: the relationship between EMG activity and muscle force output depends upon whether the contraction is isometric or isotonic, and also on the state of fatigue.

The problems of standardisation and reliability were addressed in some detail in a report which set out standard terms and units for the reporting of EMG research (*ad hoc* Committee of the International Society of Electro-physiological Kinesiology, 1980). Although this report was published nearly twelve years ago, it contains a wealth of information on the recording and processing of the myoelectric signal and still provides a baseline for terms and standards in EMG research.

1.6.2 Standardization of Recordings from the Masseter

Early EMG studies generally have been criticised for lack of quantification of the EMG response, lack of control groups, and poor descriptions of the populations under study (Dahlstrom, 1989).

The standardisation of recordings from the masseter muscle has received much attention. It has been shown that the relocation of electrodes on the face results in a large variability in the signal, and it is the relocation rather than the removal and replacement which causes the variability (Frame, Rothwell & Duxbury, 1973). A further study showed that repeatable results could be obtained if elaborate efforts were made to locate the electrodes accurately between sessions (Nouri *et al*, 1976).

In a study which examined the effects of applying electrodes to different areas of the masseter muscle at the same session and on different sessions, signal amplitude was the most variable parameter with onset and duration being slightly less variable (Garnick, 1975). It was pointed out that it is important to use control subjects to ensure validity of results.

One reason that reproducibility is difficult with the jaw-closing muscles is that their small size makes accurate relocation of electrodes unlikely unless elaborate procedures are employed. If it is important to detect small differences in signal amplitude, which is the case when dealing with muscles which are not necessarily suffering from a discrete myopathy, then even these procedures may not be sufficiently reliable.

A large review of the literature on the use of surface electromyography in dentistry was reported by Lund & Widmer (1989). Their most widespread criticism was that many of these studies failed to include a control group, and when a control group was used it was not matched for variables such as sex, age, and history of bruxism.

1.6.3 Normalisation Procedures

A much simpler and more reliable method of obtaining reproducible between-session results is to normalize EMG activity to a standard load (Hosman & Naeije, 1979). The static load used is unimportant as long as it remains the same for all the experiments in a series. The maximal clenching force remains remarkably constant between sessions (van Steenberghe & de Vries, 1978; Hosman & Naeije, 1979), and this is also the most convenient force to use as it is not necessary to use a bite force meter. It is more constant if a bite force meter is not used, in fact, because the limiting factor will almost certainly not be the periodontal mechanoreceptors. Hosman & Naeije (1979) showed that the relationship between normalized integrated EMG and clenching force was linear up to 80% of maximum force. At higher force levels the EMG increases at a greater rate than the force output.

1.6.4 Inter-electrode Distance

Variations in inter-electrode distance between 1-2 cm has little effect on the EMG signal amplitude, but distances above 2 cm result in increased amplitude (Pancherz & Winnberg, 1981).

It has been pointed out by Dahan & Boitte (1986) that variations between individuals are better estimated when recordings are taken from only one side. If mean values for left and right side are used then this will increase the experimental error. For this reason bilateral recordings should be taken only when muscle asymmetry is to be studied.

1.6.5 Reliability of Estimators of Power Spectrum

An assessment of the reliability of the mean power frequency of the power spectrum of the masseter and anterior temporalis muscles led to the conclusion that there is significant intra-subject variability in this parameter between sessions (Barker, Wastell & Duxbury, 1989). This is to be expected because they were not, in fact, testing the reliability of the mean power frequency as a representative parameter of the spectrum, but the variation in this parameter (and hence the spectrum itself) between sessions. One would expect this variation to occur in view of the demonstrated variation in signal power and likely variation in skin impedance and tissue density when electrodes are replaced at a different session.

1.6.6 Tonic Resting Activity

There is considerable interest in measuring tonic, resting activity of the jaw-closing muscles, particularly in the investigation of bruxism and the effects of treatment on this condition. It has recently been claimed that between-session reliability is good for the masseter muscle with the use of simple electrode relocation procedures (Burdette & Gale, 1990), but with correlation coefficients (r values) between 0.5645 and 0.6503 it is difficult to see how they reached that conclusion. Even for the measurement of tonic activity it would be preferable to use normalized amplitude values for between-session comparisons.

1.7. MUSCLE FIBRE COMPOSITION

The jaw-closing muscles are required to perform regular and repetitive chewing movements, occasional heavy biting, and fine positioning of the mandible. Consequently these muscles have a varying fibre arrangement in order to facilitate the various activities. The masseter muscle has a multipennate architecture, as does the medial pterygoid, and the temporalis has a fan-shaped arrangement. It has been shown that fibres are differentially recruited to suit the jaw movement required, and that to enable this precise recruitment the fibres belonging to individual motor units are restricted to small territories (Stalberg & Eriksson, 1987; Tonndorf, Sasaki & Hannam, 1989). It is possible that each compartment has a different optimal length, the effect being to produce several local maxima.

Muscle fibres may be classified by histological methods according to oxidative capacity, ATP-ase and glycogen content. They may also be classified into functional categories of slow or fast twitch, fatigue resistant or fatigue susceptible (Denny-Brown, 1929; Burke, 1967; Burke, *et al*, 1973). A combination of these classifications has been presented (Van Boxtel *et al*, 1983):

Type 1: Slow-twitch, oxidative. These fibres have a greater endurance than other types, i.e. low fatigability.

Type 11a: Fast-twitch, oxidative-glycolytic. Intermediate fatigability.

Type 11b: Fast-twitch, glycolytic. High fatigability.

The jaw-closing muscles have a heterogeneous fibre composition, probably reflecting their complicated activity pattern (Eriksson & Thornell, 1983). This was a thorough histochemical and morphological study of masseter, medial pterygoid and temporal muscle fibre characteristics in young male cadavers. It was concluded that the variability in fibre-type composition is probably a result of genetic influences and various levels of utilisation. This may suggest varying abilities to adapt to hyperactivity, to resist fatigue and to resist the development of cranio-mandibular dysfunction. Marked intra-muscular variability occurred, particularly in the deep fibres of the masseter. They found the Type 11 fibres to be much smaller in diameter than Type 1 fibres, and that Type 11A fibres were rare. They did see a large proportion of Type 11A fibres in one individual, however, suggesting a high level of parafunctional activity (these fibres are fast-twitch yet fatigue-resistant, and Salmons & Henriksson [1981] have reported that endurance training appears to increase their number). This situation contrasts with that in the limb muscles where the different fibre types are more evenly distributed throughout the muscle and have almost an equal proportion of type 1, 11A and 11B fibres (Miller, 1991).

Eriksson & Thornell (1983) found that although there was considerable heterogeneity in muscle fibre composition, Type 1 fibres occupied more than 70% of the muscle fibre cross-sectional area in most parts of the three muscles studied. This supports the finding that the jaw muscles have a higher resistance to fatigue than the limb muscles (Steenberghe, de Vries & Hollander, 1978; Clark & Carter, 1985). This also supports the work of Goldberg & Derfler (1977) which showed that the majority of the motor units in the masseter muscle are recruited at low forces. The remaining muscle of mastication, the lateral pterygoid, has a more homogeneous structure and also has a higher proportion of Type 1 fibres, these occupying more than 80% of the total cross-sectional area of the muscle (Ericksson *et al*, 1981). There are no type 11A fibres present in either head of the lateral pterygoid muscle.

The superficial part of the temporalis muscle was comprised of 50% type 11B fibres, which indicates an ability to develop high forces and to contract rapidly. A strong positive correlation has been shown between type 11 fibre size and bite force (Ringvist, 1974). This greater proportion of Type llB fibres would explain the difference that exists between the masseter and temporalis muscle power spectra, with the masseter having a median frequency lower than that of the temporalis muscle (van Boxtel *et al*, 1983; Christensen & Donegan, 1990). The deep part of the temporalis muscle contained predominantly Type 1 fibres, which would make it suited to postural activity. Although the jaw-closing muscles support the mandible in the so-called postural position, they cannot be considered as true postural muscles as they are not necessarily active with upright posture (Klineberg, 1991).

In a study of length-related changes in the masseter muscle, Miles, Nordstrom & Turker (1986) found that the recruitment force and motor unit waveform changed significantly with muscle length. They pointed out that isometric force threshold has been used to categorise motor units in human studies, but that this may not be reliable in view of the dependence of this parameter on muscle length. A sharp rise was found in threshold forces beyond the mid-open position.

1.8 MEASUREMENT OF PAIN

1.8.1 Rating Scales

The problem of the clinical measurement of pain was well described by Bond (1984) when he said *"The fact that pain is a subjective phenomenon, and private to each of us, presents difficulties for those wishing to measure it, for how is it possible to estimate the extent of another's mental experiences?"*.

The most widely used measure in clinical pain research is one of the forms of rating scale (Reading, 1984). These include the verbal rating scale (VRS) and the visual analogue scale (VAS). The VAS has been discussed in some detail by Huskisson (1983) and he states that it is a simple and yet sensitive scale which is very widely used. It consists of a line, usually 10 cm in length, each end of which represents the limit of the pain experience i.e. one end is defined as "no pain" and the other as "extreme pain". The patient is then asked to mark the point along the line which corresponds to the severity of his pain. Problems with the VAS include failure of the subject to understand the concept, some variation in reproducibility along the length of the line and doubts regarding the relationship of the measurement to the true pain experience (Huskisson, 1983).

1.8.2 Sensory Decision Theory

Sensory decision theory (SDT), or signal detection theory, is a method of simultaneously measuring the sensory and the psychological aspects of pain (Christensen, 1988). A review of the technique has been presented by

Clark (1974). Sensory decision theory is concerned with the subject's ability to discriminate a stimulus above background "noise", i.e. it measures the accuracy of judgment of stimulus intensity and the error rate. It separates the purely sensory component from attitudinal or judgmental variables and so has become widely used. Hit rate (HR) is the rate of correct positive responses during many trials, and the rate of wrong positive guesses over many trials is the false affirmative rate (FAR). The HR and FAR are the important parameters to be measured.

Unfortunately there are a number of problems with SDT, one being that it requires a fairly large number of repetitive stimuli for good results (Wolff, 1984). The design of the experiment must be such that an adequate HR and FAR are generated for correct measurement. Factors such as fatigue and boredom are significant in reducing the validity of the results. The pain problem must be appropriate for the use of SDT e.g. it does not separately assess the intensity and aversive qualities of pain (Chapman, 1980). SDT does not seem to be appropriate for many clinical pain problems, but does have an important role in more fundamental investigations (Wolff, 1984). SDT has been used in the investigation of dental pulp pain (Chapman, Chen & Bonica, 1977).

1.8.3 Category-scaling Methods

Methods of measuring perceived exertion are useful as indicators of the degree of physical strain when exercising. The problem is to quantify subjective symptoms and relate these to objective findings. There are two types of measurement of perceptual intensity of exertion, the ratio-scaling method and the category-scaling method. Ratio-scaling is unsuitable for inter-individual comparison. Borg's RPE (Ratings for Perceived Exertion) scale (a category method) has been widely used, particularly for exercise testing and for the prescription of exercise intensities for rehabilitation purposes (Borg, 1982). His new category scale with ratio properties has value in the measurement of other subjective symptoms, apart from perceived exertion, such as pain. This new scale consists of a range of numbers, such as 0 to 10, and these numbers are anchored by words or expressions with a quantitative meaning.

1.9 THE CRANIOMANDIBULAR DISORDERS AND FATIGUE

1.9.1 Definitions

The craniomandibular disorders (CMD) are a group of disorders involving the masticatory musculature, the temporomandibular joint, or both (McNeill, 1990). These conditions have also been referred to as temporomandibular disorders, TMJ pain dysfunction syndrome, myofascial pain dysfunction syndrome, or, paradoxically, simply "TMJ" (even though the problem in a particular individual may be of muscle origin and not involve the joint).

These disorders classically involve one or more of the triad of pain in the head and neck, abnormal sounds from the TMJ, and mandibular dysfunction. The word "dysfunction" is often used loosely (Reynolds, 1988), but a suitable definition is "*disturbance, impairment, or abnormality of functioning of an organ*" (Dorland, 1977). Some authors include pain as part of dysfunction (Speculund *et al*, 1983), but generally pain should be considered as a separate symptom. There can be few areas of dentistry where terms are used so loosely and standardised definitions used so infrequently as in the field of CMD.

The concept that these disorders constitute a syndrome should be accepted as erroneous. A syndrome may be defined as "*a set of symptoms occuring together; the sum of signs of any morbid state; a symptom complex.*" (Dorland, 1977).

The signs and symptoms of CMD are too varied to be classified as a syndrome (Reynolds, 1988; Bell, 1990). A disorder is *"a derangement or abnormality of function; a morbid physical or mental state."* (Dorland, 1977). The term "disorder" would appear to be more appropriate .

Masticatory muscle involvement has long been recognised in craniomandibular disorders but in spite of this Schwartz (1955) coined the term "temporomandibular joint pain-dysfunction syndrome" despite obvious muscle involvement. Later, Laskin (1969) ascribed the symptoms of this disorder directly to the muscles and advocated the name "myofascial pain-dysfunction syndrome". He proposed that the commonest cause of the disorder was muscle fatigue as a result of hyperactivity, and that this hyperactivity could be due to parafunctional habits or psychological stress. This was the beginning of a more biological approach to the problem.

The desirability of more accurate diagnosis of these conditions and of a more reliable classification scheme was emphasised in a comprehensive review by Moss & Garrett (1984) and, after a study of a large number of patients, by Rothwell (1987). There have been several recent publications which address these problems by describing the advances in diagnostic classification and standardisation of terms in CMD (Bezuur, Hansson & Wilkinson, 1989; McNeil, 1990; McNeill *et al*, 1990; Fricton, 1991). There are also five recent textbooks of particular merit, with regard not only to classification but also to broader issues (Fricton, 1988; Solberg, 1989; Klineberg, 1991a, 1991b; Miller, 1991).

1.9.2 Prevalence

It has been shown that the muscles of mastication have a higher resistance to fatigue than the limb muscles (van Steenberghe, de Vries & Hollander, 1978; Clark & Carter, 1985), when the fatigue appears it is relatively slowly followed by pain (Christensen, 1981), and yet paradoxically the craniomandibular disorders are common in clinical practice. It is claimed that approximately 20% of the general (non-patient) population are aware of symptoms of craniomandibular disorders, with 5% requiring treatment as the condition is a significant problem (Rugh & Solberg, 1985).

1.9.3 Psychological Factors

The role of psychological factors in CMD has been the subject of much debate. Unfortunately this has been fuelled by a lack of diagnostic specificity in describing the groups of patients. In a study of 93 patients referred with psychogenic facial pain, Feinmann & Harris (1984a) found a high prevalence of adverse life events and psychiatric disorders. They also found a better response to the anti-depressant dothiepin hydrochloride (Prothiaden, Boots) than to a placebo or to a soft bite guard (Feinmann & Harris, 1984b). It is unfortunate that there was no attempt to distinguish between patients with joint pain or those with muscle pain, and no information on the selection procedure for the trial. The 93 patients were selected from an original pool of 150, so there was obviously some degree of aggressive selection. The report divided the subjects into those with facial arthromyalgia (which they defined as "*Costen syndrome, temporo-mandibular joint or myofascial pain dysfunction syndrome*") and those with atypical facial pain ("*Atypical facial pain differs from facial* *arthromyalgia in that it does not specifically affect the temporomandibular joint or its musculature").*

A prospective study of the illness behaviour of 100 TMJ patients and 100 asymptomatic controls showed that the patients had increased levels of disease conviction, anxiety or depression (Speculund *et al,* 1983). However, the TMJ group were much closer to the control group than to a pain clinic population. Again no specific diagnosis was reported and so the results are of less value than would otherwise be the case.

An association between pain, depression and impairment of activity has been shown in muscle-pain patients but not in joint-pain patients (Lundeen, Sturdevant & George, 1987). The association between depression and muscle pain would tend to support the notion of treating selected muscle pain patients with anti-depressants. It was also shown that the experimental group as a whole did not have abnormally high stress levels as measured on the Derogatis Stress Profile (DSP), but that the muscle pain group had higher levels than the joint pain group. The DSP is a stress assessment profile developed from interactive stress theory, incorporating assessments of environmental stress, personality and ability to cope with stress, and response to stress (Derogatis, 1984).

1.9.4 Muscle Pain

Muscle pain may be associated with myogenous CMD and some forms of headache (*ad hoc* Committee on Classification of Headache, 1962; Christensen, 1981). One explanation for this pain is that tooth clenching and hyperfunction inhibit venous drainage from muscle, leading to an accumulation of metabolites. These metabolites, and probably extra-cellular potassium ions in particular (Mense, 1977), effect chemical irritation of nociceptive afferents in the adventitial sheath of intra-muscular blood vessels (Klineberg, 1988).

For a number of years the major hypothesis for the cause of CMD (Laskin, 1969; Miles, 1978; Laskin & Block, 1986) was that continued hyperactivity resulted in muscle spasm and hence ischaemic pain. A notion which is better supported by experimental evidence is that of local mechanical micro-trauma (implying no external trauma) following hyperactivity (Yemm, 1985). Evidence for the presence of inflammation is provided by the increase in skin surface temperature (Berry & Yemm, 1974) and increase in tissue fluid pressure (Christensen, 1971) which occurs following voluntary tooth clenching. It has also been shown that signs and symptoms similar to those of CMD can be induced in the masseter muscle by voluntary tooth clenching (Christensen, 1971) and in the lateral pterygoid muscle by vigorously protruding the mandible (Scott & Lundeen, 1980).

Intra-muscular blood flow has been shown to increase by only a factor of 2.5 in the masseter muscle during a sustained contraction at 50% MVC. The blood flow during the post-contraction hyperaemia was 27 times the initial resting flow rate (Monteiro & Kopp, 1988). The EMG activity is likely to increase by approximately 50-fold during a contraction at this level, and so apparently the blood flow rate is insufficient to meet demands during a sustained contraction. However, oxygen supply does not depend on blood flow rate alone, as more oxygen is extracted per unit volume of blood passing through the muscle during exercise. The haemoglobin molecule is made up of four haem groups containing ferrous iron, and so each haemoglobin molecule will bind a maximum of four molecules of oxygen (Keele, Neil & Joels, 1982). With the reduction in oxygen tension, the oxygen supply can be increased four times with no increase in flow rate.

A number of significant points have been raised by Christensen (1981): there is no conclusive evidence that muscle fatigue leads to so-called muscle spasm; muscle fatigue and muscle pain appear to be influenced by different determinants (this is also the contention of Monteith, 1984); there is no conclusive evidence of how ischaemia is related to jaw muscle pains; the masseter muscles and anterior temporalis are the most frequent sites of muscle pain in voluntary tooth clenching. It is apparent that the lateral pterygoid is the most frequent site of muscle pain in CMD (Franks, 1965; Scott & Lundeen, 1980).

It has been pointed out that craniomandibular disorders may be primarily of muscle origin (myogenous) or primarily of joint origin (arthrogenous), perhaps with secondary muscle involvement (Hansson, 1988). As a basis for this contention, Naeije and Hansson (1986) investigated patients who were clinically divided into myogenous and arthrogenous groups. They found that there were significant differences in RMS-integrated EMG amplitude between the two groups when clenching for 30 seconds at 50% of maximum EMG activity of the masseter muscles. However, they did not find any statistically significant differences in the rate of change of the mean power frequency. It could be that spectrum compression was minimal because the subjects maintained a constant EMG amplitude instead of a constant force output. A factor which would tend to mask any differences between the muscles in both EMG amplitude and in frequency shift was that these parameters from both left and right masseter muscles were averaged, as they were also for the temporalis muscles. Thus if only one muscle was affected by dysfunction, this would be masked by averaging the EMG parameters with those from the healthy muscles.

1.9.5. Effects of Occlusal Interferences

An occlusal interference may be defined as any premature tooth contact which causes a deviation in the final centred arc of closure of the mandible, or interferes with smooth gliding movements from a protrusive or lateral position to the position of maximum intercuspation. These interferences are commonly caused by tilting or drifting of remaining teeth following the loss of a tooth, or by poorly constructed restorations. It is believed that these interferences may have a substantial effect on the musculature of the head and neck (Guichet, 1982; Hellsing, 1987; Klineberg, 1988; Dawson, 1989). This effect may be due to alteration of the accepted reflex pattern of activity for the individual and the inducement of avoidance activity. The induced hyperactivity may have a training effect on the muscles of mastication, or may lead to muscle spasm, to localised muscle micro-trauma (Yemm, 1985), or to tooth wear. Other possible effects of hyperactivity are the inducement of intra-capsular TMJ disc displacement (Yemm, 1985) and migraine with aura on waking (Lamey & Barclay, 1987).

It has been pointed out that the teeth and their associated periodontal proprioceptors form physical reference points which are unique in the body (Klineberg, 1988). These tooth-to-tooth relationships affect muscle function, fibre orientation and motor unit composition. As pointed out previously, it has been shown that masticatory muscle control during chewing is centrally programmed (Dellow & Lund, 1971) and it seems quite likely that stress might influence this central drive, resulting in parafunctional jaw movement (Yemm, 1985). The degree of fatigue and/or spasm induced by this non-functional activity might possibly lead to muscle pain, as discussed above, or to the development of myofascial trigger points. These trigger points are small areas of exquisite hypersensitivity located within a muscle or within the muscle fascia (Travell, 1960). This myofascial pain is often intense and may be referred to a distant site, often to the TMJ or to the temporal or frontal area.

The highly developed stereognostic sensitivity of the stomatognathic system (Siirila & Laine, 1963) is significant because of the precise guidance provided by the teeth. Any change or deflective contact of teeth, even of very small magnitude, is likely to be readily detected. These changes could result in altered chewing patterns and also in aberrant movements, or postures, to avoid interferences. The importance of harmonious occlusal contacts was recognised by Watt (1966, 1981) with the development of gnathosonic diagnosis. The use of power spectral analysis of occlusal sounds has been reported recently (Shi Chong-Shan *et al*, 1991), and this has provided information on the frequency distribution as well as duration of occlusal sounds.

There have been many studies showing a significant effect of occlusal adjustment on signs and symptoms of CMD (Kopp, 1979; Weinberg, 1979; Hellsing, 1988;), but the responses were not uniform. It may be that different sub-groups within CMD patients respond in different ways and to a different extent. Some epidemiological studies have shown a positive correlation between interferences and signs and symptoms of CMD (Molin *et al*, 1976; Ingervall *et al*, 1980).

1.10 THE EFFECTS OF LOSS OF TEETH

While some natural teeth remain, muscle performance seems to be largely unaffected by loss of teeth provided occlusal interferences are not induced. Removable partial dentures have an indirectly beneficial effect on muscle performance by preventing the development of over-eruption and tilting of teeth and hence occlusal interferences. When all the teeth are lost, however, muscle performance is substantially affected, either directly or indirectly. Bite force has been shown to be greatly reduced (Haraldson, Karlsson, Carlsson, 1979; Glantz & Stafford, 1985), although it may be suspected that bite force recording in edentulous subjects tends to slightly underestimate the true MVC because the subject is closing on denture bases and not on natural teeth. Another reason for the greatly reduced bite force is that the muscles atrophy because they are unable to function with their previous vigour. It has been pointed out that complete dentures provide an inferior substitute to natural teeth (Glanz & Stafford, 1985). Muscle cross-sectional area has also been shown to be reduced markedly in edentulous subjects (Newton *et al*, 1987), which is to be expected if the muscles have undergone atrophy.

The mean power frequency of the power spectrum has been shown to be related to muscle fibre composition, with an increase representing the recruitment of type 11 fibres (Barker, 1985). Completely edentulous subjects have been shown to have a lower mean power frequency than dentate individuals, which was interpreted as showing a reduced number of type 11 fibres as a result of disuse atrophy (Wastell, Barker & Devlin, 1987).

Edentulous patients also suffer from CMD, although with a different pattern to younger dentate sufferers. The prevalence of CMD has been reported to be 19% of a population of 100 denture wearers (Zississ, Karkazis, & Polyzois, 1988). The relation of occurence of CMD to occlusal vertical dimension and jaw relationship errors was found to be to be statistically significant. Lundeen *et al* (1990) also found complete denture wearers to have a higher prevalence of CMD symptoms than the general population, but these symptoms were of a low intensity and not clinically significant. This was particularly so in the case of pain intensity.

1.11 MEASUREMENT OF BITE FORCE

1.11.1 Bite Force Transducers

The measurement of bite force presents several difficulties, one of which is that most direct methods require a certain thickness of bite force transducer. This depends on the method used, but most bite force transducers are of the order of 7 mm thick. If these are placed between the molar teeth then this results in a considerable degree of jaw opening. Although it has been reported that a jaw opening of 15 to 20 mm results in the optimal masseter muscle length (Manns *et al*, 1979), this is not a normal functional length. Some bite force measuring devices are thinner, one being some 3.4 mm thick (Floystrand, Kleven & Oilo, 1982), but these are not widely available. The other problem with bite force transducers generally is that damage can be sustained by the natural teeth or dental restorations (van Steenberghe & de Vries, 1978), and some form of custom made acrylic resin index should be applied to the beams of the bite force transducer in order to minimise this risk. Gauze may be more comfortable.

When a patient or volunteer is requested to clench maximally on a bite force transducer, it is notoriously difficult to be sure that the force produced is indeed the maximum of which he is capable. A theoretical solution to the problem would be to employ the twitch interpolation technique, as described in Section 1.1.2. However, because of the anatomy of the region, with small muscles, this is not a practical approach.

1.11.2 Periodontal Mechanoreceptors

Volunteers are hesitant about clenching forcefully in case damage results; there is also an inhibitory response from the fibres of the periodontal membrane which supports each tooth (Hannam & Matthews, 1969; Bessette, Mohl & Bishop, 1974; Kloprogge, 1975; Cash & Linden, 1982). Hannam & Matthews (1969) demonstrated the presence of a jaw-opening reflex when stimulating the canine tooth of a cat. Bessette et al (1974) were able to abolish the masseteric silent period by placing local anaesthetic about the periodontal ligament, thus adding evidence to the notion that stimulation of periodontal receptors inhibits the masseteric motorneuron pool. Thus there is some evidence that periodontal mechanoreceptors send afferent volleys in order to protect an individual tooth from overloading, and so when comparing bite force within or between individuals one must be sure that the force was obtained between the same opposing teeth in each case.

1.11.3 Position of Transducers

A variable which should be considered when measuring bite force is the position of the force transducer within the dental arch (Leff, 1966). The more posteriorly the force transducer is placed the greater the bite force recorded, partly because of the lever effect of the mandible and partly because there is a greater area of periodontal ligament around posterior teeth available to support the load. Different positions will also influence which muscles are involved in the force production. If the force transducer is placed anteriorly between the incisor teeth, with a resultant mandibular protrusion, the masseter will produce most of the force together with the medial pterygoid muscle. If the bite force transducer is more posteriorly placed, then the anterior fibres of the temporalis muscle will contribute a greater proportion of the effort (Carlsöö, 1952; Hellsing & Lindstrom, 1983).

1.11.4 Individual Muscle Force Output

A complicating factor when wishing to assess masticatory muscle performance is that it is not possible to directly measure force produced by the individual muscles, only their collective output. Indirect methods using intramuscular electrodes and supra-maximal electrical stimulation of motor nerves have been used (Desmedt & Godaux, 1979), but the technique is difficult and invasive in this region.

1.11.5 Average Bite Force Values

In Western populations, average maximum bite forces between the molar teeth are usually said to be in the range of 600-750N (Hagberg, 1987). In a study on ten young women the mean maximum bite force between the molar teeth was 396N (Hagberg, Agerberg & Hagberg, 1985). Maximum bite forces between the incisor teeth have been found to vary between 140N to 200N (Hellsing, 1980), and from 120N to 350N between the canine teeth (Lyons & Baxendale, 1990).

1.12 BRUXISM

1.12.1 Aetiology

Hyperactivity may result from occlusal interferences or from parafunctional habits such as nail biting, cheek biting, gum chewing, or bruxism. Hyperactivity implies that *"the muscle activity induces signs or symptoms of deviations from a somatic state of well-being"* (Christensen, 1981). Bruxism may be defined as the parafunctional grinding of the teeth (Glossary of Prosthodontic Terms, 1987). It is perhaps the most potentially damaging parafunctional activity, and it is generally considered to be due to an enhancement of central motor drive induced by stress (Yemm, 1985; Klineberg, 1988). Movement generally may be consciously or subconsciously performed; it may be started consciously and continued in a rhythmical subconscious manner, or be more reflex in nature. Central motor drive is the mechanism by which this skeletal muscle activity is regulated (Hellsing, 1987).

Aetiologic factors have been separated into genetic, local, systemic, psychogenic, and occupational (Klineberg, 1991). Bruxism has been found to be more prevalent in the children of bruxists (Abe & Shimakawa, 1966), and in students with blood relatives who are bruxists (Reding, Rubright & Zimmerman, 1966). In two publications which have been widely quoted, Ramfjord (1966a,b) claimed to have demonstrated a significant association between tooth contact interferences and bruxism, but unfortunately there were no control groups. Subsequent studies by other groups have shown that adjustment of the occlusion to eliminate interferences does not have a consistent effect on bruxism (Bailey & Rugh, 1980; Rugh, Barghi & Drago, 1984).

In a well-designed study by Sherman (1985) it was shown that patients with jaw pain due to bruxing were no more anxious (as determined on the Minnesota Multiphasic Personality Inventory) than other dental patients. He also demonstrated that patients with pain due to elevated muscle contraction levels responded very well to biofeedback therapy. The effect of an occlusal splint on the signs and symptoms of nocturnal bruxism has been shown to be significant (Sheikholeslam, Holmgren & Riise, 1986). These signs and symptoms, however, returned to pre-treatment levels when the patients were instructed to stop wearing the splint.

1.12.2 Muscle Performance

Bruxists have been shown to have increased endurance when maintaining an isometric contraction and also increased bite force (Helkimo & Ingervall, 1978), which is perhaps to be expected because of a probable training effect of the hyperactivity. One of the consequences of this increased activity is tooth wear, or attrition. Teeth may maintain their position within the supporting alveolar bone as wear takes place, with the result that the lower face height (chin-to-nose distance) decreases, or they may overerupt and so maintain the original lower face height. If a change in lower face height occurs then the jaw-closing muscles will have a different working length. It seems that they adapt readily to a different working length (Goldspink, 1976; Klineberg, 1991), and clearly the change is imperceptibly slow and probably has little functional significance in the majority of patients. There are some, however, who suffer from a craniomandibular disorder which often improves upon restoration of the lower face height. This effect might be due to the consequent change in occlusal relationship of the teeth which inevitably occurs rather than the change in lower face height *per se*.

1.13 SUMMARY OF REVIEW OF LITERATURE

Relevant literature suggests a certain degree of concensus on various important topics, and also reveals areas which are contentious or where knowledge is incomplete. A brief summary of these factors is presented in order to clarify the aims of this investigation:

In prolonged intermittent submaximal contractions of limb muscle, activation by the CNS is fully maintained i.e. central fatigue does not occur.

Slowing of relaxation is probably due to reduced rate of calcium uptake by the sarcoplasmic reticulum and probably, in addition, reduced activity of the actomyosin cross-bridges. However, the precise mechanism is still unproven.

Power spectral compression clearly occurs with fatigue, and is mainly due to changes in muscle fibre conduction velocity. The median frequency is a suitable estimator of the power spectrum.

Normalisation procedures enable valid between-session and between-subject comparisons of EMG signals to be made, but care is required if MVC is the standard load employed.

Great care is required when recording bite force. Muscle force production is influenced by, among other factors, the periodontal mechanoreceptors.

The jaw-closing muscles are more resistant to fatigue than the limb muscles. Muscle fatigue is only slowly followed by pain. The manner in which ischaemia is related to muscle pain is not clear. There is very little evidence that fatigue leads to so-called muscle spasm, and the role of muscle fatigue in CMD is unclear. Local mechanical micro-trauma still seems a likely explanation for some types of pain in CMD. Pain similar to that experienced in CMD can be induced experimentally by prolonged contraction of the masseter and temporalis muscles.

The effect of occlusal interferences on bruxism is insignificant, but there is a weakly significant association between occlusal interferences and CMD. Bruxism is considered to be largely induced by stress.

Patients with muscle-pain have slightly higher levels of stress and depression than patients with joint pain, but the significance of this is unclear.

Thus the role of fatigue in CMD requires clarification; the link, if any, between fatigue and pain is not yet established. It must be recognised that CMD is a group of related disorders and the role of muscle fatigue might vary according to the specific disorder.

1.14 AIMS OF INVESTIGATION

The aims of this work were to investigate various mechanisms and methods of measurement of fatigue in the jaw-closing muscles and obtain a better understanding of the craniomandibular disorders. The specific aims were as follows:

- To investigate bite force, endurance and fatigue in bruxists and normal controls. To investigate the measurement of bite force with the mandible in a possible laterotrusive position of parafunctional activity.

- To study any change in EMG amplitude during a sustained isometric contraction in the jaw-closing muscles and assess the use of this parameter to monitor the state of fatigue in healthy individuals.

- To study the use of power spectral analysis and the reported shift in median frequency which occurs during fatigue. To relate any shift which might occur to changes in amplitude.

- To investigate the measurement of subjective perception of fatigue and pain in healthy individuals and to compare this with objective measures.

- To study the relaxation rate in the masseter muscles of patients with CMD, and any changes in this rate which might occur with fatigue.

CHAPTER 2.

GENERAL METHODS AND SPECIFICATIONS

2.1 ETHICAL COMMITTEE APPROVAL

Approval was obtained from the Area Dental Ethics Committee of the Greater Glasgow Health Board prior to all the experiments involving human volunteers (see Appendix G).

2.2 TYPE AND POSITION OF ELECTRODES

A bipolar electrode configuration was used in every case, with a ground electrode being placed on the ear lobe or forehead.

2.2.1 Temporalis Muscle

The electrodes were placed over the anterior fibres of the temporalis muscle. The muscle was palpated and the area of maximum muscle movement on clenching was chosen. This was approximately 4 cms mid-way above a line joining the tragus of the ear and the outer canthus of the eye, and was invariably within the hair-bearing area of the scalp. The electrodes were placed in line with the direction of the muscle fibres, and with an inter-electrode distance of 2 cm. Copeland-Davis stainless steel clip electrodes were used for the experiment reported in Chapter 3, but intra-dermal hook electrodes were used in subsequent work. These hook electrodes were constructed by bending platinum sub-dermal electrodes

(Type E2, Grass Instrument Co, Quincy, MA), which are straight, to the dimensions provided by Ahlgren (1967). It was considered necessary to use either clip or intra-dermal hook electrodes rather than discs because of the presence of hair. If a more anterior electrode position is used, and so avoiding hair-bearing skin, then it is likely that activity will be detected from the orbicularis oculi muscle and possibly also from the frontalis muscle.

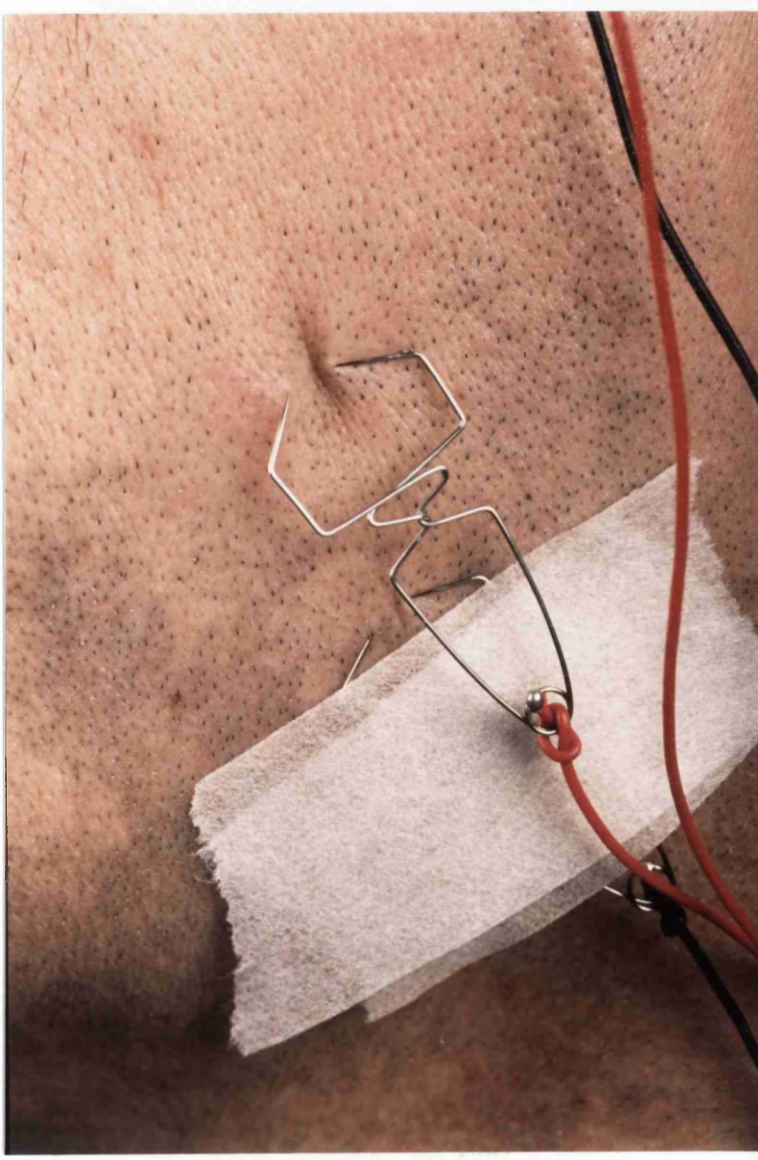


Figure 2.1 Copeland-Davis electrodes attached to the skin.

2.2.2 Masseter Muscle

The area of the masseter muscle from which recordings were taken was the lower anterior part of the main belly of the muscle. The electrodes were placed in line with the main direction of the muscle fibres, the inferior electrode being placed near to the lower border of the mandible and towards the palpable anterior edge of the muscle. This usually resulted in the electrodes being placed on a line extending from a position approximately 15 mm anterior to the angle of the mandible to the outer canthus of the eye.

Copeland-Davis clip electrodes were used for the work reported in Chapter 3. In all subsequent work disc electrodes were used, these being silver/silver chloride and 9 mm in diameter (SLE Ltd, Croydon, Surrey). Double-sided adhesive discs were used to retain the electrodes, and electrode gel (Neptic, Sandev Ltd) placed with a blunt-ended 19 gauge needle. The centre-to-centre distance was 2 cm. The skin surface was prepared by rubbing briskly with gauze soaked in surgical spirit. As the electrode gel was applied the needle was rotated lightly against the skin to further improve the contact.

2.3 AMPLIFIER SPECIFICATIONS

The pre-amplifier and isolating amplifier used for the experiment reported in Chapter 3 were both manufactured by the Institute of Physiology, University of Glasgow. The amplifiers used in subsequent experiments were components of the Neurolog System (Digitimer Ltd), and consisted of the NL824 4-channel AC pre-amplifier and NL820 isolator amplifier. The general layout of equipment may be seen in Figure 2.2.

2.3.1 Pre-amplifiers

The University of Glasgow pre-amplifier was a single-channel amplifier with a gain of X1000. The commercial pre-amplifier used subsequently was a four-channel, low-noise, differential AC amplifier (NL824, Digitimer Ltd). The lower cut-off frequency was set to 3Hz and the higher cut-off frequency was > 10kHz. The input impedance was 100MΩ. The noise level, with inputs short circuited, was <1.5μV RMS.

The pre-amplifier was placed close to the volunteer so as to keep the wires from the electrodes as short as possible. This was desirable to minimise electromagnetic interference. The wires from each electrode pair were also twisted together in order to keep any interference the same in each wire.

2.3.2 Voltage Isolators

It is necessary, for safety reasons, to isolate human subjects from possible direct contact with the mains 240 volt supply in the event of equipment failure. This may be achieved in several ways, and optical isolators were used in the experiment reported in Chapter 3. The principle of an optical isolator is to utilize light-sensitive diodes for the transmission of a voltage-determined light impulse. This is then converted back to an electrical current and amplified.

The isolator amplifier used in the experiments reported in Chapters 5, 6 and 7 was an NL820 which used transformer techniques (i.e. an isolating transformer) to provide both both signal and power supply isolation from the power supply ground. The input impedance was 10kΩ, noise < 4mV at 150kHz.

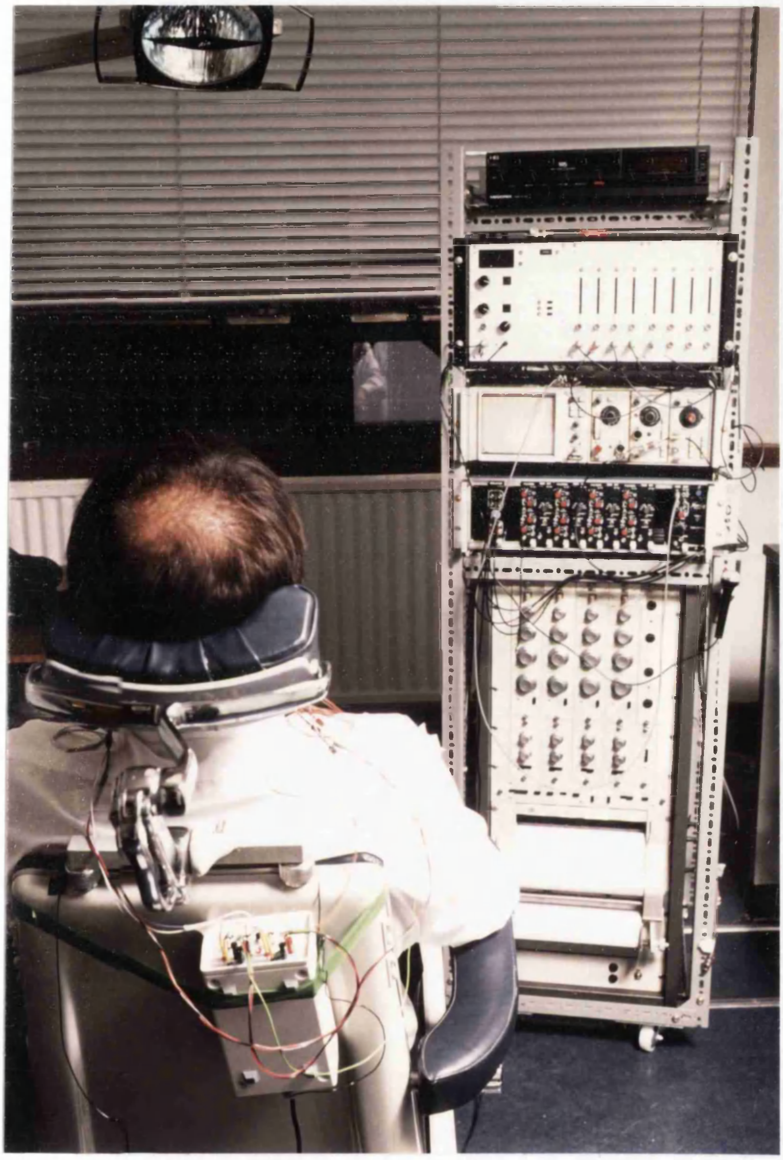


Figure 2.2 General layout of equipment in the clinic. The PCM-8 may be seen second from top in the rack. Note that the pre-amplifier is positioned on the dental chair as close as possible to the volunteer.

2.4 BITE FORCE TRANSDUCER

Bite force was measured using a stainless steel bite force transducer (see Appendix E). This was used in conjunction with a DC-coupled differential amplifier (NL107, Digitimer Ltd, Welwyn Garden City) which is intended for use as a bridge amplifier and has an integral power supply. The bite force transducer was calibrated against known weights before each session and checked again afterwards. The calibration was calculated in Newtons (1Kg = 9.98N).

The force level was displayed on an oscilloscope screen (Tektronix 5103N, Tektronix Inc., Beaverton, OR 97077, USA) before being passed to a 4-channel chart recorder (Devices, Digitimer Ltd, Welwyn Garden City, Herts.)

Small autopolymerizing acrylic resin indices were fabricated with the canine teeth in contact with the metal faces of the bite fork. These indices protected the teeth against the possibility of enamel fracture during heavy biting and assured closure in the desired position. The total thickness of the bite force transducer and the acrylic indices was 7 mm.

2.5 SIGNAL STORAGE

Signal storage was achieved by the use of a PCM-8 A/D video recorder adapter (Medical Systems Corp., Greenvale, NY 11548). This enabled up to eight channels of data to be stored on high quality video tape cassettes. Prior to the introduction of the PCM-8 it was necessary to store signals on FM (frequency-modulated) tape, which was less convenient than video cassettes and considerably more expensive.

The PCM-8 operated by multiplexing analogue inputs through a single A/D converter into a digital data stream. This digital data then modulated a video carrier in a format compatible with a standard VHS video and the encoded data was fed to the video input of a video recorder. Retrieval of data was achieved by playing the video tape back through the PCM-8. The signal was decoded, D/A converted, demultiplexed, and presented at the analogue outputs of the PCM-8 at the same amplitude as recorded. There was also an audio channel to record and replay audio notes.

In the 8-channel mode the sampling frequency was 11kHz, and in the 4-channel mode 22 kHz. The frequency response was DC-7kHz (4-channel) and DC-3.5kHz (8-channel). The PCM-8 employed a sensitive method of error detection and correction to compensate for tape drop-out, dirt on the tape, and poor quality tape (PCM-8 Users Manual).

2.6 SIGNAL PROCESSING AND ANALYSIS

Signal processing and analysis was carried out using a signal analysis package (Spike 2, Cambridge Electronic Design, Cambridge). A computer interface (1401, Cambridge Electronic Design) was used to digitise the data in separate channels and data aquisition software was used to capture the data. The sampling rate for EMG data was 1660 Hz, and 550 Hz for the force data.

A text file within Spike 2, FFTEMG.TXT, was used to obtain the power spectra (see Appendix B). A section of each channel was specified for analysis by two vertical cursors. The FFT calculation applied by CED used a 16 bit word, and removed edge effects with a raised cosine window. Any

DC offset, manifesting as a peak in the spectrum at zero frequency, was dealt with by removing the first (and sometimes the second) "bin" before calculating the median frequency. One bin is one point on the FFT. The formula for calculating the amount of information lost per bin is:

$$\frac{\text{sampling frequency}}{2} \times \frac{1}{\text{number of bins}}$$

$$= \frac{1660}{2} \times \frac{1}{1024}$$

$$= 0.81 \text{ Hz per bin}$$

The area of the spectra to be used for the calculation of the median frequency was specified with two vertical cursors; this area was 0 - 550Hz. The median frequency was displayed on the screen.

To measure relaxation times, which required the use of one horizontal and two vertical cursors, the programme FASLOPE.TXT was used. This was also within the data analysis section of Spike 2. One EMG channel and one force channel could be displayed. Sections of these channels could be marked by vertical cursors and expanded. The vertical cursors were provided with a display showing time (seconds) to five decimal places. The horizontal cursor was also provided with a digital display, permitting the measurement of amplitude.

CHAPTER 3.

BITE FORCE AND JAW-CLOSING MUSCLE FATIGUE IN HUMAN VOLUNTEERS WITH ADVANCED TOOTH WEAR

3.1 SUMMARY

The maximum bite force was recorded in five volunteers with advanced tooth wear and in a control group of five volunteers with no abnormal tooth wear. They were then asked to maintain a force of 50% of their maximum biting force for as long as possible while surface electromyograms from the masseter and temporalis muscles were recorded. The bite force and endurance time were found to be slightly increased in the group with tooth-wear, but no conclusions could be reached regarding the state of fatigue. Two significant problems for fatigue studies of the jaw-closing muscles were identified: the use of the canine position for recording bite force and the thickness of the bite force transducer.

3.2 INTRODUCTION

The problem of advanced tooth wear (or perhaps more correctly tooth surface loss) is seen with increasing frequency in dental clinics. There are many reasons for this, not least of which is the fact that a greater percentage of the population are retaining their teeth into their middle years and beyond. Patients' expectations are rising and general dental practitioners are increasingly recognising the process and referring these patients to specialists for an opinion or, more usually, for treatment.

The term "tooth surface loss" refers to the loss of the surface of teeth as a result of attrition, erosion or abrasion, or often a combination of all three. The process of particular interest in this investigation was attrition, defined as the loss of substance of teeth or dental restorations by mastication or contact between occluding or approximal surfaces (Watson & Tulloch, 1985).

In cases of attrition, where there is no obvious dietary factor, there is usually a history of bruxism. The forces exerted during bruxing activity have been reported to be between 30% and 60% of a maximum voluntary contraction (Clarke, Townsend & Carey, 1984), which is a large force when compared to normal chewing forces. Up to eleven bruxing episodes per night were also reported, with an average duration of 11 seconds. Bruxism also occurs during the day, particularly at times of stress.

It seems reasonable to suggest that the jaw-closing muscles of bruxists might sustain a training effect from this activity, becoming stronger and possibly more resistant to fatigue. The picture is not entirely clear on this, however, as it is likely that the activity may often occur in one particular laterotrusive position.

A view which is generally held regarding the aetiology of bruxism is that it is a centrally induced activity and perhaps peripheral factors, such as occlusal interferences, play a precipitating role in some cases (see Chapter 1, section 1.12). It was pointed out by Chaffin (1971) that fatigue in limb muscles results in a reduced ability to perform accurate movements and to judge the exertion of light forces; it is possible that this impairment of judgement of light forces may also have some relevance in bruxists. Chaffin also defined localized muscle fatigue, saying that it results in discomfort and decreased performance; decreased ability to carry out precise coordinated movement; increased muscle tremor occurs; also there are subjective feelings of pain and a "*desire to abandon the task*".

One of the problems associated with the study of fatigue of the jaw-closing muscles is that it is not possible to measure the force output of each individual muscle, only their collective force. Also it has been shown by Hellsing & Lindstrom (1983) that there is a rotation of activity among the synergist muscles which is quite beyond voluntary control and serves to further complicate the situation.

During a sustained isometric contraction the surface detected signal has been shown to increase in power as a result of metabolic fatigue. Thus the EMG/force ratio increases in an attempt to maintain the force output, due to recruitment of additional motor units (Edwards & Lippold, 1956).

The aims of this experiment were to investigate the strength, endurance and resistance to fatigue of the masseter and anterior temporalis muscles in bruxists compared to a non-bruxing control group. These parameters were to be studied with the canine teeth in a cusp-to-cusp position on the bite force transducer to investigate fatigue in this specific position. The feasibility of using change in EMG amplitude during a sustained isometric contraction as a measure of fatigue in the jaw-closing muscles was also to be investigated.

3.3 METHOD

3.3.1 Volunteers

Ten volunteers participated in this study, five of whom showed advanced attrition (Figure 3.1) and five of whom did not. The controls were age-matched to the experimental volunteers and both groups were males aged between 32 and 60 years. The volunteers with attrition had a history of bruxism, were partially dentate, and showed a degree of attrition corresponding to a score of 3 or 4 on the Smith and Knight Tooth Wear Index (Smith & Knight, 1984) for the occlusal or incisal surfaces (Figure 3.2). They were chosen as being representative of the patients referred to the Glasgow Dental Hospital and School with tooth surface loss. They were clearly suffering from attrition rather than a detectable dietary or systemic cause. The controls were also partially dentate but did not have a history of bruxism and had no abnormal tooth wear. Dental Ethical Committee approval was obtained for the project, and informed consent obtained from each participant.

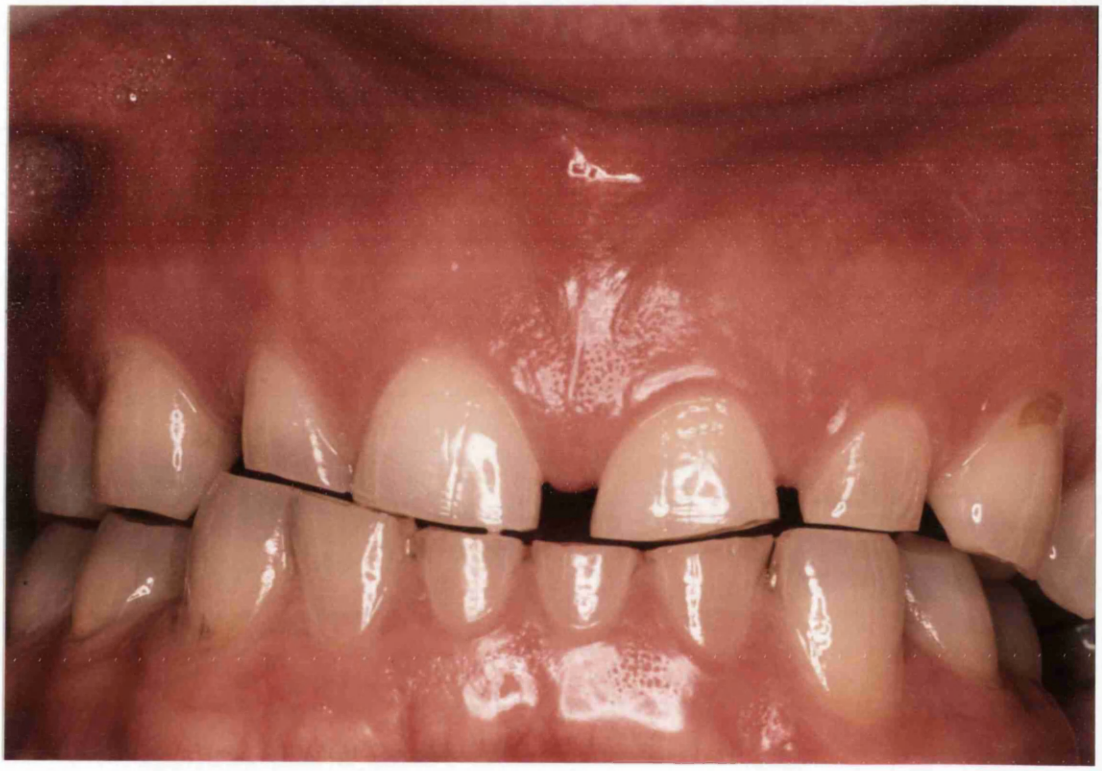


Figure 3.1 One of the volunteers with attrition.

Score*	Surface	Criterion
0	B/L/O/I	No loss of enamel surface characteristics
	C	No change of contour.
1	B/L/O/I	Loss of enamel surface characteristics.
	C	Minimal loss of contour.
2	B/L/O	Loss of enamel exposing dentinefor less than one-third of the surface.
	I	Loss of enamel just exposing dentine.
	C	Defect less than 1mm deep.
3	B/L/O	Loss of enamel exposing dentine for more than one-third of the surface.
	I	Loss of enamel and substantial loss of dentine, but not exposing pulp or secondary dentine.
	C	Defect 1-2mm deep.
4	B/L/O	Complete loss of enamel, or pulp exposure, or exposure of secondary dentine.
	I	Pulp exposure or exposure of secondary dentine.
	C	Pulp defect more then 2mm deep, or exposure of secondary dentine.

* In case of doubt a lower score is given.
B=buccal or labial; L=lingual or palatal; O=occlusal; C=cervical.

Figure 3.2 The tooth wear index (Smith & Knight, 1984), reproduced from the *British Dental Journal*, vol.156.

3.3.2 Electromyography

Electromyograms were recorded from the masseter muscle and the anterior fibres of temporalis. Copeland-Davis stainless steel surface electrodes were used in a bipolar configuration. These clip electrodes are intended to maintain a constant impedance, and were placed with their centres 2cm apart and in line with the main direction of the muscle fibres (Greenfield & Wyke, 1956). A ground electrode was placed either on the ear lobe or on the forehead. The signal was amplified X1000, optically isolated (Figure 3.3) and rectified-integrated with a time constant of 200 ms. The data was displayed on a 4-channel chart recorder with the paper speed set at 10 cms/min. The preferred chewing side was used for the experiment.

The method of quantifying the change in amplitude of the EMG signal (ΔEMG) during the sustained contraction was to measure the increase in amplitude which occurred during the course of the contraction (ΔA) and express this as a percentage of the initial rise from the resting amplitude to the amplitude at 50% MVC at the start of the sustained contraction (ΔA_1). Thus $\%\Delta EMG = \Delta A/\Delta A_1 \times 100$ (Figure 3.4).

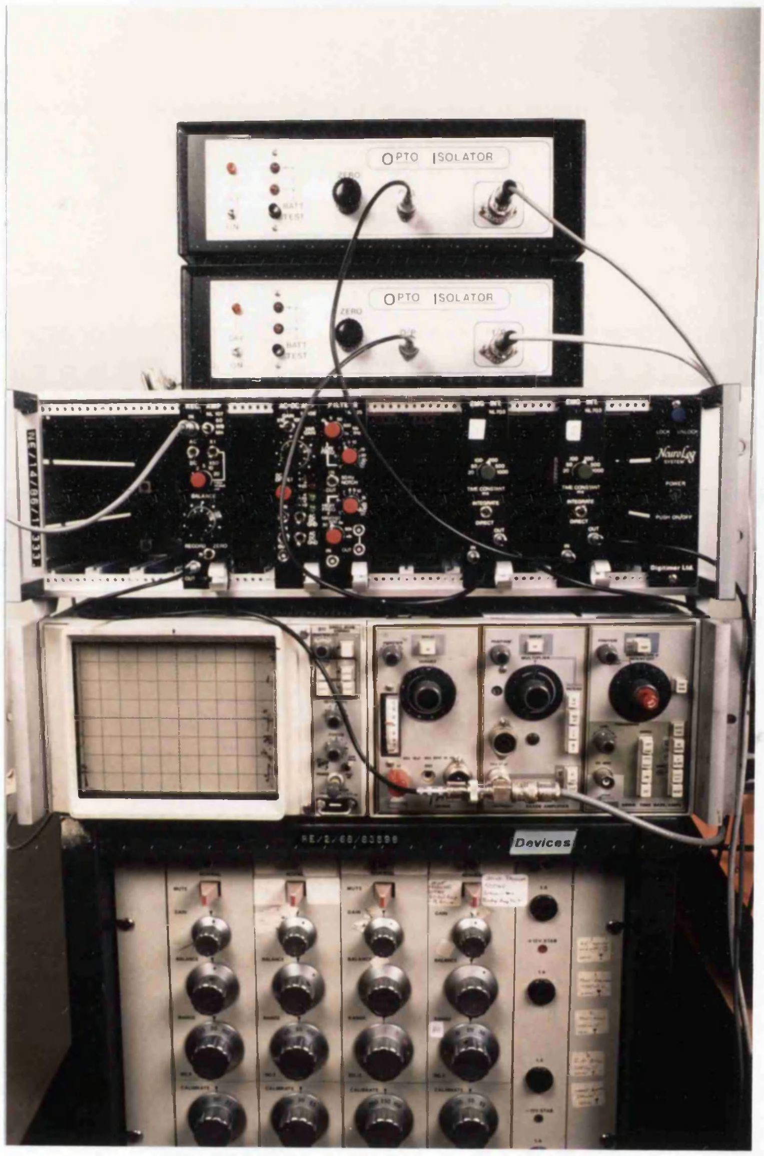


Figure 3.3 The two single-channel optical isolators on top of the Neurolog case.

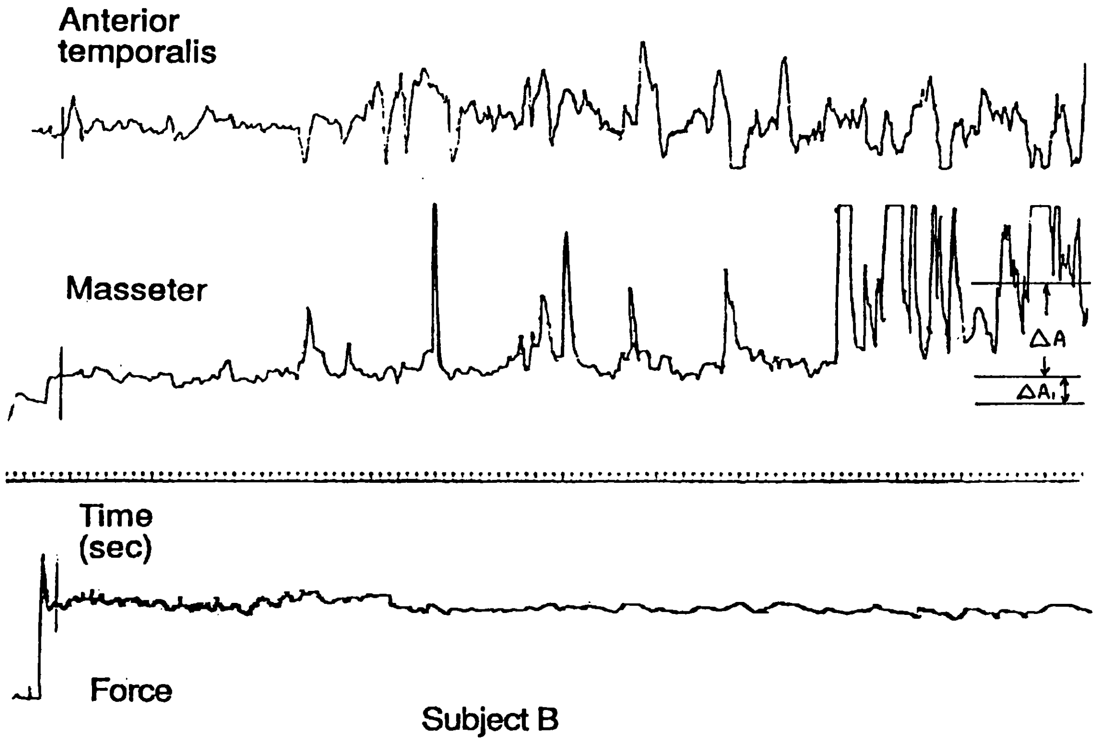


Figure 3.4 RMS-integrated EMG records and force record from one volunteer. The horizontal lines indicate the levels from which measurements of EMG amplitude were taken.

3.3.3 Experimental Protocol

The procedure was explained to the volunteers and they were allowed to familiarize themselves with the bite fork and the oscilloscope screen which provided visual feedback. The volunteers were then asked to carry out a maximum voluntary contraction (MVC) several times, with a short rest in between, until the maximum had clearly been obtained (Figure 3.5). Each volunteer was then requested to sustain a force equal to 50% of the MVC for as long as possible. This force level was achieved by observing the marker on the oscilloscope screen.

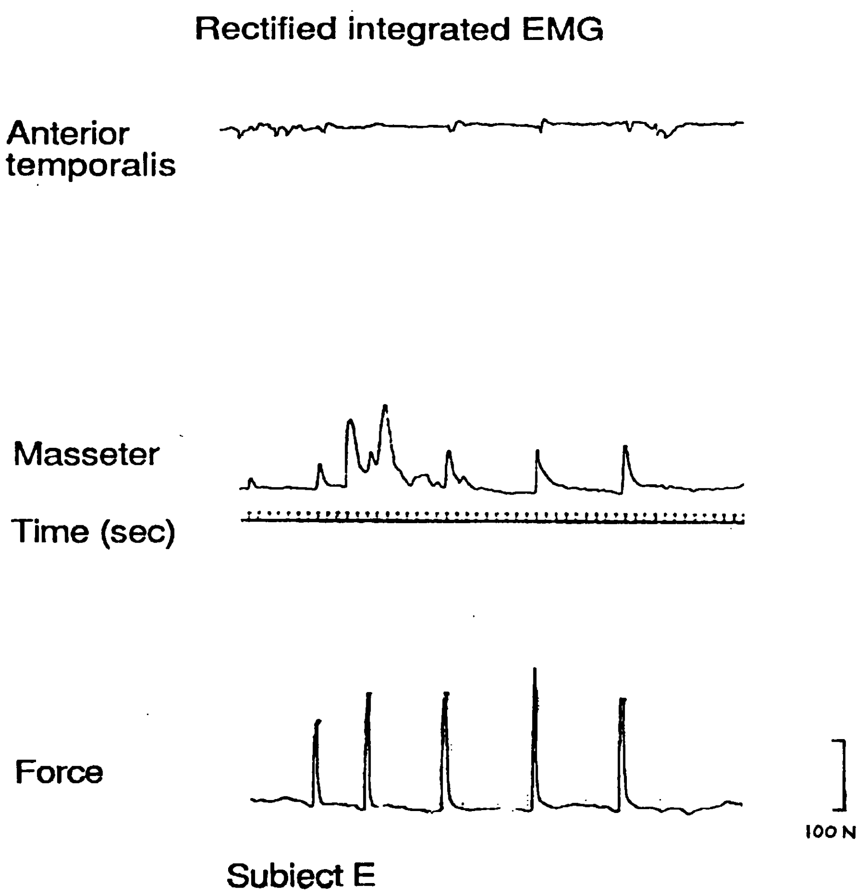


Figure 3.5 Rectified-integrated EMG and force records from one volunteer to show a series of maximum voluntary clenches.

3.4 RESULTS

The maximum bite force achieved by the group with tooth wear was generally higher than that achieved by the controls (Figure 3.6), their mean bite force being 260N (SD 58.1) compared to a mean of 220N (SD 107.7) for the controls (Tables 3.1 and 3.2). Two members of the control group, however, had very large bite forces of 320N and 350N.

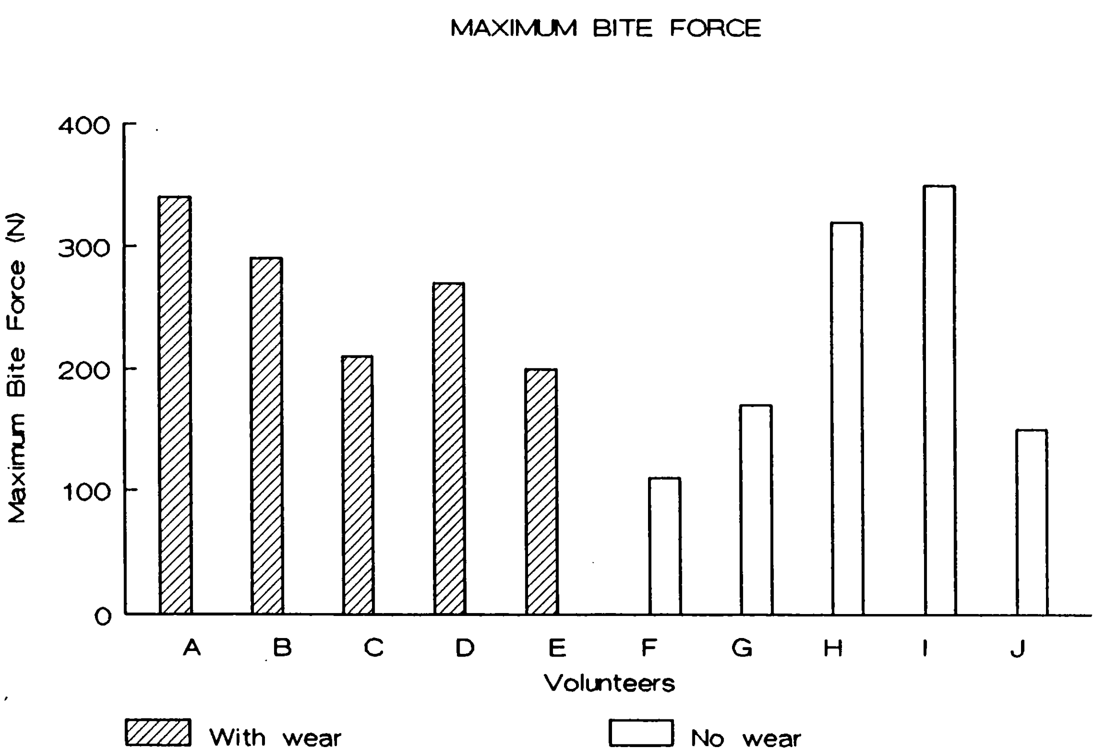


Figure 3.6 The maximum bite force obtained from each volunteer.

Volunteer	Endurance (mins)	Force (N)	Percentage Change in Amplitude	
			Temporalis	Masseter
A	2.7	340	150	0
B	2.2	290	100	300
C	1.3	210	100	0
D	1.4	270	0	8
E	2.7	200	0	0
Mean:	2.06	260	70	61
± SD	0.68	58	67	133

Table 3.1. Results from volunteers with tooth wear.

Volunteer	Endurance (mins)	Force (N)	Percentage Change in Amplitude	
			Temporalis	Masseter
F	1.9	110	250	50
G	1.4	170	120	0
H	1.3	320	0	-100
I	1.4	350	330	160
J	2.1	150	20	-100
Mean:	1.62	220	144	2.0
± SD	0.35	107	143	109

Table 3.2. Results from volunteers with no tooth wear (control group)

The time which each volunteer was able to sustain a contraction was termed the endurance time (Figure 3.7). The endurance time of the attrition group, with a mean of 2.06 minutes (SD 0.680), was slightly longer than that of the controls, whose mean endurance time was 1.62 minutes (SD 0.356) (Tables 3.1 and 3.2).

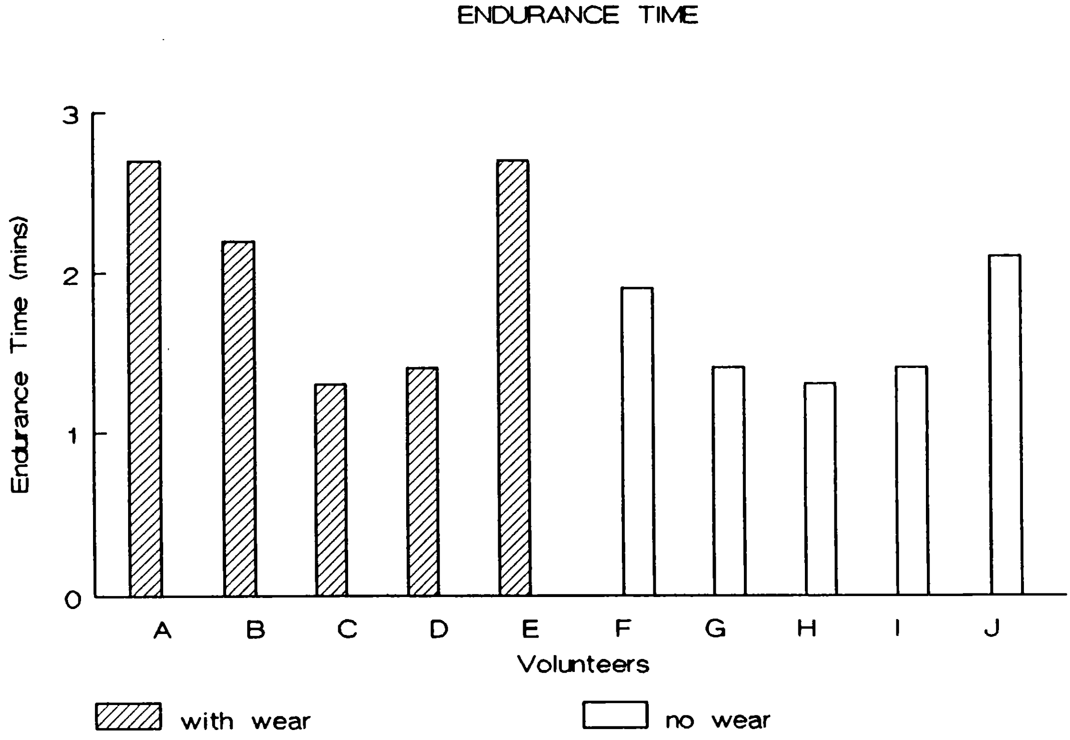


Figure 3.7 The time for which each volunteer was able to sustain a contraction.

When these two parameters of bite force and endurance time were subjected to an unpaired t-test there were no statistical differences between the means of the experimental and control groups. The values for force were $t = 0.77$, $p = 0.47$, $DF = 6$. The values for endurance were $t = 1.28$, $p = 0.25$, $DF = 6$. Because of the small sample size and the difference in the standard deviations, a Mann-Whitney analysis was also carried out for each of these parameters but again no statistically significant differences could be demonstrated.

The change in EMG amplitude was slightly greater in the temporalis muscles than in the masseters, but no other pattern of change could be seen (Figures 3.8 and 3.9). Two volunteers showed a decrease in EMG amplitude from their masseter muscles. There was a large range in the levels of change of EMG amplitude with very large standard deviations. Unpaired t-tests showed no statistically significant differences between the two groups, either for the masseter or for the temporalis muscles. For the masseter $t = 0.77$, $p = 0.47$, $df = 7$, and for the temporalis muscle $t = -1.04$, $p = 0.34$, $df = 5$. A Mann-Whitney analysis also failed to show any difference between the two groups at the 5% level of confidence.

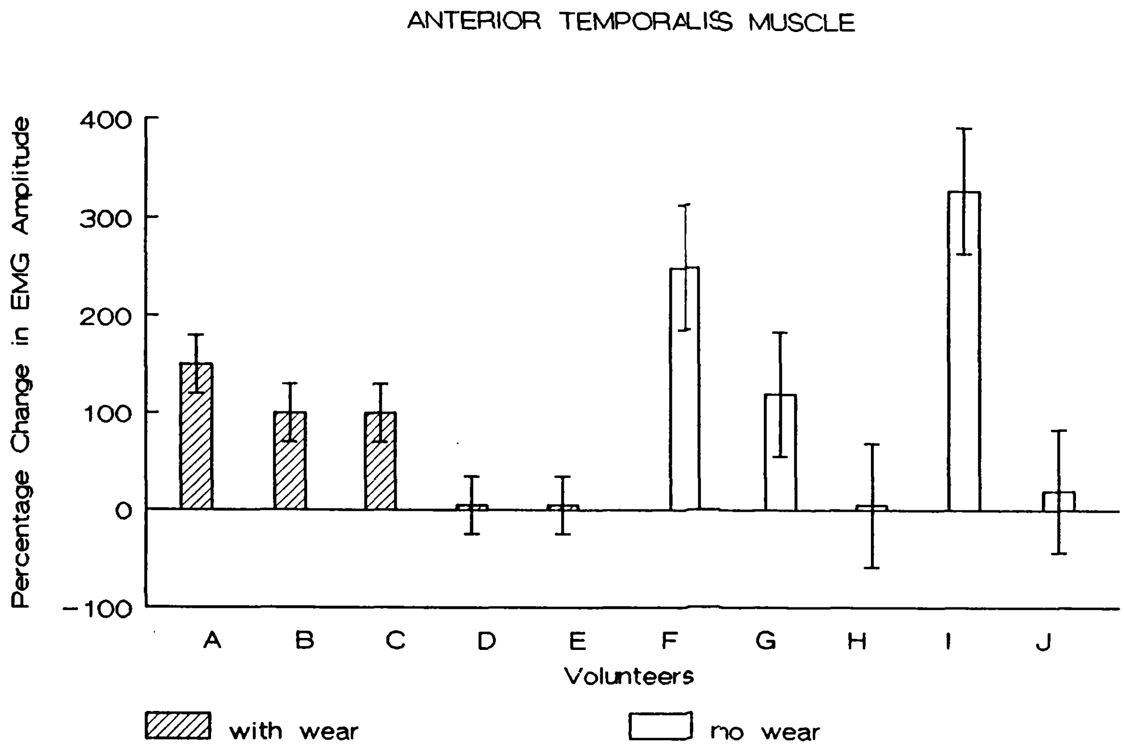


Figure 3.8 The change in temporalis muscle EMG amplitude for each volunteer, the error bars representing standard errors.

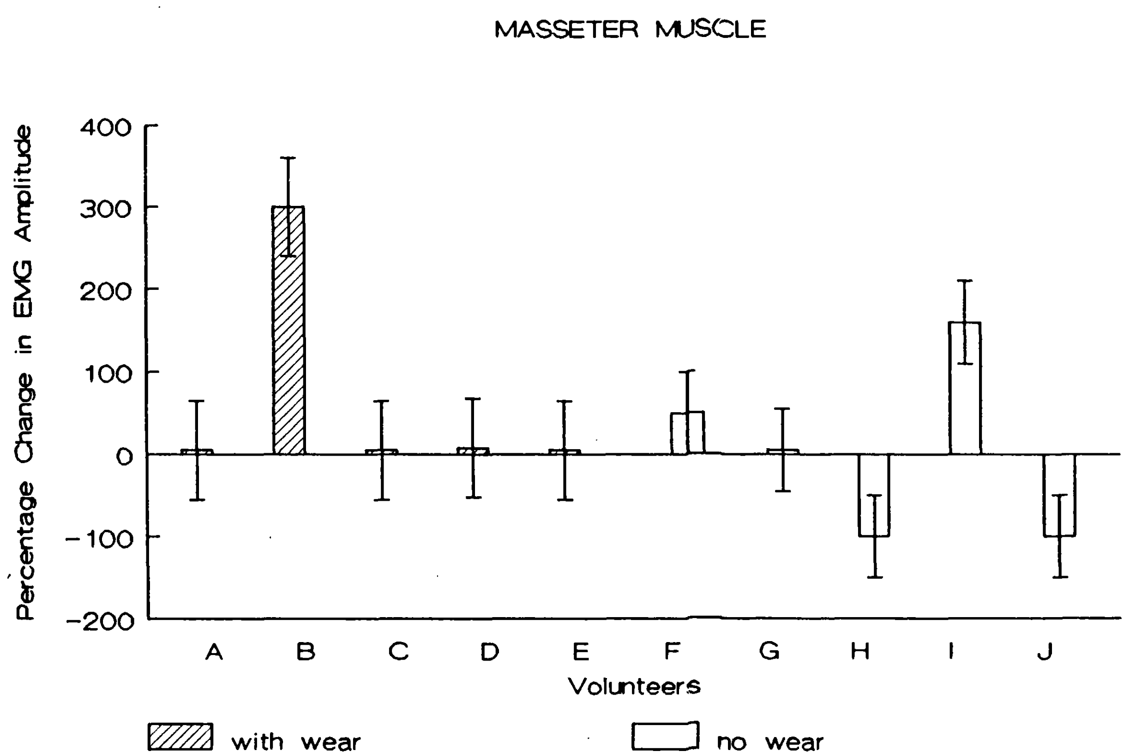


Figure 3.9 The change in masseter muscle EMG amplitude for each volunteer, the error bars representing standard errors.

3.5 DISCUSSION

The large variations in amplitude during the sustained contractions were a little difficult to explain, but this is often seen in an advanced state of fatigue (Figures 3.4 and 3.10). In order to make some comparison with another muscle system, recordings were taken of the first dorsal interosseous muscle of the hand from one volunteer (MFL) who was not one of subjects of the experiment (Figure 3.11). The same equipment and regime was used as for the jaw-closing muscles in the current experiment. A large and rapid increase in amplitude occurred during the course of the contraction, with comparatively small variations.

The large and increasing variation seen in the amplitude of the signals from the masseter and temporalis muscles probably resulted in a mean amplitude which was misleading. The mean of a rapidly-varying amplitude will be low compared to the maximum and so will not reflect the increasing power of the signal that is occuring with the onset of fatigue.

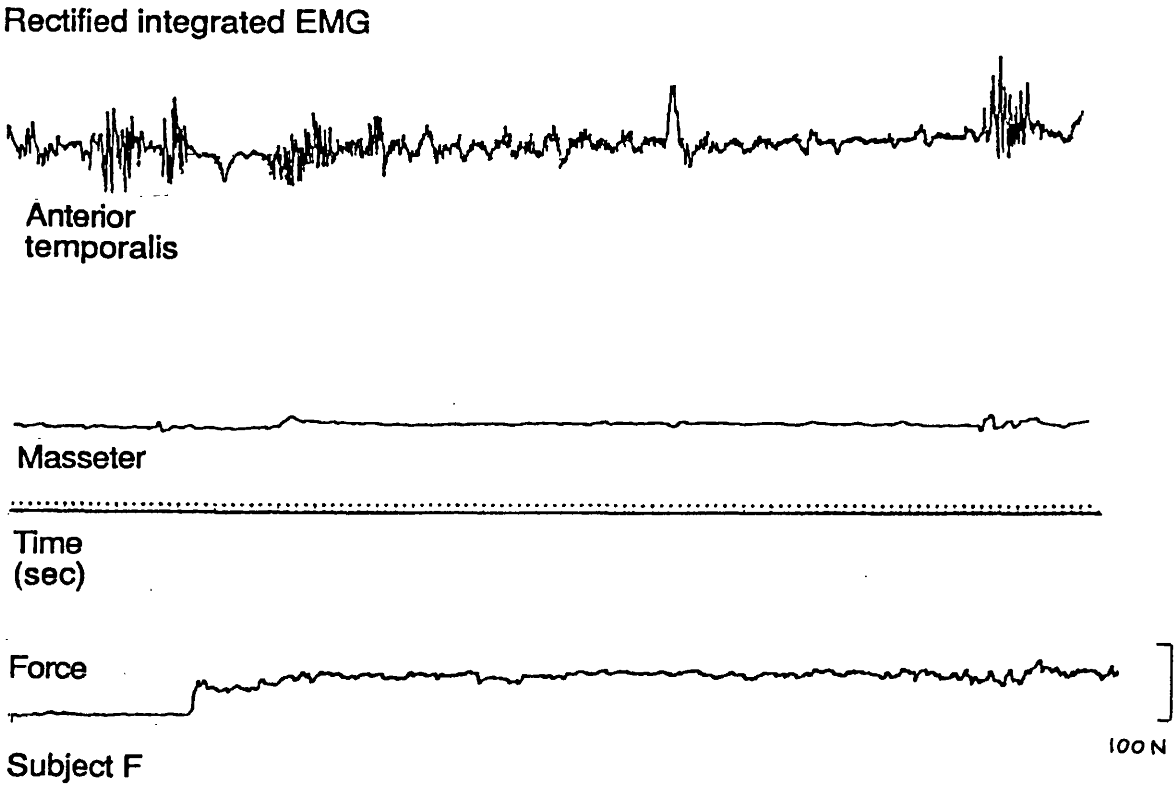


Figure 3.10 EMG and force records from one volunteer.

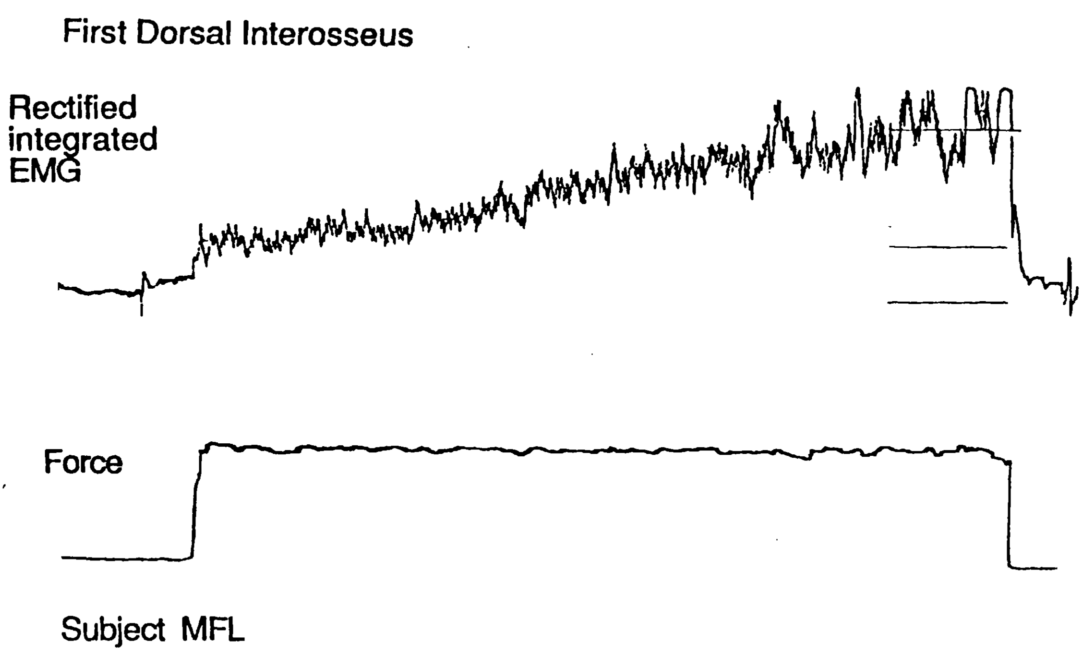


Figure 3.11 EMG and force records from the first dorsal interosseous muscle. The steady rise in rectified-integrated EMG can be seen.

A possible explanation for the decrease in EMG activity observed in two volunteers might be that a rotation of activity had occurred, perhaps to the medial pterygoid muscle. This illustrates the problem of rotation of synergist activity which occurs in the jaw-closing muscles.

The reason that the canine position was used to record force in this pilot study was that many patients with attrition show considerable wear on their canines, indicating heavy functional or parafunctional contacts. Helkimo & Ingervall (1978) found that clenching or grinding resulted in an increased bite force when measured at the incisors but not at the molars and they suggested that there could have been a training effect on the muscles at mandibular positions away from the inter-cuspal position. They also found that there was a very large range of bite forces from 30 N to 450 N at the incisors. The range in this preliminary study was 110 to 350 N in the canine area.

A difficulty with volunteers showing attrition is that the vertical overlap of the canine teeth is often nil, while it is invariably greater than this in people without attrition. This results in different degrees of opening between the two groups when closing on the bite fork. The use of the incisor position would still involve this problem, as often worn incisors are also in an edge-to-edge relationship.

The measurement of bite force is fraught with difficulties, firstly because it is difficult to be sure whether a volunteer is applying full effort or not. A theoretical solution to this would be to employ the twitch interpolation technique as described in Chapter 1 Section 1.1.2. Secondly, when using any eccentric position it is impossible to achieve the same degree of protrusion and laterotrusion in each volunteer, as this will vary according to the relative size of their skeletal bases and their occlusal patterns.

Another difficulty with bite force studies is that it is not easy to reduce the thickness of the bite fork to less than 7mm as the beams become too weak to resist the forces involved. This is a large opening and is quite a different situation to that occurring in either normal or para- function. The extrapolation from results obtained with this muscle length to the length in the normal contact position should be interpreted with caution in endurance and fatigue studies. Although the thickness of the force transducer is only 7mm, by the time any vertical overlap is taken into account the total amount of opening is a good deal more. As the jaws open there is muscle lengthening; the angle at which the muscles are applying the force changes, and changes to different degrees in different individuals. If a lateral movement is incorporated the contribution of different muscles changes and the situation becomes even more complex.

It seems clear that a very much thinner device would be helpful. The use of piezoelectric foil of the order of 60 microns thick, which is now commercially available, would be a step forward in obtaining accurate information about bite force. An investigation of a system utilizing this principle is reported in Chapter 4.

Fatigue and bite force studies both present the difficulty of a volunteer's cooperation. Some volunteers might well try harder than others to endure the discomfort of a prolonged contraction. Some might have more pain than others, while some may be able to tolerate the same level of pain better than others. It is certainly true that all of the participants in this study ceased to maintain the contraction because of pain and not specifically because of an inability of the muscles to continue. There is no obvious answer to this problem, but the number of volunteers should be as large as practically possible, and the control group should be matched for age, sex, and occlusal pattern.

Another solution might be to test pain tolerance and then to normalize the endurance time to the pain tolerance, but this adds yet another unpleasant procedure to the experimental session. On the other hand, alternative methods for quantifying fatigue, such as power spectral analysis, would be simpler and would probably be more meaningful in clinical research.

The most significant problem was that the use of the canine position introduced a laterotrusive position of the mandible; this meant that the lateral pterygoid and masseter muscles on the contralateral side had to exert a relatively large force in order to maintain this position. In several subjects pain on the contralateral side was the reason for abandoning the sustained contraction. This meant that endurance of the jaw-closing muscles was not fully tested on the ipsilateral side, which highlighted a significant complication with the use of this canine position. This phenomenon of pain on the contralateral side during unilateral biting has also been noted by other workers (Kydd, Choy & Daly, 1986).

It has been shown that resistance to fatigue varies between muscles. The phenomena which may contribute to this difference are; recruitment and firing rate differences, the proportion of slow twitch to fast twitch fibres, cross talk from adjacent muscles, and agonist/antagonist muscle interaction (Lawrence & De Luca, 1983). Agonist/antagonist muscle interaction is particularly relevant where joints must be stabilized, as may be the case with the masseter and temporalis. It is likely that this relationship takes a different form in the mandible because of the stability provided by the teeth, or contact with the force transducer, and that the contralateral lateral pterygoid muscle assumes the role of a partial antagonist to the contralateral masseter.

3.6 CONCLUSIONS

Bruxists do seem to have demonstrated increased bite force at the canines, even though the difference between the means was not statistically significant. They also seemed to be able to maintain a given force longer than non-bruxists, again even though this is not statistically significant. However, no conclusion could be drawn regarding possible differences in resistance to fatigue between the two groups.

The most significant conclusions are that the recording of bite force between the canines presents complications in jaw muscle fatigue studies; the use of bite force transducers of any thickness which is greater than a normal functional limit (probably in the region of 0.5mm) might present complications in fatigue and endurance studies.

CHAPTER 4.

AN EVALUATION OF A COMPUTERISED OCCLUSAL ANALYSIS AND FORCE MEASURING SYSTEM.

4.1 SUMMARY

A computerized system has recently become available to assist in occlusal analysis. An evaluation of this system is described, with particular emphasis on the measurement of bite force. A hand-held testing device and a NENE universal testing machine were used to apply force. A limited clinical trial was carried out on two volunteers with known occlusal interferences present. It was concluded that the system does not measure bite force accurately, but may be useful as a clinical tool if used with care.

4.2 INTRODUCTION

A computerized system, the T-Scan (Tekscan Inc., Boston, Mass., USA), has recently been developed for the analysis of the occlusal contacts of teeth (Figures 4.1 and 4.2). The first units were delivered in the USA in May 1988 and in Britain a short time later. The T-Scan is a self-contained computerised system intended to assist in occlusal analysis by providing information on the timing, magnitude and distribution of occlusal contacts. Later models may also be linked to a separate computer for data processing and storage.

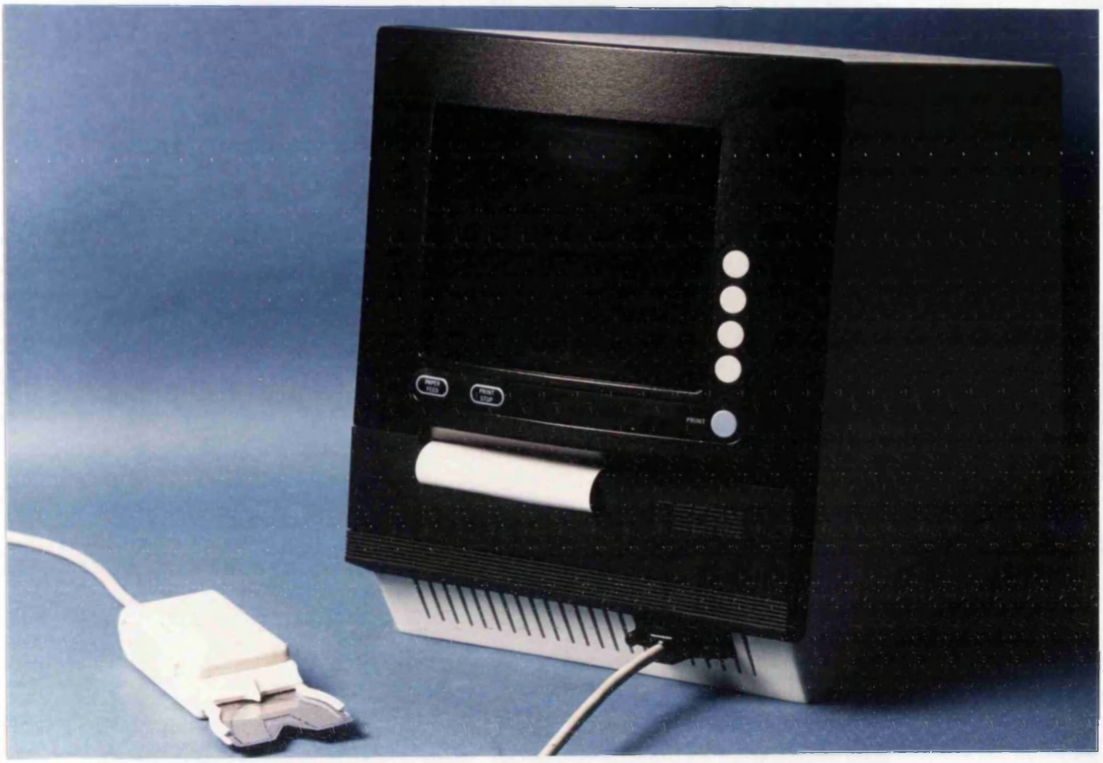


Figure 4.1 The T-Scan with sensor handle attached.

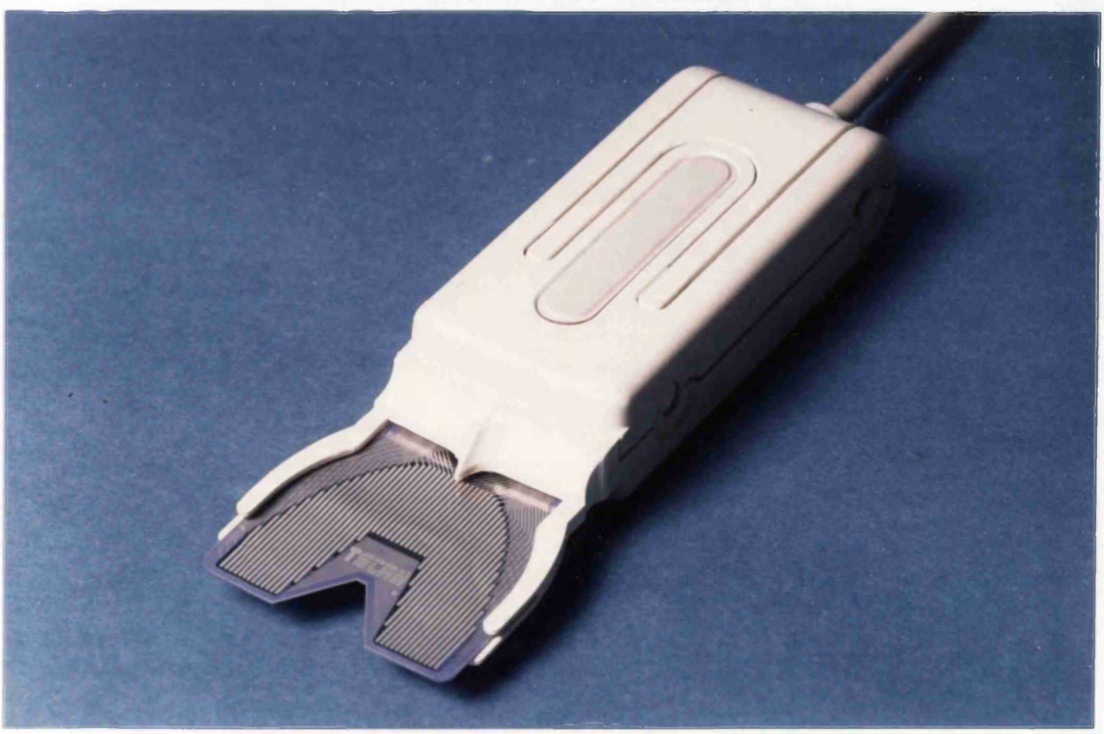


Figure 4.2 The sensor handle with sensor in place.

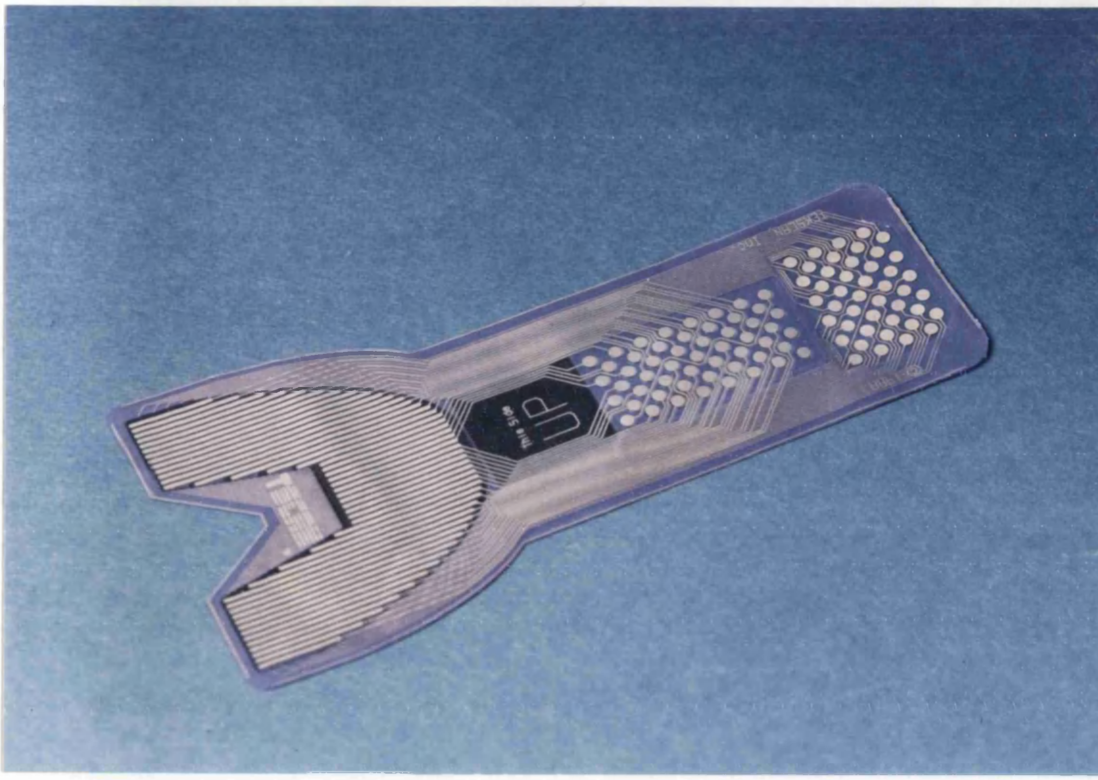


Figure 4.3 The sensor foil.

The T-Scan system consists of a piezoelectric foil sensor (Figure 4.3), sensor handle, hardware and software for recording, analysing and viewing the data. In addition to a monitor screen, there is also an integral printer to obtain hard copy.

The sensor foil is made up of several layers of conductive inks on a polyester film substrate and is held in a rigid plastic supporting handle for intra-oral use. The manufacturers state that the sensors are of the order of 60μ thick, although when measured on a digital micrometer (Digimatic Indicator, Mitutoyo, Japan) they were found to be consistently between 80μ and 90μ. Information on occlusal contacts may be obtained from the system either as a time analysis or a force analysis, and both of these will give position of contacts on an predetermined arch form. The force analysis may be obtained as either a Force Movie, which is a three-second continuous recording of force consisting of some 180 frames, or as a Force Snapshot, which is an instantaneous single record of force taken when the sensor handle button is depressed.

The claim in the manual provided with the system that "*... force information will appear on the screen as columns whose height is proportional to the contact force*" was of particular interest as this would make the system a useful research tool.

There have been five publications by the developers of the system (Maness, Chapman & Dario, 1985; Maness, 1986; Maness et al, 1987; Maness & Podoloff, 1989; Chapman, Maness & Osorio, 1991), one independent evaluation of the sensor foils (Harvey, Hatch & Osborne, 1991), and one evaluation of the sensitivity and reliability of the system in abstract form (Hsu, Gallo & Palla, 1990) at the time of writing. There had been no comprehensive evaluation of the ability of the system to measure force.

The aim of this investigation was to test the accuracy of the system when measuring force. In addition, the practicality of the system for clinical use was to be assessed. The clinical trial was very limited, being restricted to two volunteers.

4.3 METHOD

Measurement of force was tested by applying a known force to the sensor, taking a force snapshot, printing this pattern and measuring the height of the column produced on the hard copy (Figure 4.4). The column height on the hard copy was measured to an accuracy of ± 0.01 mm, using vernier callipers. This column height was then compared to the actual force applied. A total of 75 different applications of force was made, both with a hand-held device and with a universal testing machine. Single point force applications were made at 5N, 15N, 30N, and 60N. This was considered to be an appropriate range for the representation of single tooth contacts.

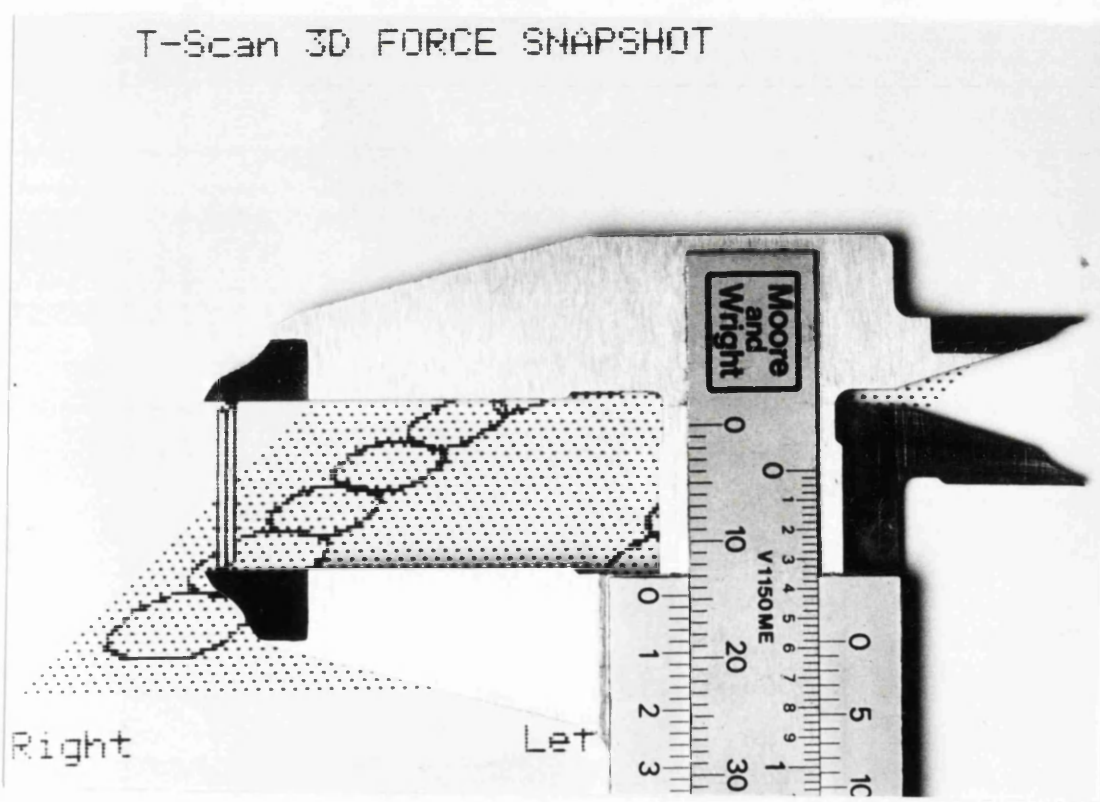


Figure 4.4 Method of measuring the column height on the print-out using calipers.

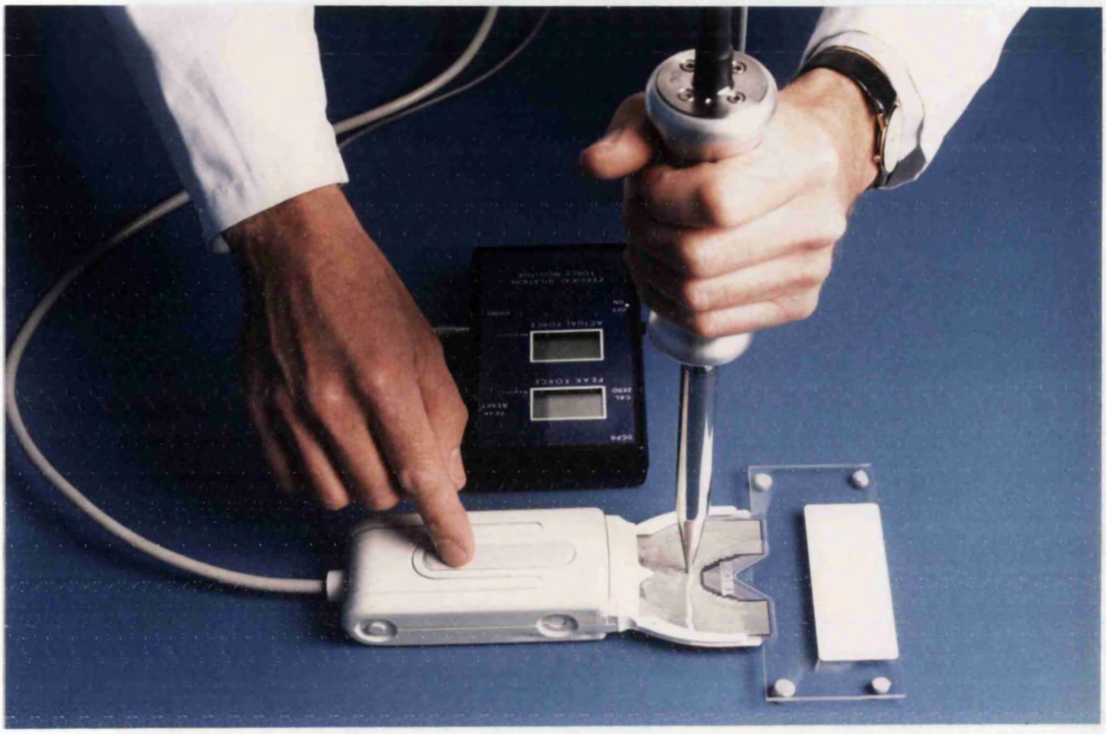


Figure 4.5 The hand-held force transducer and Perspex sensor support.

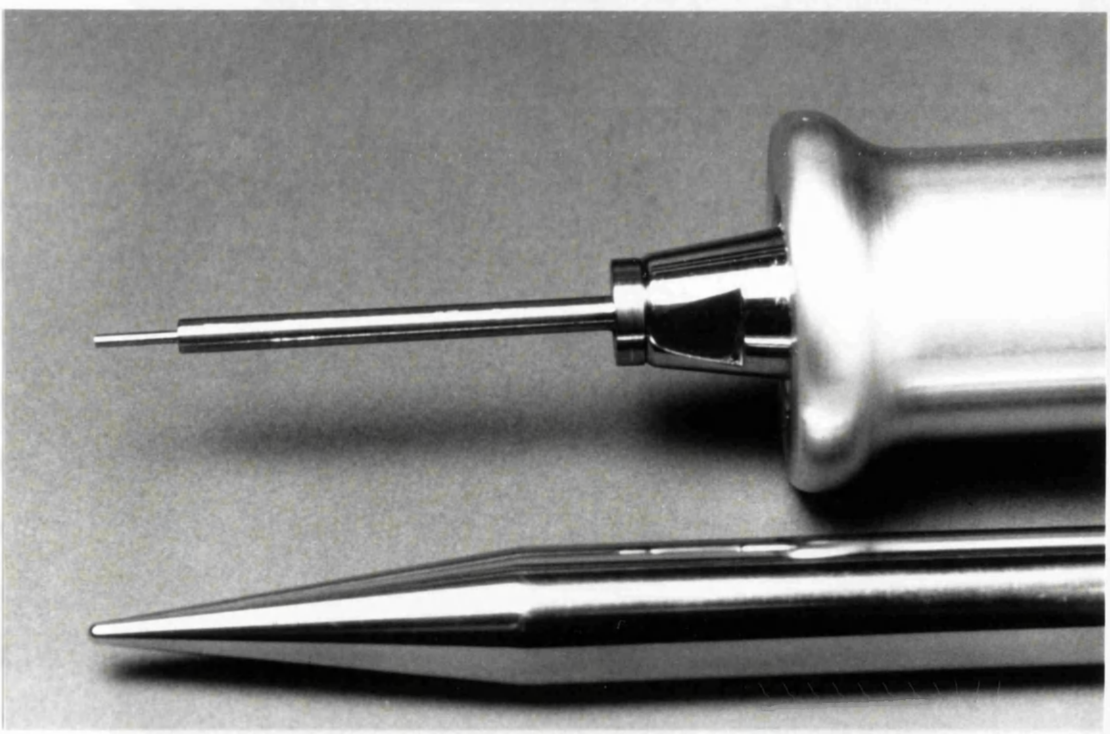


Figure 4.6 The interchangeable probes for the hand-held force transducer, with the 0.75mm diameter probe attached to the device and the 2.5mm probe below.

For the first series of force applications the hand-held device was used. This force transducer was designed and manufactured as a cervical dilator specifically for clinical research (Richardson *et al*, 1989). The essential elements of the system consisted of a central shaft supported by two silicone rubber bushes. These bushes were much stiffer in the lateral than in the axial direction. Axial displacement of the shaft was measured using a variable resistance linear displacement transducer. The accuracy of the device was 1N and was checked by the manufacturers prior to use. The device had two interchangeable probes (Figures 4.5 and 4.6). The measuring device gave a readout of the applied force in two ways, one as the applied force at any moment in time and the other as the maximum force applied since it was last reset. This capability to store the maximum applied force was useful as it meant that the actual applied force could be read more precisely because this remained on the screen after the force was released, and remained until the reset button was depressed.

One of the two probes had an end radius of 0.75mm, the other an end radius of 2.5mm. It was considered that these dimensions approximated the cusp size of a tooth reasonably well. The sensor was supported on a Perspex sheet while the force was applied, so in fact the situation was that of a round-ended probe applied to a flat Perspex sheet with the sensor foil interposed (Figure 4.5). A total of thirty force applications was made with the 2.5 mm probe. These were applied at various positions on the same sensor for twelve applications. Subsequently a new sensor was used for each new twelve force applications. A further twelve applications were made using the 0.75 mm probe, making a total of forty two applications with the hand-held force transducer.

The 0.75 mm probe was then mounted in a NENE universal testing machine (Nene Instruments Ltd., Wellingborough, Northamptonshire, England) and the foil placed on the platform of the machine (Figure 4.7). Twenty four force applications were made at various points on two different sensors (Figure 4.8). Then three applications of the same force were made in exactly the same place on a new sensor in order to test the reproducibility under repeated contacts. Two different force levels were used. The next step was to record a force movie while a known force was maintained for the duration of the movie, this being repeated at three different force levels.

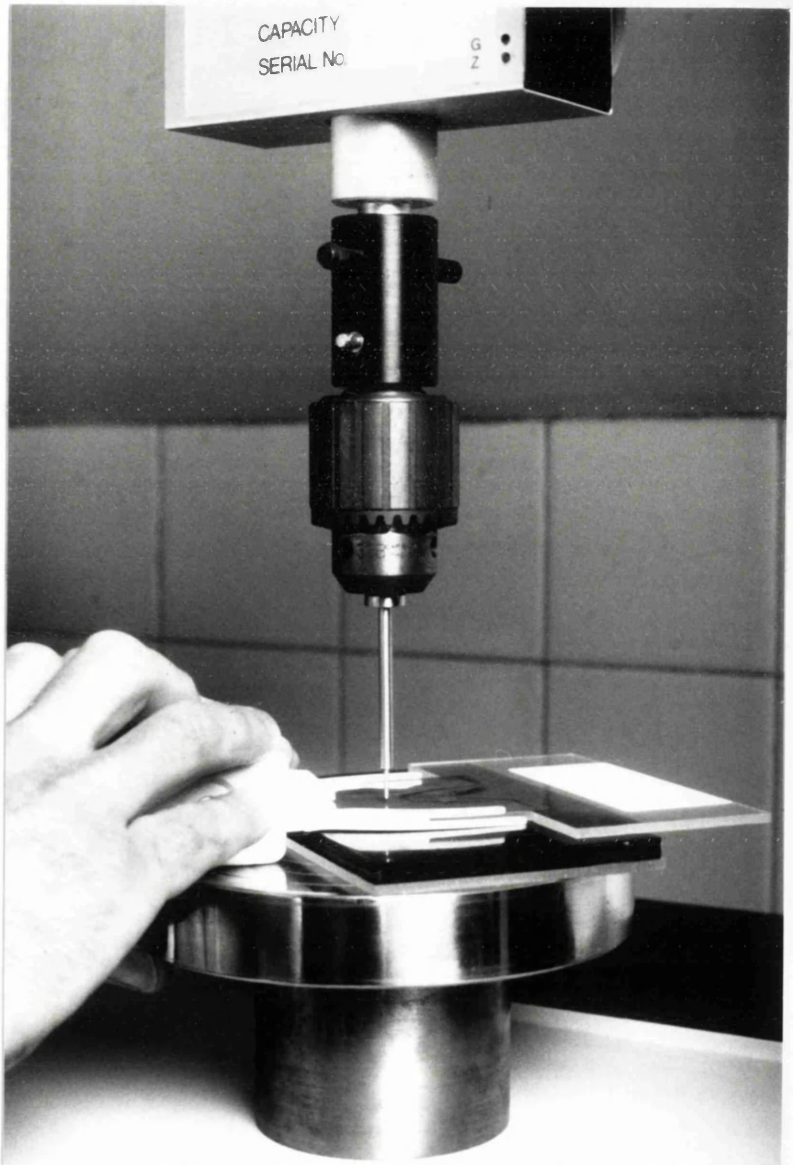


Figure 4.7 The 0.75mm probe attached to the NENE universal testing machine.

Ni NENEsoft

TEST REPORT: SAMPLE 2

Load at Peak	0.102	kN
Time at Peak	0.169	min
Load at End	0.000	kN
Time at End	0.373	min
Load at 0min	---	

0.169 0.000 0.373

Product		TEST1
Sample ID		3
Date		
Operator		SELF
Test Speed	(mm/min)	5.00

Load vs. Time (TM)

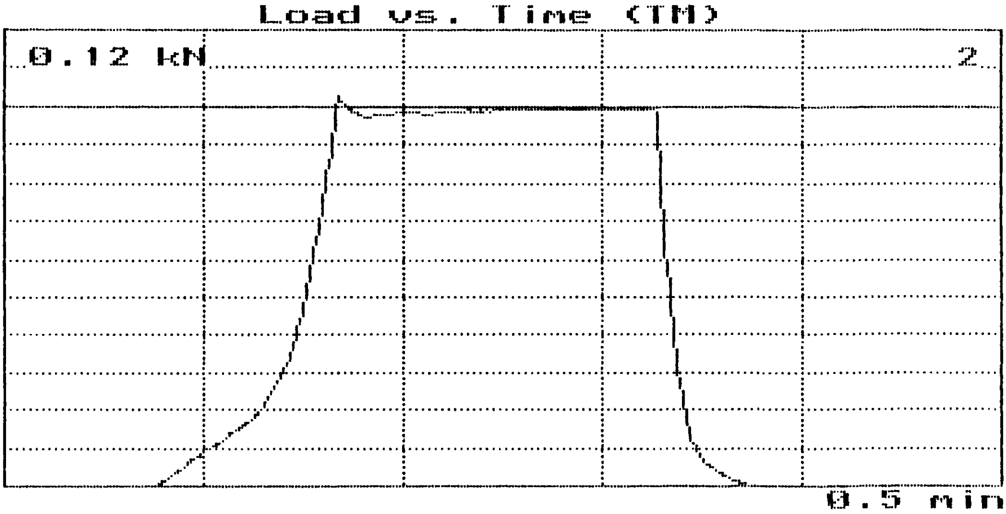


Figure 4.8 Print-out from the NENE testing machine to show the pattern and timing of force application.

For the final part of the laboratory study, upper and lower fully dentate acrylic resin casts were mounted in an articulator (Dentatus ARD) and placed in the testing machine (Figure 4.9). Twelve force applications were made, at four different force levels, using a new sensor for each application. The range of forces applied was from 98N to 299N, representing the sort of forces achieved in light to moderately heavy clenching with a full complement of teeth.

To assess the practicality of the system to evaluate tooth contact, a clinical trial on two volunteers was undertaken. Volunteers who were known to have non-working side and protrusive interferences were obtained, and the ability of the machine to detect these interferences was evaluated. These interferences were demonstrated with marking paper and then both upper and lower arches were photographed from an occlusal view. The T-Scan was subsequently used to obtain a force movie and the pattern of interferences detected was compared with the pattern on the photographs.

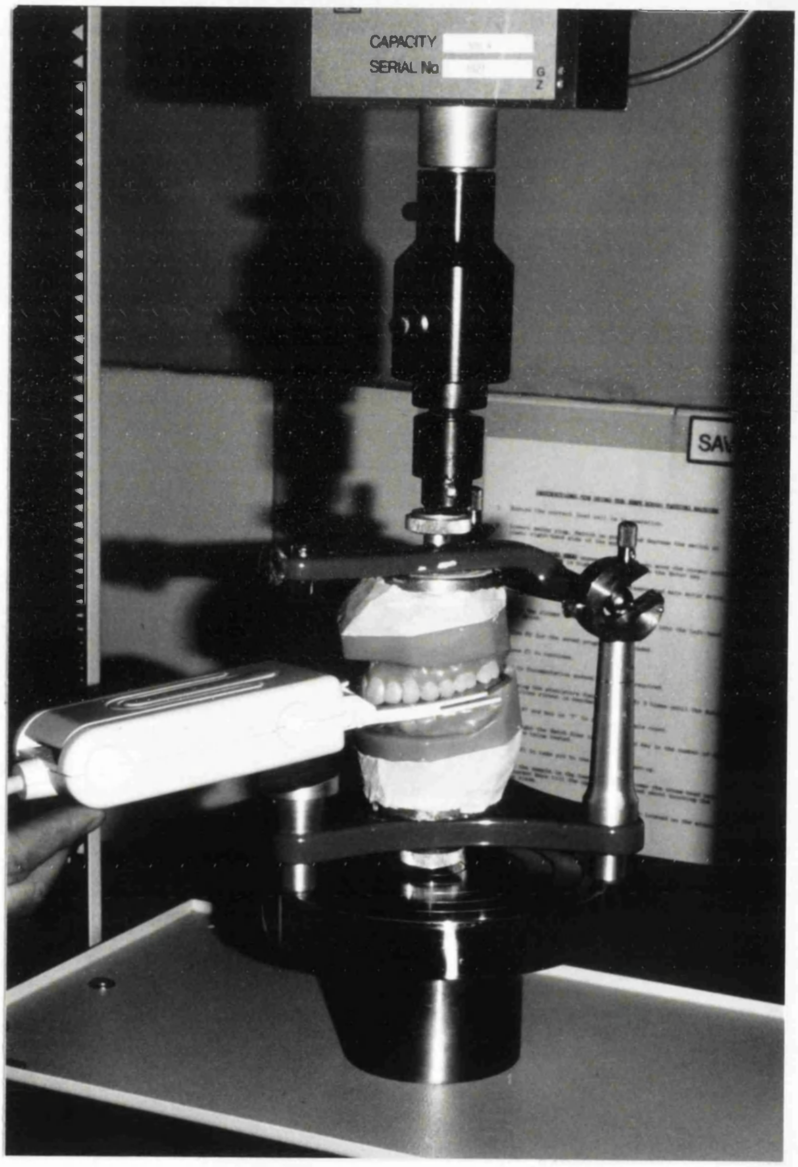


Figure 4.9 Acrylic resin casts mounted in an articulator, in place in the universal testing machine. The sensor handle, with sensor, may be seen between the teeth.

4.4 RESULTS

The results of the single point force applications show that for a given force there were columns of widely differing height produced by the T-Scan (Tables 4.1 - 4.7). When a linear regression analysis was applied to all the data in Tables 4.1 - 4.5 and Table 4.7, the correlation coefficient was 0.472, giving an r^2 value of 0.222. This meant that only 22.2% of the variation in the measured column height was explained by the estimate of the force applied. The degree of association between the two values was very poor indeed. The linear estimator of the column height is:

$$\text{Height (mm)} = 4.84 + 0.102 \text{ Applied Force (N)}$$

However, this is of little predictive value. For any single force application there was a large variability in the column height (Figure 4.10). In clinical use it is obviously desirable to obtain a consistent column height for any one force application.

Applied Force (N)	T-Scan Column Height (mm)
5	3.20
5	2.88
6	3.74
6	6.10
17	6.92
19	14.68
15	10.44
29	16.70
29	6.12
30	15.38
62	9.28
60	16.50

Table 4.1 Force applied with hand-held force transducer, using 2.5mm probe.

Applied Force (N)	T-Scan Column Height (mm)
5	6.12
5	4.00
5	2.96
16	5.52
16	11.38
15	5.74
28	11.46
30	19.80
30	7.38
60	8.94
60	16.62
58	16.48

Table 4.2 Force applied with hand-held force transducer with 2.5 mm probe attached.

Applied Force (N)	T-Scan Column Height (mm)
3	3.16
4	5.04
3	3.24
10	7.14
11	8.00
10	5.10

Table 4.3 Force applied with hand-held force transducer.

Applied Force (N)	T-Scan Column Height (mm)
5	3.06
5	4.61
5	4.11
15	2.74
16	6.02
16	6.94
31	7.85
31	8.84
31	8.18
61	3.12
61	2.67
59	6.82

Table 4.4 Force applied with hand-held force transducer, using 0.75 mm probe.

Applied Force (N)	T-Scan Column Height (mm)
6	2.76
6	5.30
6	3.96
15.3	2.82
15.8	5.88
15.8	6.00
30.3	4.86
30.3	10.32
30.3	3.14
59.2	13.52
59.8	4.22
59.4	9.30

Table 4.5 Force applied with NENE universal testing machine using 0.75 mm probe.

Applied Force (N)	T-Scan Column Height (mm)
5.3 - 5.4	3.00 (no variation)
10.0 - 11.0	5.12 (no variation)
14.6 - 15.00	8.40 - 9.12 (one pixel variation)

Table 4.6 Force applied with NENE universal testing machine using 0.75 mm probe. The T-Scan was recording in Force Movie mode.

Applied Force (N)	T-Scan Column Height (mm)
5.9	3.88
5.9	6.18
5.9	5.22
11.0	8.80
11.0	3.00
11.0	6.12

Table 4.7 Force applied with NENE universal testing machine using 0.75 mm probe. The T-Scan was recording Force Snapshots. Three applications of the same force were made in the same position on the sensor.

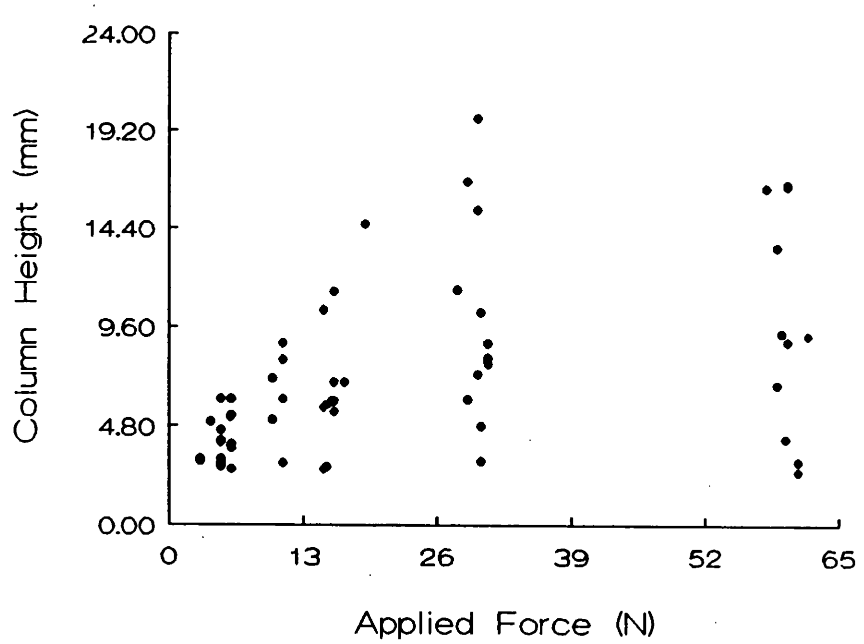


Figure 4.10 The data from Tables 4.1 - 4.5 and 4.7 showing the distribution of 60 measurements of column height produced by different applied forces. The wide variation can be clearly seen, even at low force levels.

Using the hand-held force transducer with a 2.5mm probe again produced a wide variation in column height for any given applied force (Tables 4.1, 4.2 and 4.3). A linear regression analysis of the data in Table 4.1 produced a correlation coefficient of 0.0596 with an r^2 value of 0.355; for the data in Table 4.2 the correlation coefficient was 0.674 with an r^2 value of 0.455; for Table 4.3 the correlation coefficient was 0.869 with an r^2 value of 0.755. Once again the variability was very wide. The results were similar when the 0.75 mm probe was used (Table 4.4), with a correlation coefficient of 0.027 and an r^2 value of 0.001.

The results from the NENE testing machine showed a similar picture to the results obtained with the hand-held force transducer (Table 4.5). The correlation coefficient was 0.585 with an r^2 value of 0.342.

When a force movie was recorded while maintaining a constant force by the NENE testing machine, there was no variation in column height (Table 4.6). This indicated that there was no detectable drift in the system and that the force movie mode was operating accurately with the information that it was detecting. In one of the three tests there was one pixel variation of the column height, which was only to be expected in such a system, and measurement of this variation showed the resolution of the hard copy to be 0.72 mm.

Three repetitions of the same force to exactly the same position on the foil produced columns of widely varying height (Table 4.7), although it must be said that it was possible that some very slight degree of movement of the sensor might have occurred. The correlation coefficient was 0.237 with an r^2 value of 0.056.

The results of the test with the acrylic casts on an articulator in the NENE testing machine showed an increasing number of occlusal contacts detected as the applied force increased. However, the T-Scan columns were of varying height and there was a wide variation in relationship to the applied force (Table 4.8). The correlation coefficient was 0.788, giving an r^2 value of 0.621.

Applied Force (N)	No. of Contacts	Height of Tallest T-Scan Column (mm)
98	2	3.68
98	2	2.68
98	5	2.94
199	10	12.32
199	5	3.72
199	11	8.88
249	12	8.88
249	11	12.34
249	7	8.92
299	13	11.16
299	13	9.34
299	13	10.00

Table 4.8 Acrylic resin models on articulator, mounted in the NENE universal testing machine. A new sensor was used for each of these force applications.

The results of the clinical tests showed that the force movie was useful for detecting occlusal interferences (Figures 4.11-4.14).

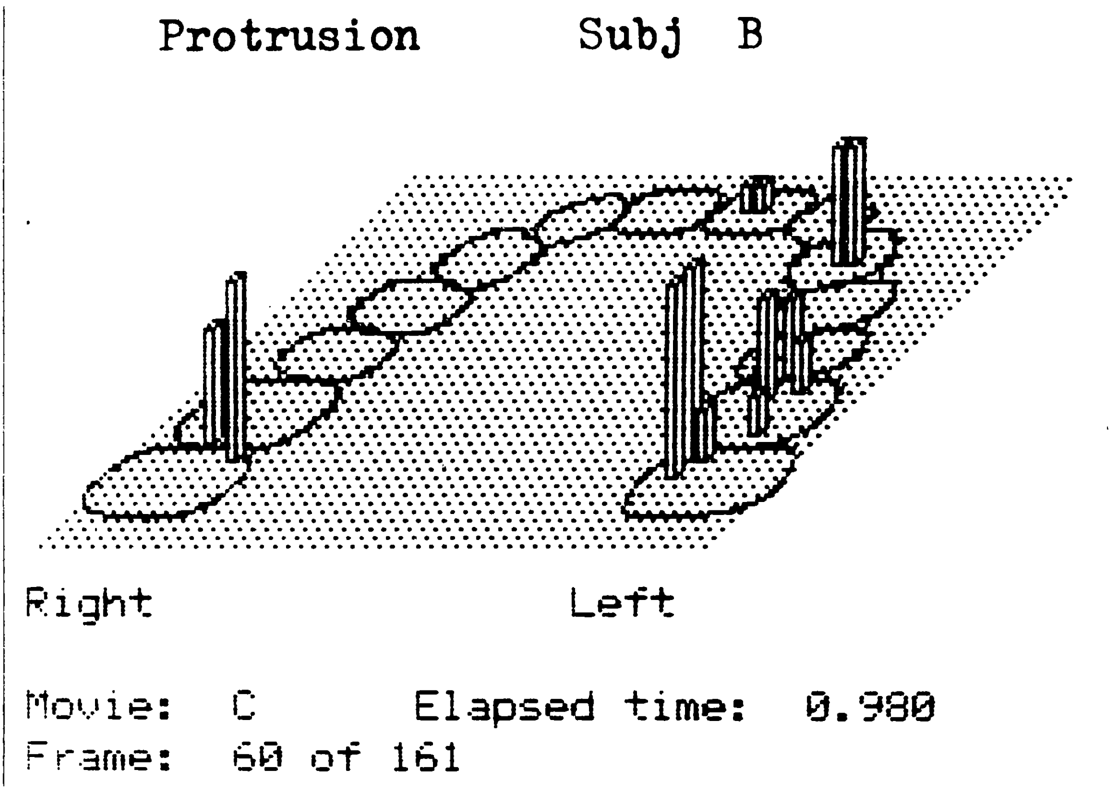


Figure 4.11 A print-out of frame number 60 of a 161-frame force movie, taken while the volunteer made a protrusive movement.

Figure 4.12 Subject B showing articulating paper marks produced by a protrusive movement. The interfering contacts on the palatal cusps of the first molars may be seen. The contact on 1.1 could be seen in a later frame of the force movie, as it had not occurred by frame 60.

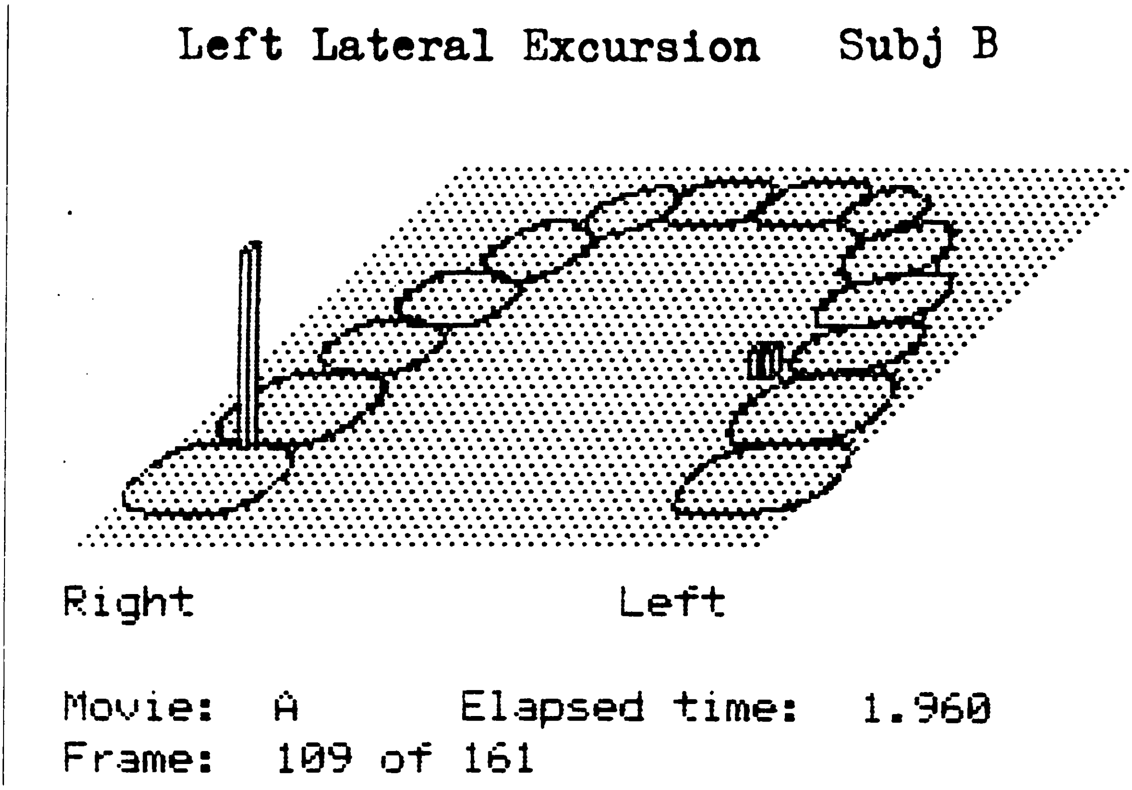


Figure 4.13 A print-out of frame number 109 of a 161-frame force movie of Subject B making a left lateral excursion.

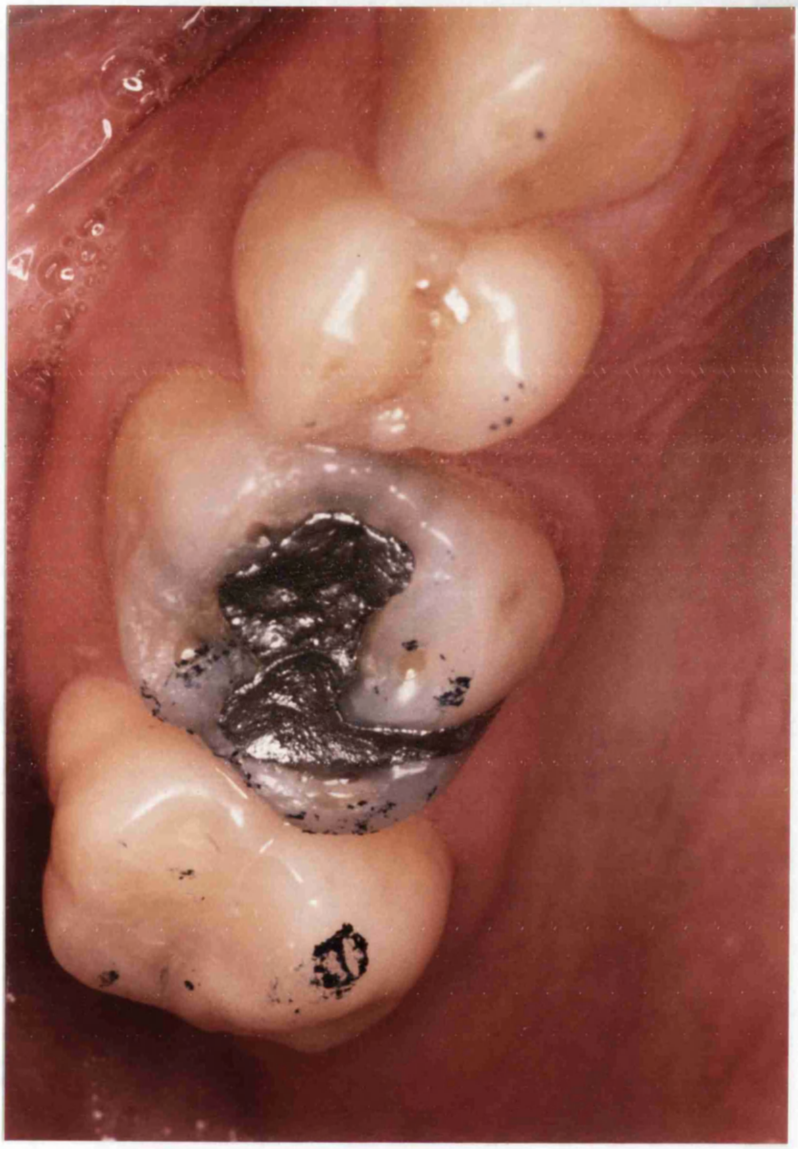


Figure 4.14 Articulating paper marking of the non-working side contact on the palatal cusp of 1.7 for volunteer B.

4.5 DISCUSSION

The manufacturers claim that a force record may be made for a patient and this can be kept as a record of occlusal contacts and compared with the situation at a subsequent visit, or after occlusal adjustment. In view of the fact that a given tooth contact force can produce a different column height each time it is recorded, it is clear that the column heights are largely irrelevant and simply serve to indicate the presence of a contact and not force of contact. Also, it can be seen from Table 4.8 that the number of contacts recorded for a given force application was not consistent, and there was not a consistent relativity between forces applied at different areas when viewed in a single frame.

The designer of the system explained that the sensor is constructed with conductive inks in a grid pattern (William Maness - verbal communication). In order to achieve a consistent force/resistance curve, i.e. a consistent force/ column height relationship, the force must always be applied in the centre of each grid. Every sensor foil is tested in this way before it leaves the factory. The manufacturers use a mechanical robot to apply force to ten different points around the sensor, each point being in the centre of a grid. The obvious problem with this, of course, is that as there are approximately 1500 grids on a foil it is clearly not possible to achieve this precise positioning clinically. The manufacturer explained that there was a compromise between accuracy of position measurement, which obviously requires a large number of grids, and accuracy of force measurement, which requires the smallest number of grids.

The force movie was shown to be useful for detecting occlusal interferences. It was quick, relatively easy to use and accurate, within the obvious limits of the system, in the two volunteers tested. It should be pointed out, however, that the volunteers were both dentists and were able to make unguided lateral and protrusive excursions. When guided movements are required it becomes very much more difficult, as a chairside assistant is required to hold the handpiece and press the record button at precisely the right moment.

A study has been published very recently which lends support to the results of this work (Hsu, Palla & Gallo, 1992). It was found that the sensors did not have the same sensitivity throughout the surface and that the T-Scan always recorded fewer contacts than were actually present.

4.6 CONCLUSIONS

The T-Scan was not accurate at measuring force, either with two different force applicator sizes or at varying force levels. However, the device did provide a constant column height to a constant sustained force when recording in the force movie mode.

When acrylic resin casts of a complete dentition were applied to different sensors and loaded with the same force, different numbers of contacts were recorded. In the two clinical evaluations the occurrence of non-working side contacts was demonstrated clearly by the T-Scan.

In view of the above findings it must be concluded that:

- it is not valid to directly compare two different T-Scan recordings of occlusal patterns of the same patient.

- the T-Scan does not measure force accurately.

- the T-Scan may be useful for detecting the presence, but not relative force, of tooth contacts.

CHAPTER 5.

FATIGUE AND EMG CHANGES IN THE MASSETER AND TEMPORALIS MUSCLES DURING SUSTAINED CONTRACTIONS IN HEALTHY VOLUNTEERS

5.1 SUMMARY

Local muscle fatigue was investigated in the anterior temporalis and masseter muscles during sustained isometric contractions. Each volunteer's subjective perception of fatigue or pain was recorded at intervals during the sustained contractions, and this level was then compared to objective measures of fatigue. These objective measures included shift in median frequency of the power spectrum of the surface-detected EMG signal, and change in signal amplitude.

This relationship was investigated while closing on a bite force transducer placed between the second premolar and first molar teeth unilaterally, and also while clenching with the teeth together without the bite force transducer.

It was found that the subjective perception of fatigue, as measured on a visual analogue scale (VAS), had a nearly linear relationship with time, and that the relationship between the VAS score and median frequency shift was rather closer than the relationship with amplitude change.

5.2 INTRODUCTION

It is possible to conduct fatigue studies with the use of a bite force transducer and hence to monitor the collective force output of the jaw-closing muscles. It may also be done with the teeth clenched together, in which case contraction levels are monitored by the EMG amplitude of one of the jaw-closing muscles. In both configurations the contractions are isometric, but a sustained contraction without a bite force transducer will not be of constant force if the EMG amplitude is kept constant.

It became clear after the experiment reported in Chapter 3 that fatigue should be measured using as many parameters as possible, particularly shift in median frequency of the power spectrum. Power spectrum analysis has been shown to provide a sensitive indicator of localized muscle fatigue (see Section 1.4.3). It was also clear that these parameters should be measured from previously-recorded data rather than the direct measurement of EMG amplitude from a chart-recorder.

The evaluation of the T-Scan system, reported in Chapter 4, showed that the use of piezoelectric foil was no viable alternative to the bite force transducer.

In view of the variability in the measurement of EMG amplitude in Chapter 3, and the fact that no change was demonstrated in muscles that were clearly fatigued, a further study was planned. The aims of the investigation were to assess the volunteer's perceived state of fatigue in the jaw-closing muscles during sustained isometric contractions and relate this to changes in EMG amplitude and frequency shift in individual muscles. The relationship between amplitude and frequency shift and the subjective perception of fatigue were to be assessed both with and without the use of a bite force transducer.

5.3 METHOD

Local Dental Ethics Committee approval of the experimental protocol was obtained and eight informed healthy volunteers, with no symptoms or signs of craniomandibular disorders, were asked to clench on a bite force transducer several times to obtain their maximum voluntary contraction force (MVC). The bite force transducer was placed between the second premolar and first molar teeth on the preferred chewing side. The volunteers were then asked to maintain 50% MVC for as long as possible, using force displayed on an oscilloscope screen for visual feedback. During the course of this sustained contraction they were presented with a fresh visual analogue scale (VAS) at approximately fifteen second intervals and asked to mark the scale while maintaining the contraction. It is important to note that a fresh, unmarked, scale was presented to the volunteer each time and so they had no idea of where their previous mark was placed. The volunteers were also asked to record their overall state of jaw fatigue, and not to attempt to be specific as to side or muscle.

After resting for five minutes, the experiment was repeated without the use of the bite force transducer. For this part of the experiment visual feedback was provided by the EMG activity of the right masseter muscle, the signal being rectified and integrated with a time constant of 100 msec. and displayed on an oscilloscope screen.

EMG was recorded with 9 mm diameter silver/silver-chloride surface disc electrodes (SLE Ltd, Croydon CRO 2SQ, U.K.) from the masseter muscles bilaterally, and with intra-dermal platinum hook electrodes (Grass Instrument Company, Quincy, MA 02169, U.S.A.) from the anterior fibres of the temporalis muscles, also bilaterally. The signals were amplified X2,000 and were recorded on video tape, along with the force record, via a multiplexing and digitising adapter (PCM-8, Medical Systems Corp., Greenvale, NY 11548, U.S.A.) for off-line analysis (see Chapter 2 for details).

The signals were subsequently played back through the adapter, band-pass filtered with cut-off frequencies of 8 and 800 Hz, and then RMS-integrated with a time constant of 200 ms. The RMS value was used as this is considered to give the best estimate of the power of the signal (Basmajian & De Luca, 1985a). Hard copy was obtained through a chart recorder and the average signal amplitude was measured manually during the four second time interval where a VAS score had been recorded.

In order to obtain the power spectra the original signal was again played back through the video adapter to obtain analogue outputs (for details see Chapter 2) and digitised at a rate of 1660 Hz to a personal computer. At the time that each VAS score was recorded, four seconds of data encompassing this point were sampled and 256-point Fast Fourier transforms carried out using C.E.D.'s Spike 2 software (Cambridge Electronic Design, Cambridge, U.K.). The median power frequency was calculated for each four-second sample. The median frequency was chosen as the parameter to describe the power spectrum as it is said to be less sensitive to noise than other parameters which are commonly used (Stulen & De Luca, 1981).

5.4 RESULTS

When clenching on the bite force transducer at 50% MVC there was a large inter-individual variation in the time that the contraction could be sustained (endurance time), from 59 seconds to 220 seconds (Figure 5.1). The endurance time was considerably longer when clenching with the teeth together (without the bite force transducer) than when clenching on the bite force transducer.

The MVC varied four-fold between volunteers (Figure 5.2). The volunteers' ability to accurately maintain 50% MVC during the course of the sustained contraction also varied, but with most able to hold 50% ±10%.

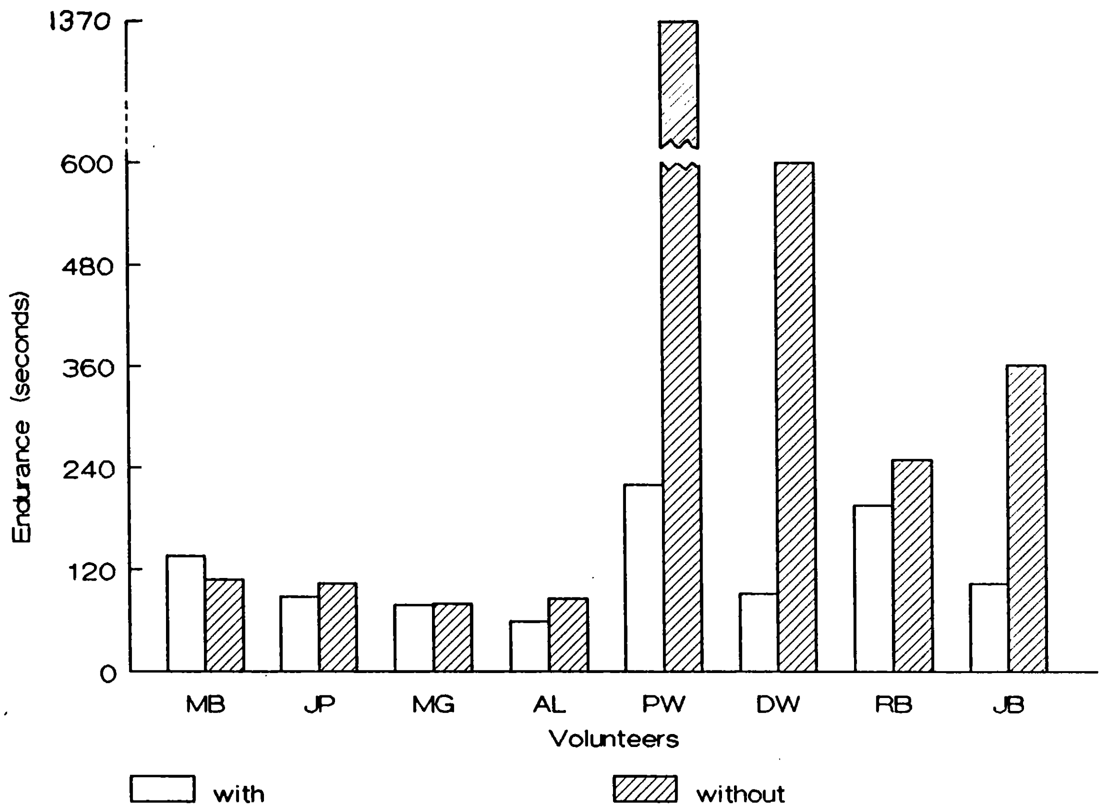


Figure 5.1 The endurance time for each volunteer, both with and without the bite force transducer. The endurance time of volunteer PW was 1370 seconds, but this was not depicted in full on the bar chart as it would have had the effect of compressing the visual impact of the remaining values.

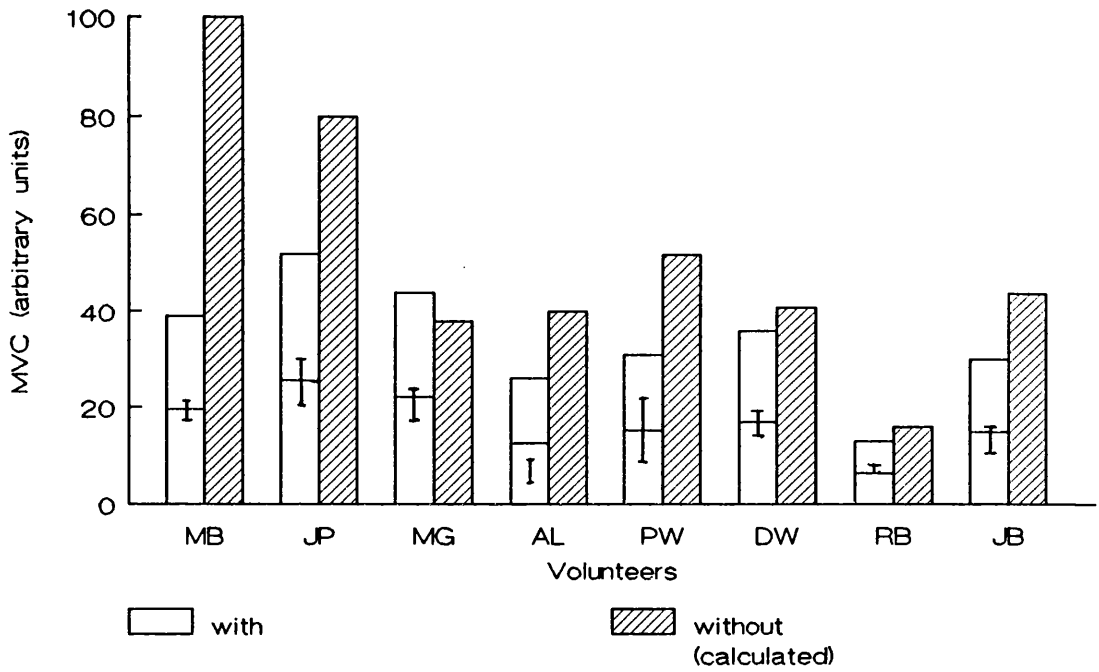


Figure 5.2 The MVC is shown for each volunteer when closing on the bite force transducer. A line across each bar has been drawn at the 50% MVC level, and error bars represent each volunteer's variation when attempting to sustain a contraction at 50% MVC. The calculated value of the MVC without the bite force transducer is also shown for each volunteer.

The MVC without the bite force transducer (i.e. with the teeth clenched together) was estimated by adding the EMG amplitude from the four muscles at a maximum clench without the force transducer, then with the force transducer, and as the MVC_{with} was known then the $MVC_{without}$ could be estimated by simple calculation. This calculation was valid because the electrodes were not moved and the amplification of the signal was kept the same for each channel in both configurations, i.e. both with and without the force transducer. The effects of sweating on signal amplitude should be considered, and these will be discussed in Section 5.5. Clearly the amplification could be altered between channels and between volunteers.

It can be seen from Figure 5.2 that the $MVC_{without}$ was higher than MVC_{with} in all cases except one (MG). The difference between the mean MVC values was 47%.

When the curves were plotted for VAS versus time for each volunteer, it can be seen that they all produced relatively straight lines with few outlying values (Figures 5.3 and 5.4).

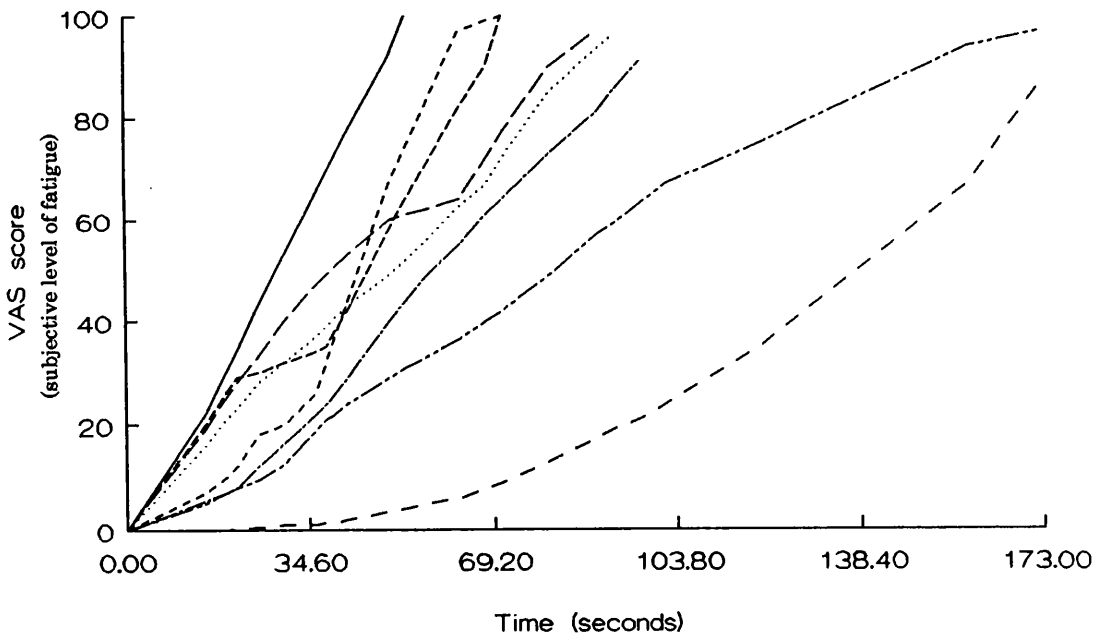


Figure 5.3 The VAS score versus time for each volunteer when clenching on the bite force transducer.

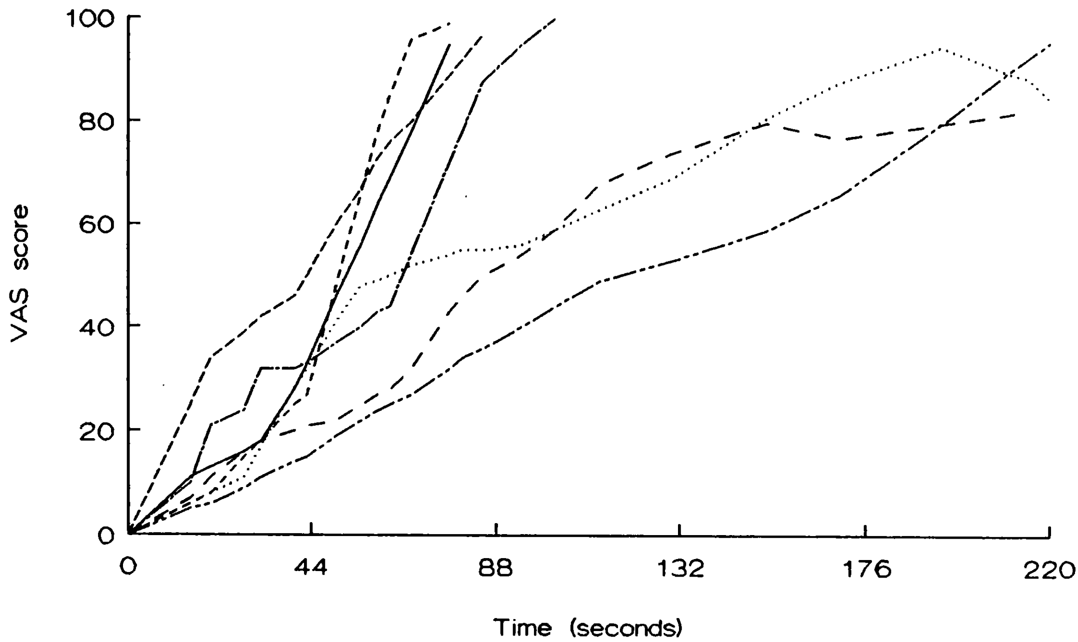


Figure 5.4 The VAS score versus time for each volunteer when clenching without the bite force transducer.

A linear regression analysis was performed (MINITAB 7 software) and the correlation coefficients for the regression of VAS on time for each volunteer (both with and without the bite force transducer) were very high, showing that most of the values were very close to the regression line (Table 5.1). In all but two cases the correlation coefficients were above 0.954 and the r^2 values above 0.919. As these r^2 values demonstrated, time was an almost perfect predictor of the VAS score.

Volunteer	DW	RB	MG	JP	PW	MB	AL	JB
Corr. coeff. (with)	0.998	0.994	0.968	0.982	0.954	0.992	0.998	0.990
r^2 (%) (with)	99.6	98.8	93.7	96.4	91.9	98.4	99.7	98.1
Corr. coeff. (without)	0.747	0.997	0.958	0.993	*	0.981	0.970	0.870
r^2 (%)	55.7	99.4	91.7	98.6	*	96.2	94.1	75.7

Table 5.1. Correlations between VAS and Time for all volunteers when clenching with the bite force transducer, and then without. * represents no data.

The EMG amplitude was measured at the beginning of each sustained contraction, and also at each 4-second period within a contraction corresponding to a VAS score. The amplitude was then normalised to the MVC level for each subject. Similarly, the median frequency of the power spectrum of a 4-second period of EMG at the beginning of a contraction, and then 4-second periods corresponding to VAS scores, were obtained (Figures 5.5 - 5.8). The percentage changes for each period of time were calculated and are presented in Tables 5.2 and 5.3. The negative values indicate a reduction in the case of amplitude, or an increase in the case of frequency, i.e. the change is in the direction opposite to that expected for an actively contracting muscle.

To determine whether there was any significant difference by muscle or by volunteer, with and without the bite force transducer, a repeated measures analysis of variance was carried out using the SPSS/PC+ statistical analysis software (Tables 5.4 and 5.5). These showed no significant difference between the change in amplitude with and without the bite force transducer, or between the change in frequency with and without the bite force transducer. There were no significant interaction effects between muscle groups or volunteers on the amplitude changes with or without the bite force transducer (Table 5.4). However, there were significant differences between muscle groups and volunteers in frequency change with and without the bite force transducer (Table 5.5), but these masked any overall effect of the presence or absence of the bite force transducer. There were unusual results from two muscle groups for one volunteer and these aberrant values are responsible for the findings of significant differences between muscle groups or subjects. They manifest their effect because of the small sample size, and with a larger sample size such results would be unlikely to be significant.

The VAS scores were correlated with amplitude and also with median frequency, both with the bite force transducer and without (Tables 5.6 and 5.7). It can be seen that there is a very high correlation between these parameters, particularly median frequency, and VAS scores for some muscles. Chi-squared tests were performed to determine whether there was any significant difference in the distribution within the correlation categories between VAS and amplitude, and VAS and median frequency. In the case of the sustained contraction on the bite force transducer the Chi-squared value was 0.593 with 2 degrees of freedom, $p > 0.5$ i.e. no significant difference. In the case of the sustained clench without the bite force transducer, the Chi-squared value was 6.975 with 2 degrees of freedom, $0.05 > p > 0.02$, i.e. a significant difference.

The median frequencies at the beginning of the contractions, both with the bite force transducer and without, may be seen in Table 5.8. These values were higher for all muscles at the beginning of the sustained contraction without the bite force transducer than with the bite force transducer.

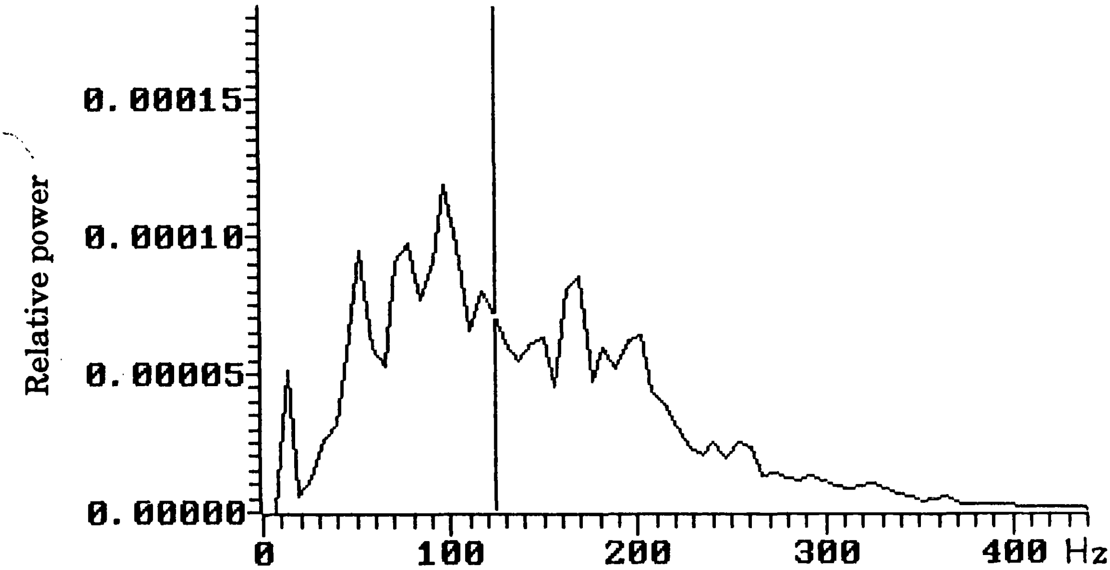


Figure 5.5 The power spectrum from the left masseter muscle of volunteer MG for the first four seconds of a sustained contraction on the bite force transducer.

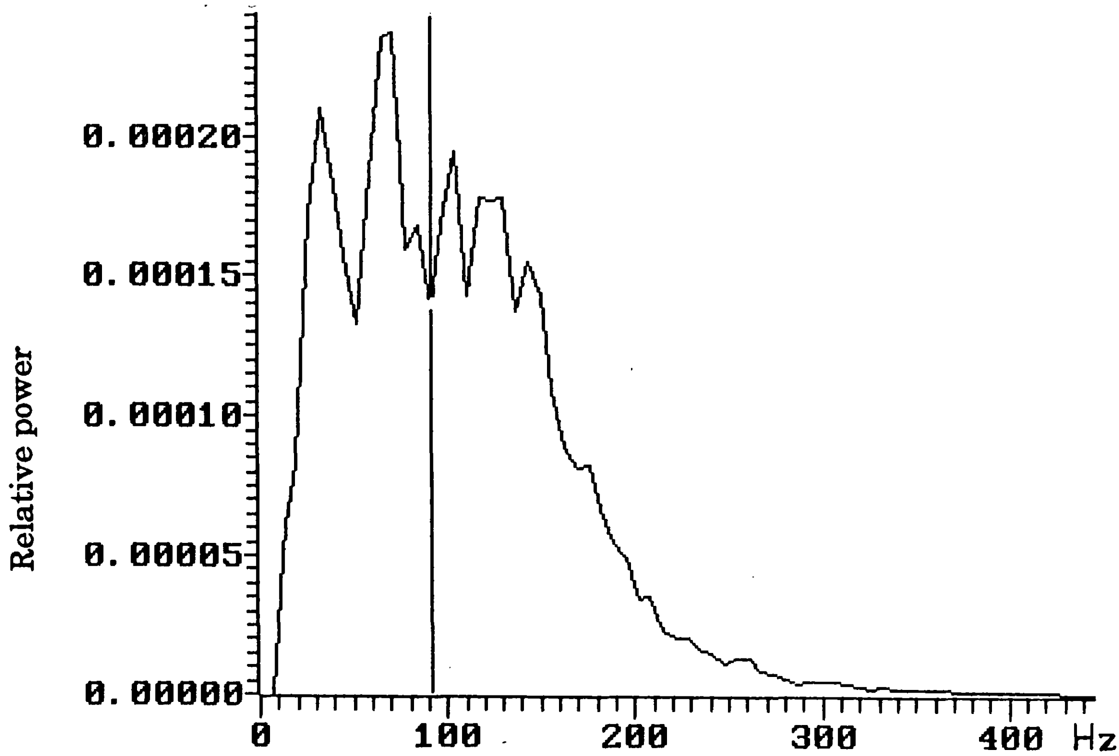


Figure 5.6 The power spectrum from the left masseter muscle of volunteer MG for the last four seconds (VAS score was 100) of a sustained contraction on the bite force transducer.

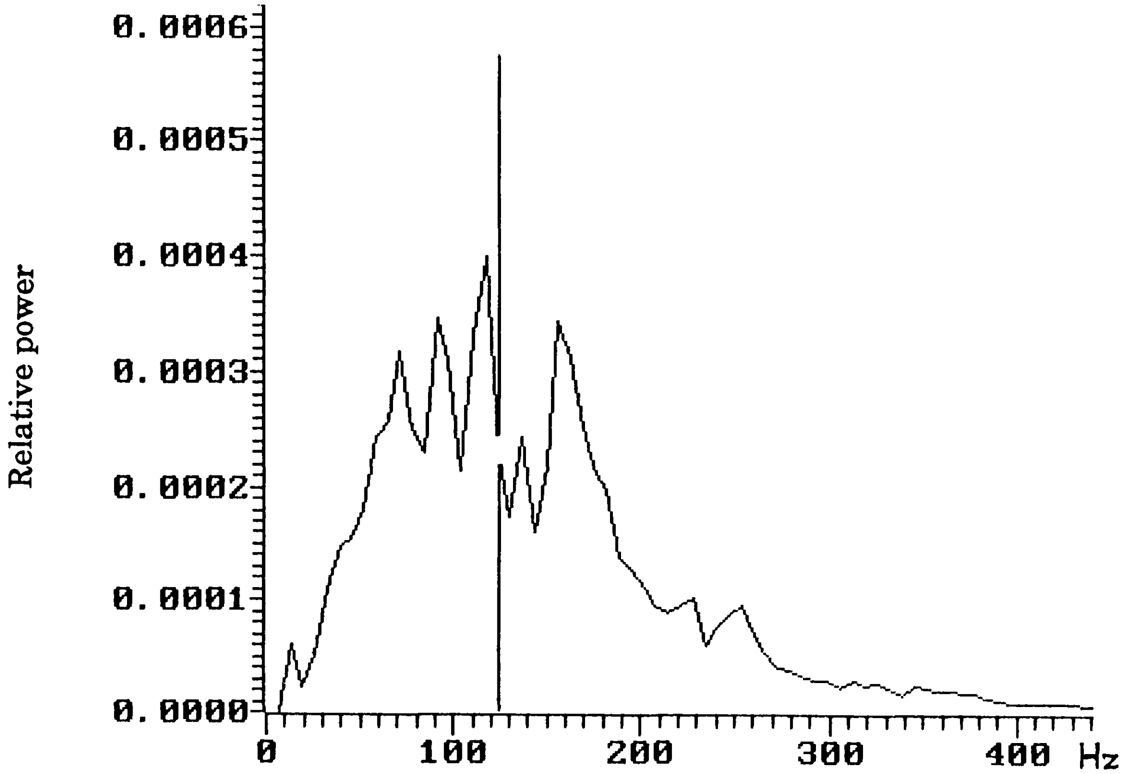


Figure 5.7 The power spectrum from the left masseter muscle of volunteer MG for the first four seconds of a sustained contraction without the bite force transducer.

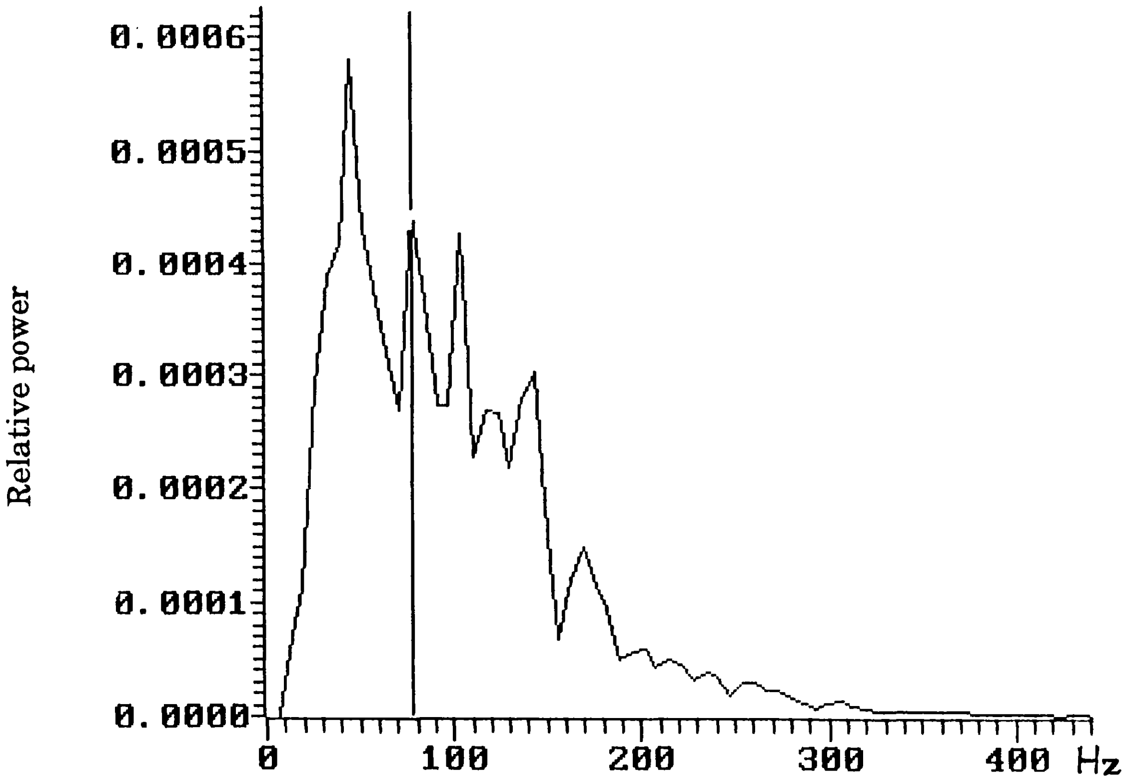


Figure 5.8 The power spectrum from the left masseter muscle of volunteer MG for the last four seconds (VAS score was 100) of a sustained contraction without the bite force transducer.

	DW	RB	MG	JP	PW	MB	AL	JB	
RAT	4.4	73	45	-4	23	71	-42	58	A
RM	120	37	106	0	21	49	28	28	M
LAT	12	205	105	18	49	122	40	1500	P
LM	147	-16	15	7	57	33	41	-8	L
RAT	40	12	47	8	43	47	20	6	F
RM	10	31	20	17	33	38	33	5	R
LAT	4	14	26	0	40	44	58	26	E
LM	4	15	26	0	37	39	35	21	Q

Table 5.2. Percentage change in amplitude and median frequency over the whole period of the sustained contraction on the bite force transducer. Negative values indicate a decrease in the case of amplitude, or increase in the case of frequency.

	DW	RB	MG	JP	PW	MB	AL	JB	
RAT	-77	130	3	-27	-18	4	18	48	A
RM	22	-5	0	-7	20	22	-4	-14	M
LAT	185	383	3	-29	-16	13	12	-27	P
LM	35	35	14	-22	72	0	5	23	L
RAT	-3	37	32	10	22	41	20	17	F
RM	10	28	40	13	41	33	24	23	R
LAT	15	50	33	9	41	33	35	28	E
LM	12	48	37	9	54	30	33	30	Q

Table 5.3. Percentage change in amplitude and median frequency over the whole period of the sustained contraction without the bite force transducer, i.e. teeth together. Negative values indicate a decrease in the case of amplitude, or increase in the case of frequency.

Source of Variation	SS	DF	MS	F	Sign.of F
Residual	839605	21	39981		
Bite force transducer	74461	1	74461	1.86	0.187
Volunteer by bite force transducer	253101	7	36157	0.90	0.522
Muscle by bite force transducer	82147	3	27382	0.68	0.571

Table 5.4. Test of the within-volunteer effect of amplitude involving the bite force transducer.

Source of Variation	SS	DF	MS	F	Sign. of F
Residual	1650	21	79		
Bite force transducer	113	1	113	1.44	0.244
Volunteer by bite force transducer	1569	7	224	2.85	0.029
Muscle by bite force transducer	745	3	248	3.16	0.046

Table 5.5. Test of the within-volunteer effect of frequency involving the bite force transducer.

	DW	RB	MG	JP	PW	MB	AL	JB	
RAT	.114	.983	.864	-.091	.332	.954	-.998	.930	A
RM	.832	.788	.232	-.056	.170	.850	993	-.813	M
LAT	.873	.938	.910	.687	.943	.929	.621	.902	P
LM	.992	-.878	-.231	.736	.728	.903	.837	-.709	L
RAT	-.966	-.766	-.982	-.930	-.920	-.934	-.934	-.423	F
RM	-.753	-.895	-.754	-.995	-.760	-.830	-.988	.022	R
LAT	-.106	-.819	-.109	-.397	-.870	-.921	-.976	-.790	E
LM	-.106	-.933	-.109	-.410	-.869	-.921	-.966	-.782	Q

Table 5.6. The correlations between VAS and Amplitude, and VAS and Frequency, with the bite force transducer in place.

	DW	RB	MG	JP	PW	MB	AL	JB	
RAT	.069	.703	.513	-.955	*	.171	.572	.937	A
RM	.641	.016	.442	-.713	*	.113	-.188	-.441	M
LAT	.278	.964	.594	-.981	*	.618	.714	-.878	P
LM	.602	.740	.950	-.921	*	-.285	.570	.534	L
RAT	.121	-.967	-.953	-.915	*	-.933	-.851	-.866	F
RM	-.429	-.798	-.954	-.915	*	-.909	-.915	-.891	R
LAT	-.793	-.930	-.915	-.866	*	-.848	-.946	-.955	E
LM	-.697	-.939	-.929	-.863	*	-.925	-.916	-.964	Q

Table 5.7. The correlations between VAS and Amplitude, and VAS and Frequency, teeth clenched together without the bite force transducer.
* represents no data.

	With bite force transducer				Without bite force transducer			
Volunteer	RAT	RM	LAT	LM	RAT	RM	LAT	LM
DW	175	182	175	169	182	201	221	208
RB	162	208	136	130	175	182	182	175
MG	123	130	123	123	143	130	117	123
JP	150	187	156	150	187	231	206	200
PW	136	136	130	123	147	141	141	141
MB	123	169	162	149	143	156	156	149
AL	130	136	136	130	162	162	162	156
JB	110	117	123	123	149	169	182	175
Mean:	138	158	142	137	161	171	170	165
± SD	22	32	19	17	18	32	34	29

Table 5.8. Median frequencies at the beginning of sustained contractions, both with the bite force transducer and without, for each volunteer, with means and standard deviations.

5.5 DISCUSSION

One of the problems in the investigation of fatigue in the jaw-closing muscles is that it is not possible to measure bite force with the teeth together or, at the very least, nearly together. The bite force transducer used for this experiment required a thickness of 7mm so that the beams were stiff enough to resist the forces involved without permanent deformation. This resulted in a greater degree of opening than would occur in normal or para-function (see also Section 1.10.1). As the jaws open the muscle length changes, as does their geometric relationship (i.e. line of action). This may be part of the reason why the volunteers were only able to maintain a target bite force within ± 10%, as they were unaccustomed to maintaining such a high force at this degree of jaw opening. However, although it is clear that fatigue is dependant on muscle length in skeletal muscle, one could argue that a separation of 7mm at the first premolar teeth results in a relatively small elongation of the jaw closing muscles.

A likely explanation for part of the large inter-individual variation in endurance times (Figure 5.1) is that there was almost certainly a variation from a true MVC among the volunteers i.e. it is likely that most did not achieve a true MVC. It is notoriously difficult to achieve a true MVC from the jaw-closing muscles when closing on a bite force transducer because of the response of the periodontal mechanoreceptors (see Section 1.11.2) and also fear on the part of the volunteers of fracturing teeth and restorations. This would mean that many would be sustaining less than 50% MVC during the first part of the experiment, even though it was 50% of the obtained MVC. This is supported by the calculated values of $MVC_{without}$, because if these values are true MVCs then by simple calculation the 50% MVC sustained on the force transducer was really only 34% of a true MVC on average, as the difference between the mean values was 47%. The calculation of $MVC_{without}$ is valid if the amplification of the signal is not changed and if the effects of sweating are avoided. Sweating will provide a path between the electrodes and result in a reduced signal amplitude. The use of anti-perspirants will not solve the problem as these contain zinc chloride which will conduct an electrical current as effectively as sweat. In order to avoid this effect the room temperature was kept at or below 19°C. The inter-electrode resistance was also measured with a DC resistance meter before and after the experiment. If this conduction were present, however, it would result in a lower calculated value of $MVC_{without}$, i.e. a false negative rather than a false positive effect.

The difference in median frequencies at the beginning of the sustained contractions in each configuration (Table 5.8) is explained by the fact that there was a difference in MVC levels. At higher force levels there is a greater increase in firing rate than in synchronization in order to increase output, and hence the median frequency would be higher at the higher force level.

The measurement of perceived fatigue on a visual analogue scale is not an exact procedure, but unfortunately there is no entirely satisfactory alternative. The problems of measuring subjective discomfort or pain are well known and the use of visual analogue scales is widely accepted (Reading, 1984; Huskisson, 1983). The results of this experiment support the validity of these scales, with very high r^2 values of the correlation between VAS and time for each volunteer, and the very high values of the correlation coefficients. These figures showed the straight-line relationship between VAS and time and that there were very few outlying values. The perceived level of fatigue, of course, does not necessarily relate to any particular muscle; it is simply an overall perception from one or more muscles. It is also clear that joint discomfort or pain might contribute to the overall feeling of discomfort and fatigue which is a factor of particular significance when clenching unilaterally on a bite force transducer. It is unlikely that one can distinguish with any certainty between joint pain and pain from the lateral pterygoid muscle or deep fibres of masseter. Several volunteers complained of pain from the joint area on the contra-lateral side when clenching on the bite force transducer.

With regard to the use of electromyography to measure fatigue, it should be pointed out that both the increase in amplitude of the EMG signal and the frequency shift of the power spectrum are related. The local accumulation of metabolites results in a decrease in conduction velocity, resulting in a larger time duration of the motor unit waveforms. Both frequency shift and amplitude increase are indicators of metabolic events going on within a muscle, although signal amplitude has a reduced sensitivity compared to frequency shift (Basmajian & De Luca, 1985b). The total power of the signal is a result of a decrease in power at higher frequencies and an increase in power at lower frequencies (Figure 5.9), hence this resultant power value will be a less sensitive measure of total change than the shift in median frequency (or any of the other accepted descriptive parameters of power spectrum shape).

A note of caution should be added at this stage regarding the calculation of $MVC_{without}$ (page 135). It has been shown that as muscle length changes, then the EMG/force ratio also changes (Mackenna & Turker, 1983). As the bite force transducer induces an opening of 7 mm at the premolar area, then muscle length clearly changes when the transducer is removed and the teeth are in contact. Hence the calculated value of force is only an approximation. However, although the integrated EMG level is greater when the teeth are together, it is likely that the actual bite force may be a little higher but not as high as the EMG would indicate.

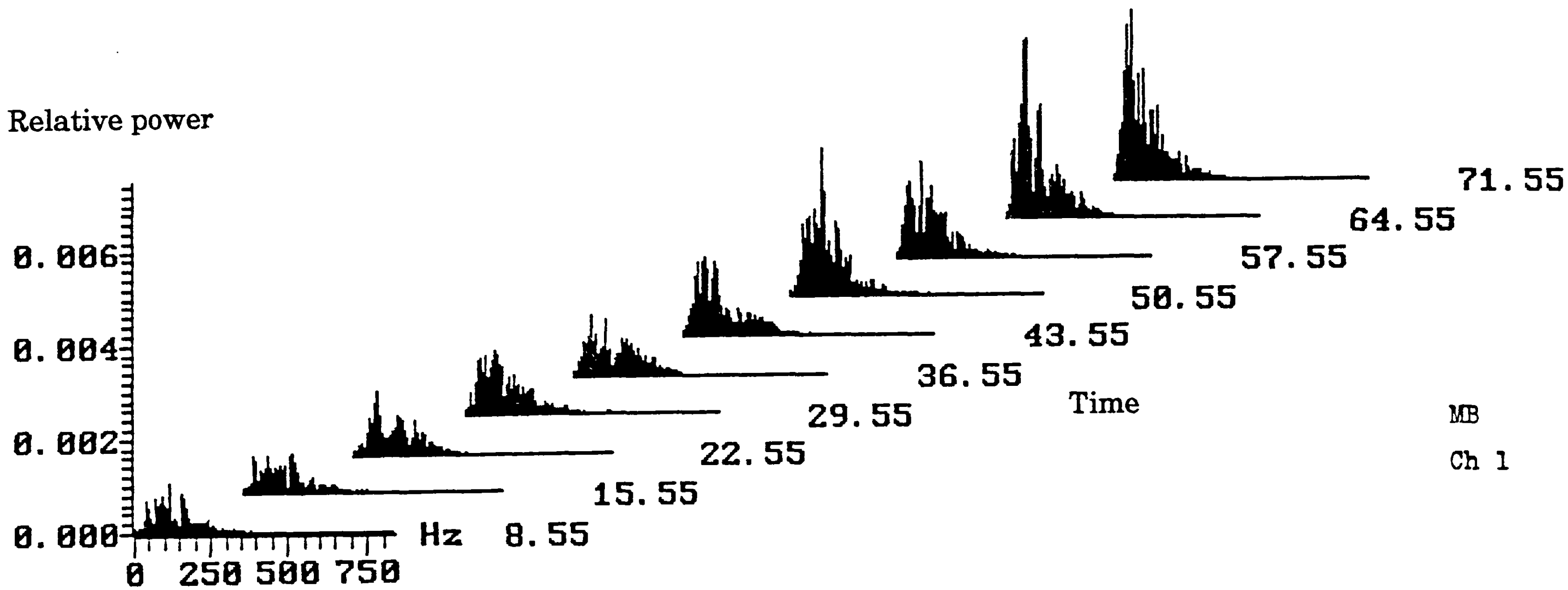


Figure 5.9 A "waterfall" presentation of consecutive power spectra from the right anterior temporalis muscle of one volunteer (MB) to show the marked increase in power with time.

The significance of differences in percentage changes of amplitude and frequency shown between muscle groups with and without the bite force transducer (Tables 5.2 and 5.3) are unreliable because of the small sample. The degree of significance could be due to extreme values distorting the result; there is also no information on the reproducibility of measurements within volunteers.

The association between VAS and median frequency change was closer during the sustained contraction without the bite force transducer than with (Table 5.7), perhaps because there was more uniformity of activity between the muscle groups without the bite force transducer, resulting in a better overall correlation. The reason for the closer correlation between VAS and median frequency rather than VAS and EMG amplitude is probably that there was greater variability in the signal amplitude than in its power spectrum median frequency. This can be seen in Tables 5.2 and 5.3 where the mean values of amplitude change for each muscle, for all volunteers, show considerably greater variation than the mean values for the median frequency change. The standard deviations of these means are also considerably greater for amplitude change than for median frequency change. The smaller degree of variability of median frequency when compared to signal amplitude appears to make median frequency a more useful measure of muscle fatigue, particularly when coupled with a theoretically greater sensitivity.

The results of this experiment shown a clear relationship between the central perception of fatigue and the peripheral process of localised muscle fatigue, but this raises the interesting question of what causes the peripheral process to be detected centrally? It has been postulated that it is the increase in centrally generated motor commands which appears to lead to the perception of tiredness, rather than the muscle afferent barrage directly (McClosky, 1985).

5.6 CONCLUSIONS

The results of this experiment have provided more evidence to support the validity of visual analogue scales, and have shown that in the case of the anterior temporalis and masseter muscles the change in EMG amplitude and change in median frequency are closely reproduced by the perceived level of fatigue. In addition, the association between the perceived levels of fatigue and the change in power spectrum median frequency is rather closer than the association between perceived levels of fatigue and change in rectified RMS-integrated EMG amplitude.

The effects of the bite force transducer were to reduce maximum bite force, reduce endurance time, and to cause pain on the contralateral side. It had no effect on the volunteer's perception of fatigue.

CHAPTER 6.

MASSETER MUSCLE RELAXATION RATE IN VOLUNTEERS WITH A MYOGENOUS CRANIOMANDIBULAR DISORDER

6.1 SUMMARY

Twelve volunteers were investigated to determine their masseter muscle relaxation rate following voluntary contractions. Four of these were patients diagnosed as having a myogenous craniomandibular disorder. EMG was recorded from the left and right masseter muscles and maximum bite force was recorded in the mid-line between the incisor teeth. A sustained contraction was maintained at 50% MVC for ninety seconds, during which there was a brief relaxation every ten seconds. Recordings were continued for a three-minute recovery period. This regime was then repeated at the 25% MVC level.

Median power frequencies were calculated for the first and last three seconds of the sustained contractions. Relaxation rates were measured for each brief relaxation during the sustained contraction and for the relaxation part of each brief clench during the recovery period.

It was found that maximum bite force values were very similar for volunteers in both the patient and control group. Relaxation rates slowed more and percentage changes in median frequency were greater in the controls than in the patients during the sustained contractions. However,

relaxation rates returned to initial levels more quickly in the controls than in the patients.

6.2 INTRODUCTION

During a sustained isometric contraction a slowing of the rate of relaxation is seen in localised muscle fatigue. This is following a voluntary contraction and should not be confused with an electrically induced twitch response. A shift in the power spectrum of the EMG signal to lower frequencies and an increase in amplitude are also observed. The reasons that a slowing of relaxation occurs are not yet proven, but it is clear that such a phenomenon does occur with fatigue (see Chapter 1 for a detailed discussion). In patients with a craniomandibular disorder due primarily to a muscle disorder (myogenous CMD), it appears from clinical observation that muscle soreness often leads to rather slow and deliberate mandibular movements. This slowing of movement is probably a defensive reaction to avoid pain. Slightly slower movements are not a perceptible manifestation of slowing of relaxation as a result of muscle fatigue, as this effect is clinically imperceptible. Slowing of relaxation would be a clear indication of the presence of fatigue if detected from EMG and force records.

Having investigated the changes in the EMG signal which occur in fatigue (reported in Chapters 3, 4 and 5), it was considered necessary that these factors, together with the relaxation rate, should be investigated in patients with myogenous CMD. As discussed previously (see Section 1.11.4), it is not possible to isolate the force output of individual jaw-closing muscles, but in a protrusive closure most of the force is produced by the masseter muscles with a small or nil contribution from the temporalis muscles (Carlsöö, 1952). The masseter muscle is also a muscle which appears to be very often involved in myogenous CMD.

The aims of this investigation were to examine the relaxation rate and changes in the power spectrum of masseter muscles in patients with painful muscles who have been diagnosed as having myogenous CMD.

6.3 METHOD

6.3.1 The Volunteers

Of the twelve volunteers for this experiment, four were patients with a myogenous CMD, four were normal healthy controls, and four were a normal healthy group of young males (age range 23-29 years). The group of males were not termed a control group, but were considered an additional group not to be used for directly comparative purposes. Most importantly, the control group was age and sex-matched to the patient group; the age range of these two groups was 17-39 years and all were females. These patients were among those referred to the Departments of Oral Surgery and Prosthodontics of Glasgow Dental Hospital and were selected at random. They were questioned carefully regarding the symptoms, history and previous treatment of their facial pain. They also received a thorough clinical examination. The proforma used for these patients was developed in preparation for this experiment in order to aid in more accurate and specific diagnosis. This proforma is reproduced in Appendix G. The only form of selection that applied to the patients was that they should have a myogenous CMD involving a masseter muscle. The control group and the group of males were also examined for signs of CMD, and only those with no signs or symptoms were accepted. All the volunteers were fully dentate with no crowns or large composite restorations on their incisor teeth.

6.3.2 Response-time of Bite Force Transducer

The response-time of the bite force transducer was measured by applying a known load and then unloading as quickly as possible. The beam with the strain gauges attached was bolted to the edge of a bench and a load was applied by a piece of string. When the required load had been applied the string was cut with a pair of scissors, thus releasing the load. The results may be seen in Figure 6.4.

6.3.3 Electromyography

Recordings were obtained from the left and right masseter muscles, and from the sub-mandibular group in the region of the anterior belly of the digastric muscle on the right side. Surface silver/silver chloride disc electrodes were used in a bipolar configuration. Skin preparation was vigorously performed using gauze soaked in surgical spirit. Signal amplification, filtering and data storage were carried out as described in Chapter 2. The inter-electrode resistance was measured before and after the experiment to check for the effects of sweating.

6.3.4 Experimental Protocol

Each volunteer was given time to become familiar with the bite force transducer (see Appendix D) and the oscilloscope screen. Visual feedback was provided by the force display. Several attempts were then made to obtain a maximum voluntary contraction (MVC) with the mandible in a protrusive position on the bite force transducer. The bite force transducer was placed in the mid-line between the upper and lower central incisor teeth. The volunteer was urged at each attempt to try to exceed the previous force output and to be sure that the mandible was in protrusion. This was the only time that the volunteer was under any degree of coercion. It was considered important to attempt to elicit a true MVC if possible, even though this was difficult for the patient group with muscle pain. Several layers of gauze were used on the bite force transducer instead of acrylic indices, as it was found that gauze was more comfortable for the teeth than acrylic resin on maximal biting. These layers of gauze increased the total thickness slightly, but this was considered preferable to the possibility of obtaining less than a true MVC.

Each volunteer was also asked to attempt to open against resistance provided by the author's hand; the palm of the hand was placed beneath the volunteer's mandible in the mid-line. This was done in order to be able to assess the level of assistance contributed by the jaw-opening muscles, if any, during a relaxation.

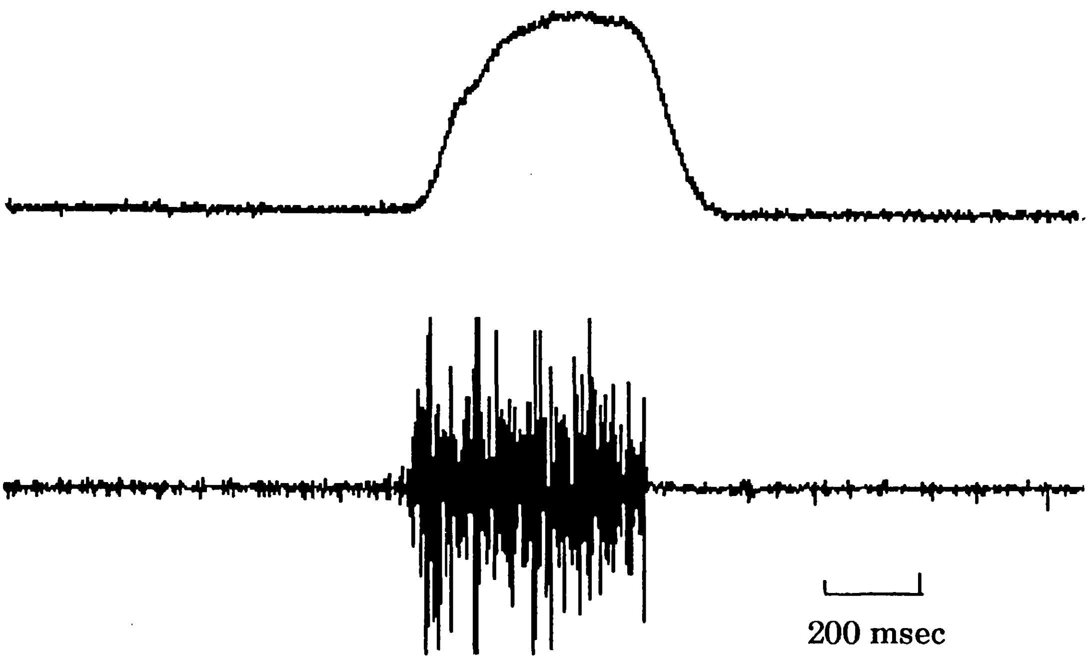
When a reproducible MVC had been obtained, each volunteer was asked to maintain 50% MVC for 90 seconds. During this period the volunteer was asked to relax and then immediately clench again every 10 seconds. At the completion of the 90 second period there followed a three minute recovery period, during which the volunteer was asked to clench briefly to 50% MVC every 20 seconds.

After a rest period of approximately five minutes the above regime was repeated, but this time the clenching level was 25% MVC. The time period over which the contraction was sustained was two minutes, with a brief relaxation every 10 seconds, followed by three minutes of recovery with a brief clench every 20 seconds.

6.3.5 Data Analysis

Sections of EMG signal of approximately 3 seconds duration were sampled from left and right masseter muscles at the beginning of the sustained contractions and again at the end, at both the 50% MVC and 25% MVC levels. The sampling rate was 1660 Hz and 1024-point fast Fourier transforms were carried out using Spike 2 data capture and analysis software (see Chapter 2). DC-offset, if present, was removed and the median frequency calculated.

In order to measure relaxation rates, data from the whole period of the experiment was captured at a sampling rate of 1660 Hz for EMG and 550 Hz for force. It was possible to display one EMG channel and the force channel in order to determine the time from which the relaxation half-time should be measured; this measurement was taken from the moment EMG activity ceased. The signal was expanded considerably on the computer screen in order to measure time accurately. The time taken for the force to fall by 50% from the moment EMG activity ceased was termed the relaxation half-time (Figure 6.1).



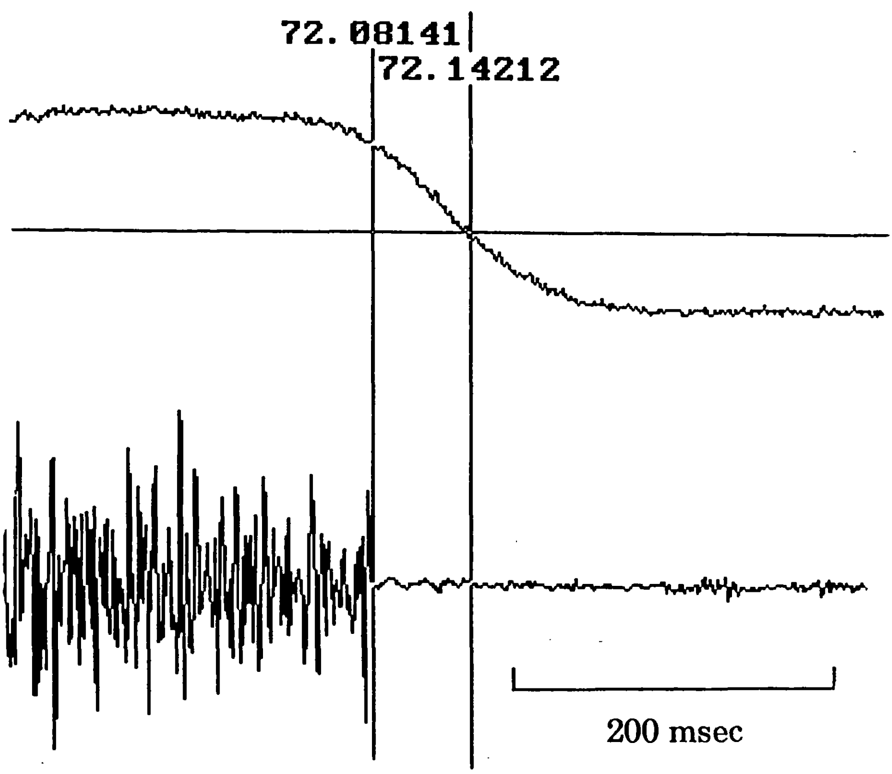


Figure 6.1 The measurement of relaxation half-time. A brief clench (volunteer JN), relaxation half-time is 61 msec. The signal has been expanded considerably more in the lower view, as can be seen by the time scale which represents 0.2 sec in both cases.

6.4 RESULTS

6.4.1 Maximum Bite Force

Maximum bite force values varied widely between individuals but were remarkably consistent between age-matched patients and controls (Table 6.1). The mean maximum bite force for the patient group was 191N (SD 33.3), for the control group was 186N (SD 77.2), and for the males was 302.5 (SD 37.7). A two (independent) sample t-test (MINITAB 7 software) demonstrated that there was no significant difference in maximum bite forces between the patients and controls ($t = 0.12$, $p = 0.91$, $df = 4$), but there was a highly significant difference between the patients and the males ($t = -4.42$, $p = 0.0069$, $df = 5$).

Vols. (pts)	Bite Force (N)	Vols. (controls)	Bite Force (N)	Vols. (males)	Bite Force (N)
CJ	150	JJ	150	AP	260
EB	210	PB	165	NH	290
CL	180	JN	130	JL	310
HM	225	LW	300	JG	350
Mean:	191		186		302
± SD	33.3		77.2		37.7

Table 6.1 Maximum bite force values (N) for volunteers in the three groups. The patients and controls were age-matched as listed (i.e. CJ is the same age as JJ, and so on).

6.4.2 Median Power Frequency

The mean percentage changes in median frequencies of the power spectra over the 90 seconds of the sustained contraction at 50% MVC were greater in the muscles of the control group than in those of the patients (Table

6.2). This difference between the patients and the controls was not statistically significant. There was very little difference between the changes in the control group and the male group. The percentage changes in median frequencies during the sustained contraction at 25% MVC were again a little greater in the control group than in the patient group, although not statistically significant (Table 6.3). An example of the changes in the power spectra, the shift to lower frequencies and the increase in power, may be seen in Figures 6.2 and 6.3.

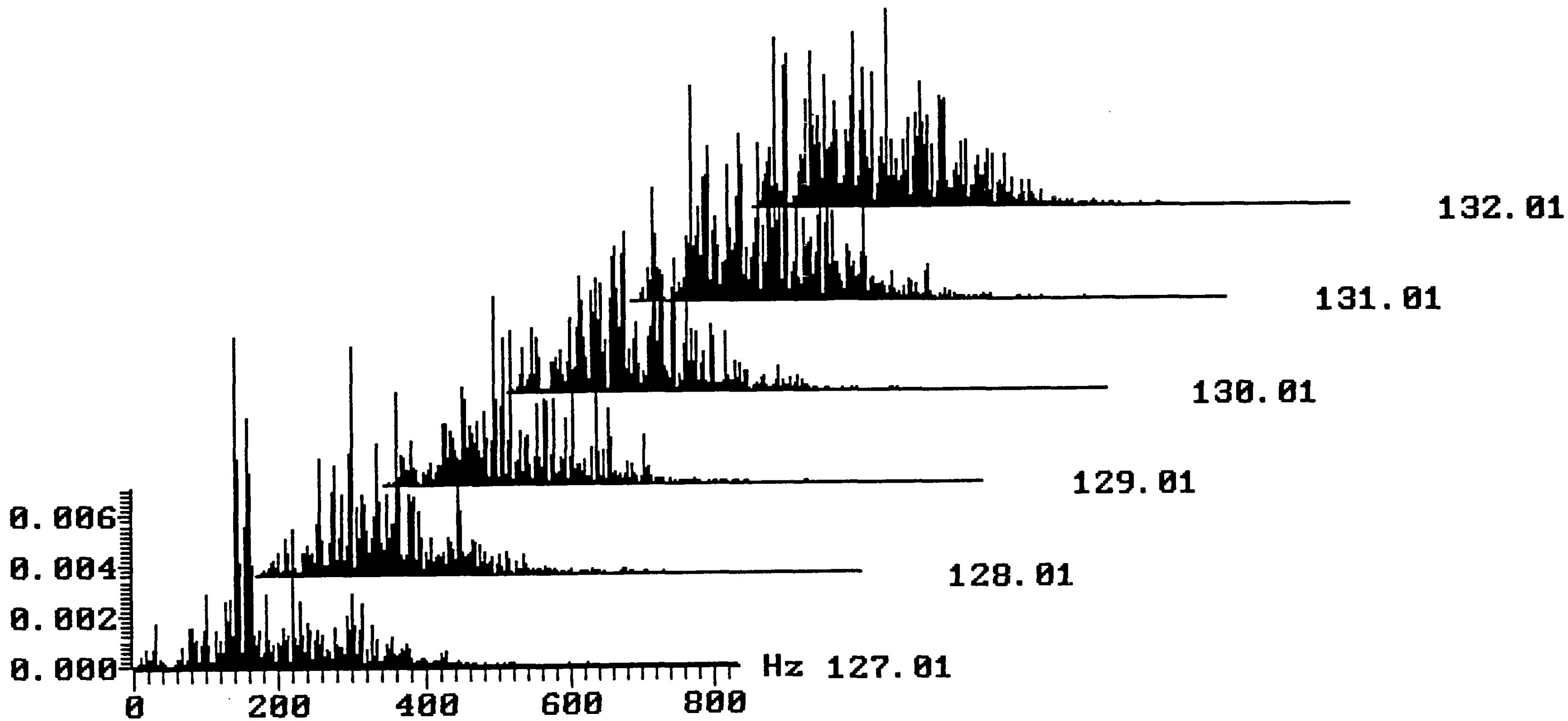
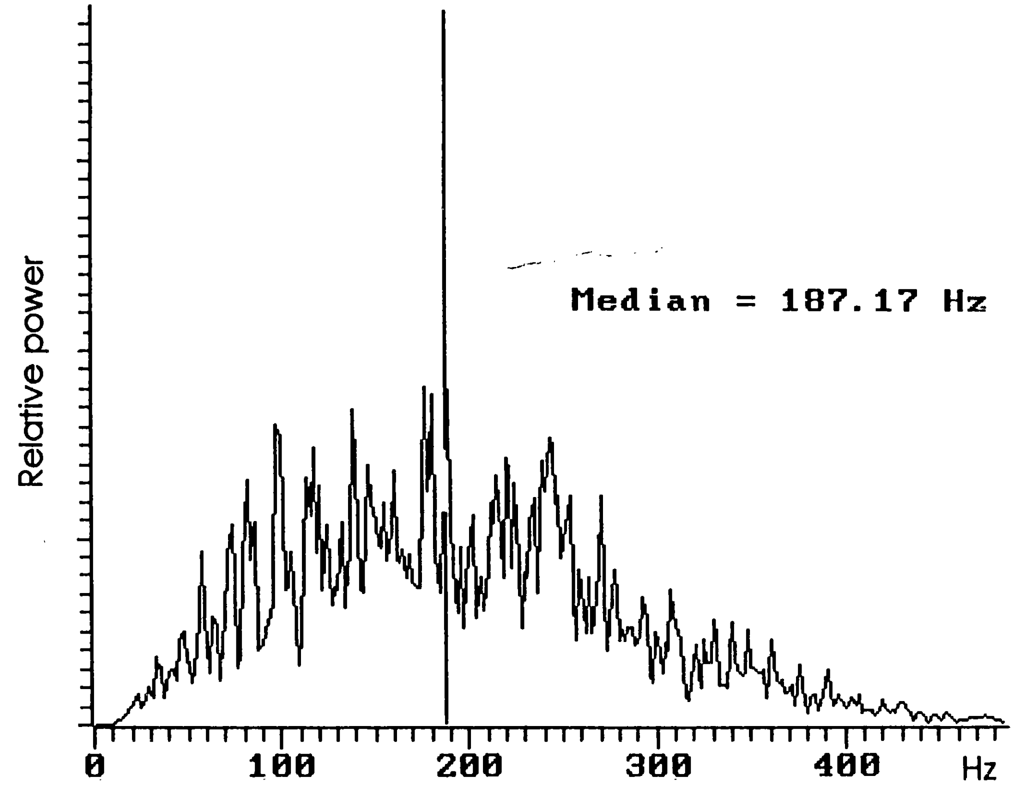


Figure 6.2 A waterfall presentation of power spectra at 1 second intervals of the last 5 seconds of a sustained clench at 50% MVC by volunteer NH. The median frequency for this 5 second period was 182.29 Hz. Time progresses at 1 second intervals from below upwards.



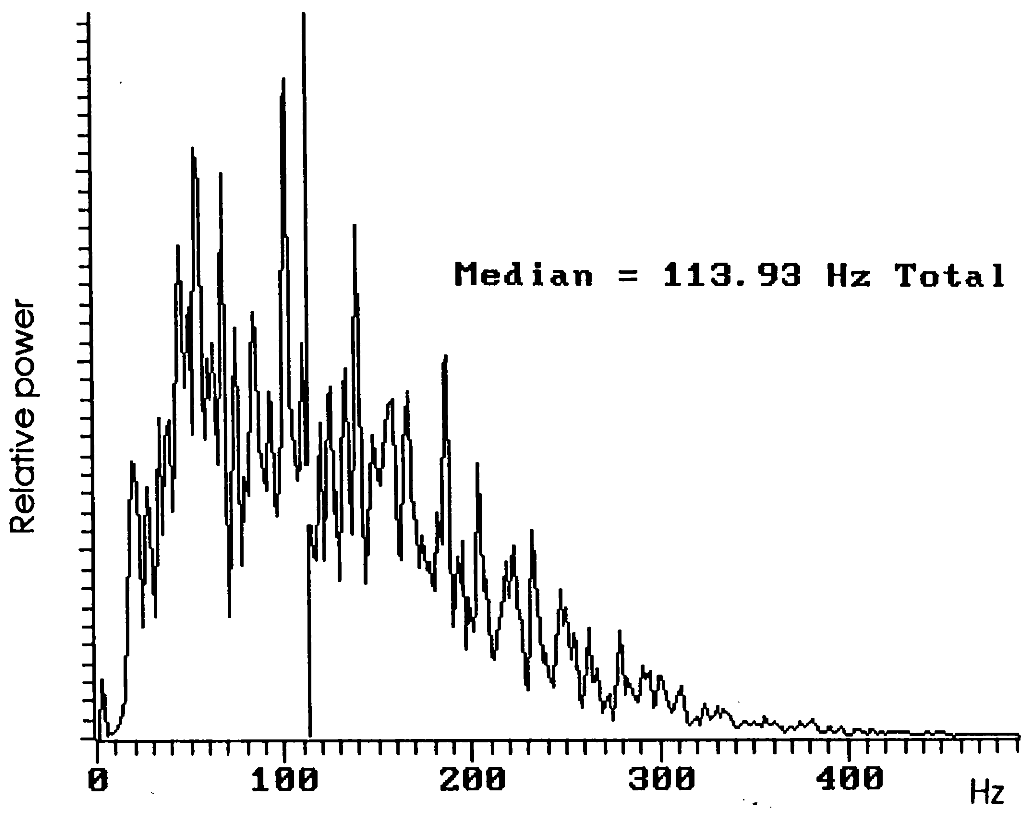


Figure 6.3 Power spectra of 3 seconds of signal from the beginning (top) and end (bottom) of a sustained contraction at 25% MVC by volunteer LW.

Volunteer (Patients)	RM	LM	Volunteer (Controls)	RM	LM	Volunteer (Males)	RM	LM
CJ	2.12	14.85†	JJ	12.69	26.54	AP	19.52	23.05
EB	7.44†	8.5	PB	14.45	13.16	NH	14.28	13.00
CL	5.98†	10.75	JN	24.00	17.46	JL	16.66	14.43
HM	11.90†	16.42	LW	44.23	30.20	JG	40.21	9.99
Mean:	6.86	12.63		23.84	21.84		22.67	15.12
± SD	4.04	3.65		14.47	7.88		11.89	5.60

Table 6.2 The percentage changes in median frequency of the power spectra over the period of the 90 second sustained contraction at 50% MVC for the right masseter (RM) and left masseter (LM) muscles. The side affected by pain (CMD) is indicated by †.

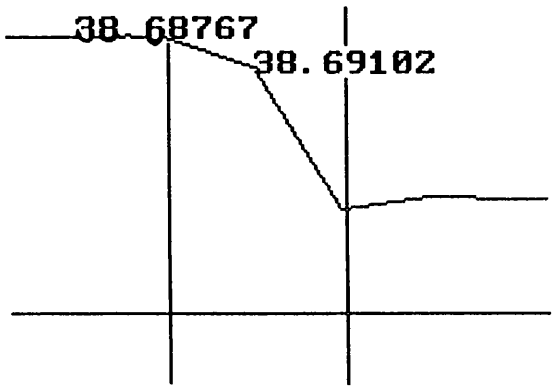
Volunteer (Patients)	RM	LM	Volunteer (Controls)	RM	LM	Volunteer (Males)	RM	LM
CJ	23.99	17.92†	JJ	7.20	25.92	AP	27.55	23.21
EB	2.01†	7.60	PB	10.45	7.41	NH	15.70	20.20
CL	24.99†	13.28	JN	18.85	30.83	JL	8.65	1.08
HM	14.72†	15.33	LW	39.13	35.29	JG	16.27	13.74
Mean:	16.43	13.53		18.91	24.87		17.04	14.56
± SD	10.67	4.39		14.35	12.25		7.82	9.82

Table 6.3 The percentage changes in median frequency of the power spectra over the period of the 120 second sustained contraction at 25% MVC for the right masseter (RM) and left masseter (LM) muscles. The side affected by pain (CMD) is indicated by †.

6.4.3 Transducer Response Time

The response-time of the bite force transducer and bridge amplifier system was 2 msec for the final 85% of the fall-off in force from a loading of 125N (Figure 6.4). The initial 15% of the fall-off was at a slightly slower rate, taking 2 msec for this part of the fall-off also. There was a very sudden change to the quicker rate after 2 msec, which could be reasonably assumed to be from the point that the string was severed rather than any delay in response from the transducer.

(a)



(b)

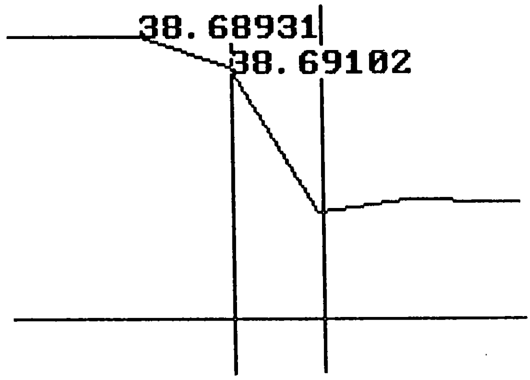


Figure 6.4 The response-time of the bite force transducer. (a) The cursors measure a time of 4 msec for the whole fall in force, whereas in (b) the final 85% of the fall occurs in 2 msec. The numbers on the vertical cursors indicate time in seconds.

6.4.4 Relaxation Half-Times

The relaxation half-times for one patient and the corresponding age-matched control are presented in Table 6.4 as an example of the magnitude of the values obtained. The data for the patients and controls for the sustained clench at 50% MVC and the 3 minute recovery period is presented in Figures 6.5-6.8, together with the regression line in each case. For each volunteer in all three groups a regression analysis was carried out and the slope, intercept and correlation coefficient were calculated (Tables 6.5 and 6.6). The correlation coefficients are calculated to assess the reliability of the regression equations. A multivariate analysis of variance (MANOVA) was then performed on the slope and intercept values from this regression data using the SPSS/PC+ statistical analysis software. From Table 6.7 it was found that there was a significant difference ($p = 0.013$) in the slopes between the groups during the recovery period following the 50% sustained contraction, with the controls showing a significantly quicker reduction in relaxation half-times than the patients. All other differences of slope, intercept, contraction force, and group were not statistically significant.

There was no contribution of activity from the sub-mandibular muscles in the region of the anterior belly of digastric during a masseter muscle relaxation. Some considerable activity was seen at times, but this did not coincide with masseter relaxations (Figures 6.9 and 6.10).

Time (secs)	CJ (patient) 50S	50R	25S	25R	JN (control) 50S	50R	25S	25R
10	92		56		59		60	
20	81	64	65	55	70	57	79	58
30	88		41		90		56	
40	135	68	*	64	74	49	91	64
50	80		97		85		76	
60	103	60	89	52	82	64	99	50
70	133		87		89		70	
80	122	92	67	75	78	61	83	48
90	136		65		93		91	
100		82	78	68		65	91	55
110			61				61	
120		98	63	67		57	113	54
140		67		43		37		57
160		79		57		56		49
180		61		63		53		38

Table 6.4 The half-relaxation times (msec) for one patient and one corresponding age-matched control. 50S represents the period of sustained contraction at 50% MVC, 50R the three minute recovery period with clenches to 50% MVC, 25S the sustained contraction at 25% MVC (* represents missing data) and 25R the three-minute recovery period with clenches to 25% MVC.

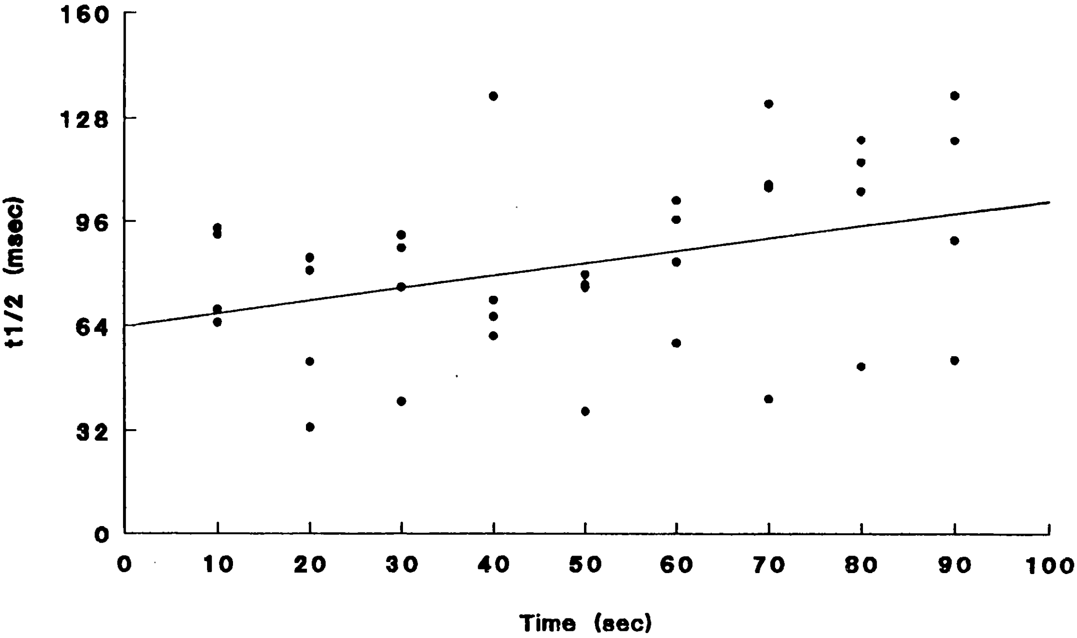


Figure 6.5 Relaxation half-times for the four volunteers in the patient group recorded during the sustained contraction at 50% MVC. The regression equation is y = 63.6 + 0.398x.

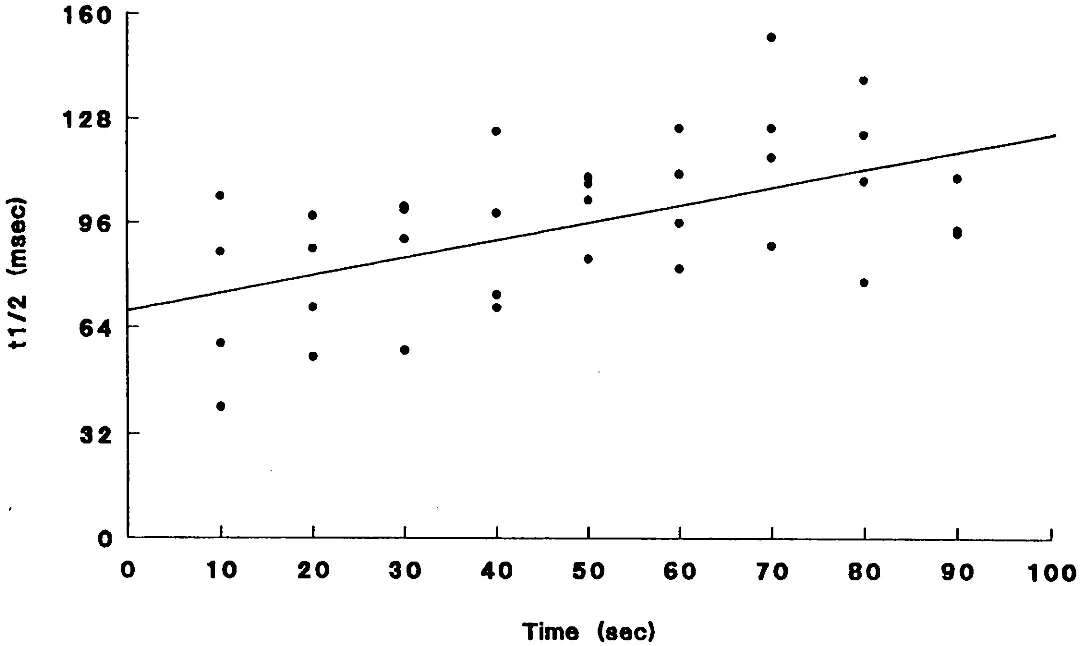


Figure 6.6 Relaxation half-times for the four volunteers in the control group recorded during the sustained contraction at 50% MVC. The regression equation is y = 70.5 + 0.533x.

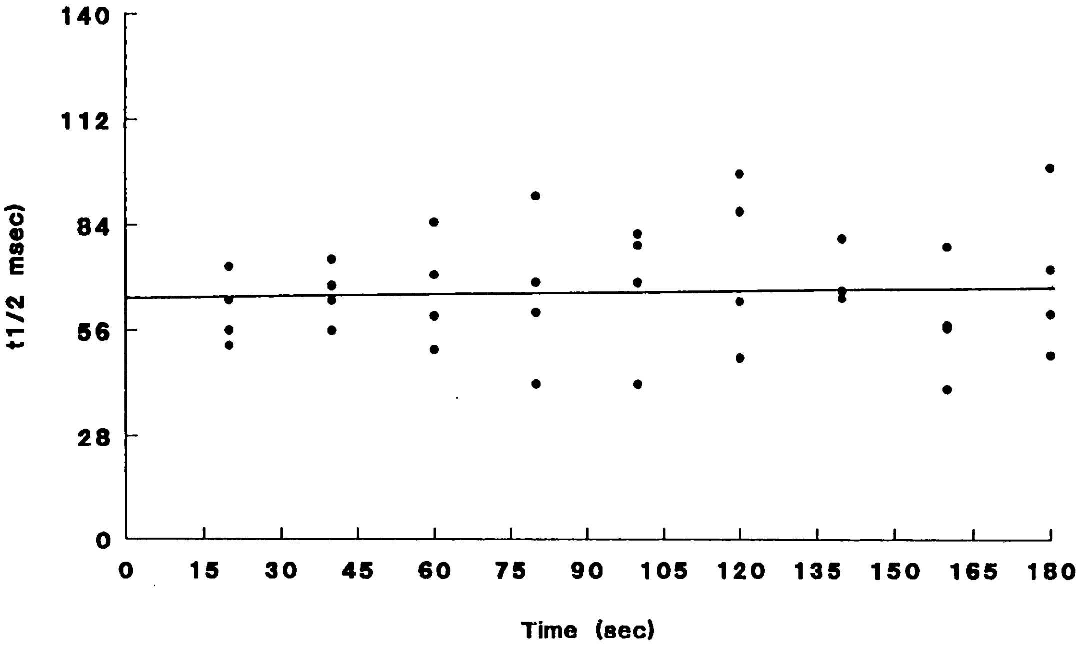


Figure 6.7 Relaxation half-times for the four volunteers in the patient group recorded during the 3-minute relaxation period, with clenches to 50% MVC. The regression equation is y = 64.15 + 0.0269x.

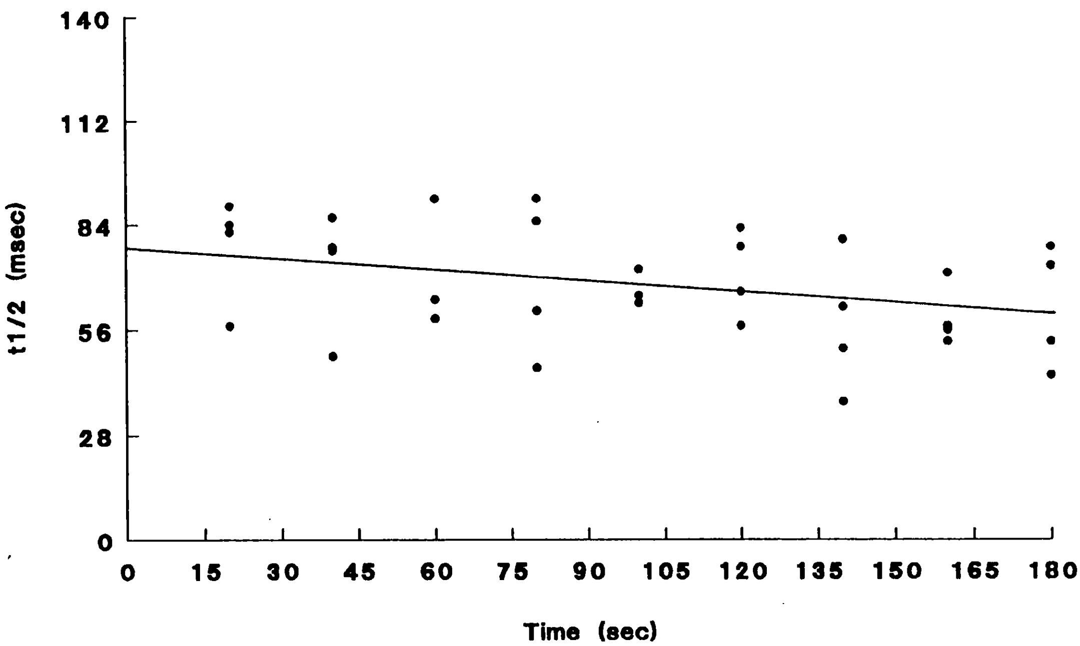


Figure 6.8 Relaxation half-times for the four volunteers in the control group recorded during the 3-minute relaxation period, with clenches to 50% MVC. The regression equation is y = 78.05 - 0.1064x.

Volunteer	Sustained 50% MVC			Recovery Period		
	Slope	Intercept	Correlation coefficient	Slope	Intercept	Correlation coefficient
Patients						
CJ	0.595	78.0	0.685	0.0342	71.1	0.135
EB	0.230	80.1	0.431	0.0142	68.0	0.073
CL	0.790	44.1	0.916	0.045	66.8	0.146
HM	-0.023	52.3	-0.046	0.142	50.7	0.103
Mean:	0.398	63.62	0.497	0.0269	64.15	0.1143
± SD	0.364	18.14	0.412	0.0153	9.15	0.0330
Controls						
JJ	1.320	27.1	0.962	-0.0767	78.8	-0.367
JN	0.273	66.4	0.676	-0.0442	59.9	-0.282
LW	0.237	102.0	0.341	-0.2280	85.6	-0.779
PB	0.303	86.4	0.825	-0.0767	87.9	-0.548
Mean:	0.533	70.5	0.707	-0.1064	78.05	-0.494
± SD	0.525	32.4	0.267	0.0825	12.70	0.220
Males						
AP	0.400	84.3	0.526	-0.1160	71.0	-0.704
HN	0.415	72.0	0.541	-0.0875	65.5	-0.531
JL	0.148	86.4	0.319	-0.0883	70.2	-0.445
JG	0.388	60.7	0.728	-0.0350	76.2	-0.262
Mean:	0.337	75.85	0.528	-0.0817	70.7	-0.485
± SD	0.127	11.93	0.167	0.0338	4.38	0.183

Table 6.5 The regression analysis of the relaxation half-times for each volunteer in the three groups, during the sustained contraction at 50% MVC and the three-minute recovery period with clenches to 50% MVC.

Volunteer	Sustained 25% MVC			Recovery period		
	Slope	Intercept	Correlation coefficient	Slope	Intercept	Correlation coefficient
Patients						
CJ	0.067	65.4	0.152	-0.0125	61.7	-0.071
EB	0.177	98.9	0.332	-0.1680	78.3	-0.563
CL	0.177	54.2	0.382	0.1870	49.4	0.422
HM	0.263	49.4	0.428	-0.0242	-0.145	-0.145
Mean:	0.171	67.0	0.323	-0.0044	63.85	-0.089
± SD	0.080	22.3	0.120	0.1459	0.404	0.404
Controls						
JJ	0.167	44.8	0.448	-0.2250	68.6	-0.847
JN	0.230	65.9	0.481	-0.0875	61.3	-0.646
LW	0.462	75.1	0.562	-0.8750	61.9	-0.366
PB	0.253	75.5	0.644	-0.0158	67.7	-0.146
Mean:	0.278	65.32	0.5337	-0.1039	64.87	-0.501
± SD	0.127	14.38	0.0877	0.0875	3.81	0.308
Males						
AP	0.151	51.7	0.399	-0.0567	50.0	-0.399
NH	0.141	86.7	0.590	-0.045	58.3	-0.304
JL	0.0902	75.8	0.353	-0.0608	61.4	-0.391
JG	0.337	55.2	0.583	-0.0208	57.3	-0.176
Mean:	0.1798	67.35	0.4812	-0.0458	56.75	-0.3175
± SD	0.1081	16.72	0.1230	0.0179	4.83	0.1037

Table 6.6 The regression analysis of the relaxation half-times for each volunteer in the three groups, during the sustained contraction at 25% MVC and the three-minute recovery period with clenches to 25% MVC.

Multivariate Tests

Test Name	Value	Approx.F	Hypoth. DF	Error DF	Sig. of F
Pillais	0.69792	2.41202	4.00	18.00	0.087
Hotellings	1.79740	3.14544	4.00	14.00	0.048
Wilks	0.34289	2.83100	4.00	16.00	0.060

Univariate F-tests

Variable	Hypoth. SS	Error SS	Hypoth. MS	Error MS	F	Sig. of F
Slope 50R	0.04023	0.02456	0.02012	0.00273	7.37195	0.013
Intcpt 50R	378.665	801.297	189.332	89.0330	2.12654	0.175

Table 6.7 Multivariate analysis of variance of the effect of the three different groups on the slope and the intercept of the regression lines of the relaxation half-times for each individual volunteer. These are the relaxation half-times recorded during the recovery period with clenches to 50% MVC at twenty second intervals.

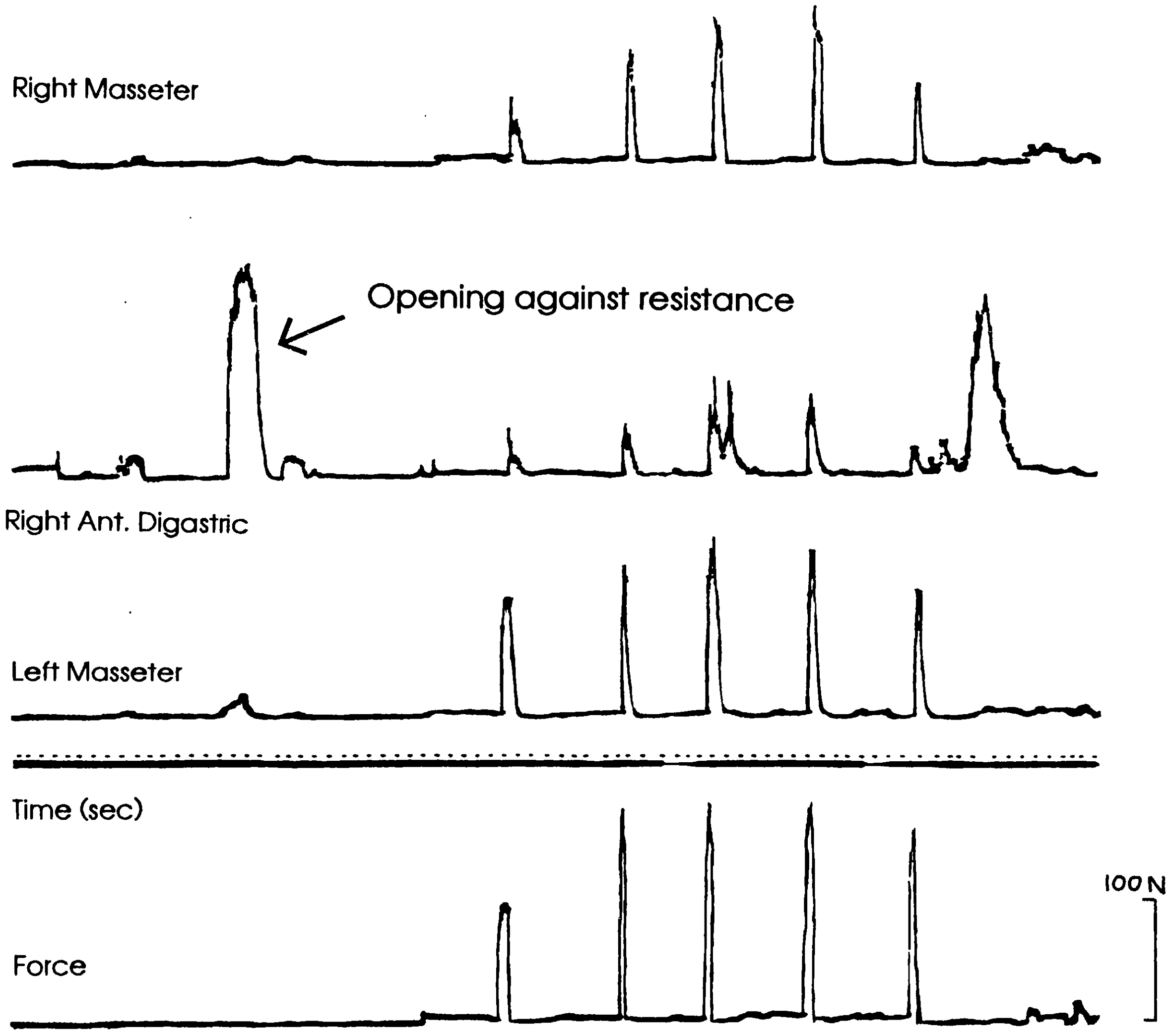


Figure 6.9 The tracing from one volunteer patient (CL) to show activity in the jaw-openers on the right side when opening against resistance. There follows a series of maximum clenching efforts.

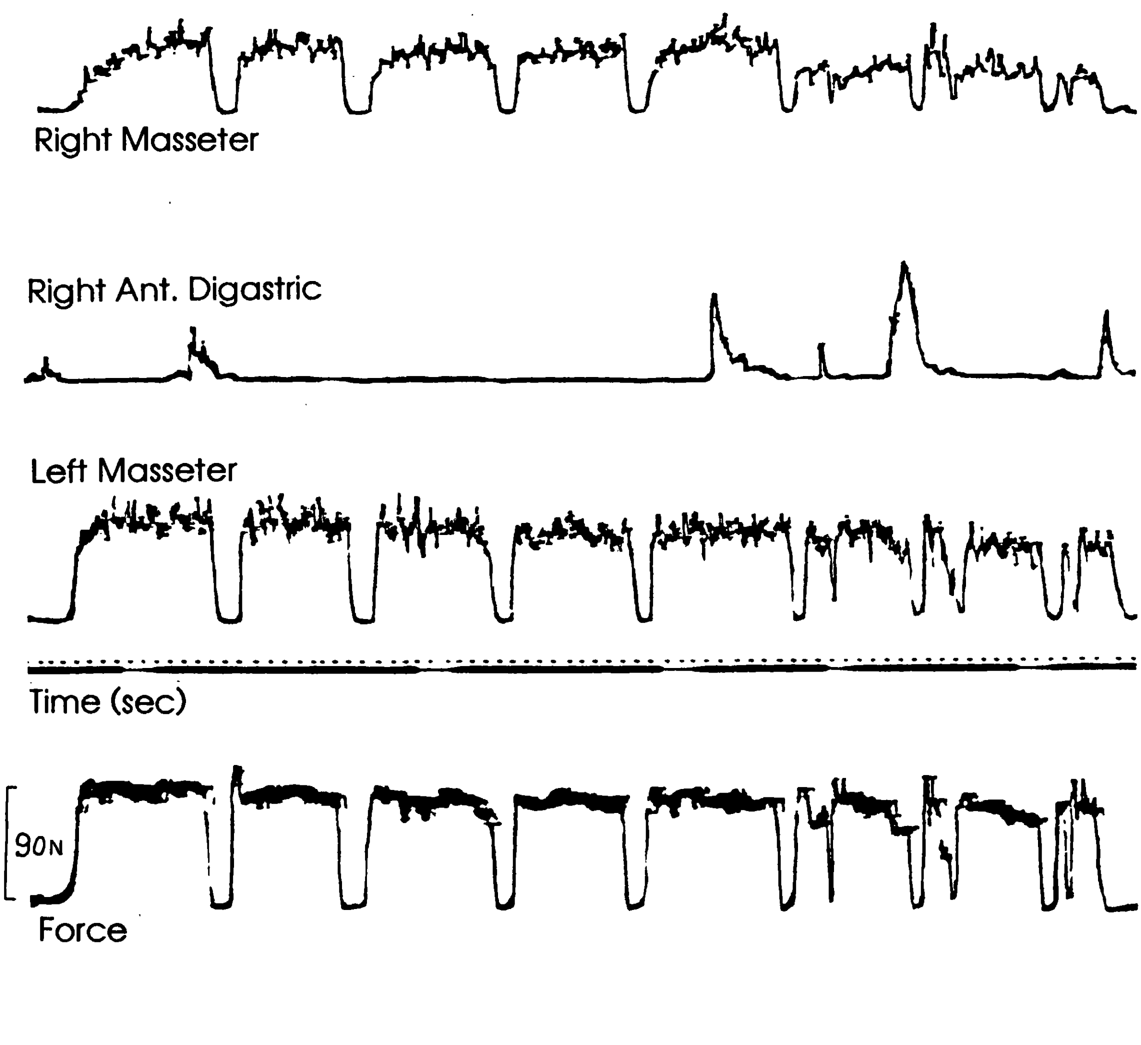


Figure 6.10 A section of tracing from the same volunteer as shown in Figure 6.9 (CL), taken at the same session, showing a series of brief relaxations during a sustained clench at 50% MVC for 90 seconds.

6.5 DISCUSSION

In view of the severity of the clinical disorder (i.e. masseter muscle pain) in the patient group, it was unexpected to find that the maximum bite force values were very similar to those of the controls, although this has also been found by other workers (Hagberg, Agerberg & Hagberg, 1986). It had been anticipated that the patients would have a significantly reduced mean maximum bite force in view of their severe muscle pain and limitation of movement. The similarity in bite force values could not be explained by differences in physical type or build between the two groups because, in addition to age and sex-matching, the two groups happened to be quite similar in physical stature. This similarity could not be realistically explained by a failure of the control group to produce a true maximum clenching effort either, as both groups were cooperative and subjected to considerable encouragement at that stage of the experiment.

A likely explanation is that only a small part of the muscle was affected by the disorder and this small part was the source of the considerable pain. During maximum voluntary effort the individual was able to overcome the protective limitation of activity of the remainder of the muscle and produce a near-normal maximal force output. This supports the concept of localized micro-trauma (see Section 1.9.4). A further explanation is that the pain was not coming from the superficial body of the masseter muscle (where the recording electrodes were placed) but from the deep fibres of the masseter, or possibly from the lateral pterygoid muscle.

There was an interesting difference in bite force values between the different age-matched pairs in the patient and control groups and this emphasised the importance of age-matching, at least in females. The large difference in maximum bite force between these two female groups and the young male group was expected.

The shifts in median frequency during the sustained contraction at 50% MVC were considerably less in the patients than in the controls or males, but the differences were not statistically significant. The failure to show significance was possibly due to the small number of volunteers in each group, and also to the large standard deviations in the mean values. However, for each individual in the age-matched pairs there was a considerable difference, with the patients showing less decrease, i.e. becoming less fatigued, than the controls. This was unexpected and is difficult to explain; a possibility is that only a small part of the muscle was involved in the disorder, or more likely that coactivation had taken place in the patients to compensate for the disorder. The side affected by CMD had no obvious effect on shift in median frequency, as may be seen in Table 6.2.

During the sustained contraction at 25% MVC the differences in median frequency shift between the groups was smaller than shown during the contraction at 50% MVC but still evident, particularly between the patients and controls. The frequency shift was slightly greater in the control group. This is the same effect as seen at the 50% MVC level and suggests that this difference in frequency shift was not entirely due to chance.

The magnitude of the half-relaxation times was larger than expected (Table 6.4). Previous workers (Edwards, Hill & Jones, 1972) found relaxation half-times of 30.6 msec for the quadriceps muscle, 29.3 msec for flexor pollicis brevis, and 30.0 msec for the first dorsal interosseous muscle, these values rising by a factor of two or three with fatigue. They found that recovery was very quick, being 50% complete in 10 seconds. The longer duration found in the present experiment was unlikely to be due to a slow response rate in the recording apparatus (see Sections 6.3.2 and 6.4.3), and so some other explanation is required. The most likely explanation is that the surface electrodes were not detecting all the activity in the masseter and some undetected activity remained, effectively slowing the rate of relaxation. The difference between the masseter muscles and those cited above is that the mechanical system to which they are linked is more complex. There are more muscles involved in controlling movement, with more complex control of the relaxed or postural position. The masseter muscles form a smaller percentage mass of muscle controlling mandibular movement than is the case in the muscle systems investigated by Edwards, Hill & Jones (1972). It is considered that tissue elasticity plays a significant role in mandibular resting posture (Yemm & Berry, 1969) and also in resistance to movement of limbs (Bierman & Ralston, 1965); perhaps the ratio of tissue mass to elasticity or friction is different in the jaws to that in the limbs. Possibly the degree of jaw opening, or muscle length, has resulted in longer relaxation half-times. The muscles were lengthened by the bite force transducer and were held at this length after the masseter muscles had relaxed.

An alternative and simpler explanation is that the volunteers were not consciously relaxing as quickly or as completely as possible. This seems very unlikely as two volunteers (JG and PB) were specifically instructed on this matter and encouraged to relax quickly and completely, but their relaxation half-times were of the same order of magnitude as those of the remaining volunteers (see intercept values in Tables 6.5 and 6.6). Relaxation half-times were not recorded with the masseter muscles completely fresh but only after 10 seconds of sustained contraction. While no reliance can be placed on the extrapolation from regression lines, the intercept values are likely to be of the same order of magnitude as the values that would have been recorded from fresh muscles.

A regression analysis was carried out on the raw data in order to reduce this to a form more convenient for analysis. The initial value is provided by the intercept, the trend by the slope and the scatter by the regression coefficient. Since the summarised data was represented by both slope and intercept together, a multivariate analysis of variance was performed (Table 6.7) using Pillais, Hotellings and Wilks tests (SPSS/PC+ software). Pillais is the most robust test of the three and so should be used with a small sample size. In the example shown in Table 6.7 the significance level should be considered 0.087 rather than the 0.048 provided by the Hotellings test. Hotellings test is unreliable if there are significant departures from normality, and with a small sample size this is difficult to ascertain.

It can be seen from Figures 6.5-6.8 that there are obvious trends shown by the regression lines. The relaxation half-times increased more in the control group than in the patient group, during both levels of sustained contraction. This indicator of increased fatigue in the control group compared to the patients is supported by the greater shift in median frequency discussed above. Moreover, reduction in half-relaxation times during the recovery period following both levels of sustained contraction was more rapid in the control group, indicating a greater rate of recovery in the control group compared to the patient group. With such a small sample size a significance at the 10% level (as shown by Pillais test) is indicative of a real difference between the rates of recovery of the patients and the controls.

The mean correlation coefficients of the relaxation half-times were lower in the patients than in both the controls and the males, indicating greater scatter of data in the patient group (Tables 6.5 and 6.6). When analysing the signals it was found that there was more ongoing EMG activity during relaxation in this group, making measurement of relaxation half-time difficult; the presence of continued activity made it difficult to decide on the appropriate point from which to measure the half-time (Figure 6.11). The presence of on-going EMG activity after relaxation in individuals with myogenous CMD was to be expected from clinical experience and also from the work of Lous, Sheikholeslam & Moller (1970). These workers demonstrated a higher level of postural activity in the masseter and temporalis muscles of patients; this higher level occured in one muscle and not all, suggesting that the cause was not emotional tension but a more specific factor.

This continued activity at rest and the slower rate of recovery fits with the clinical picture of patients with myogenous CMD.

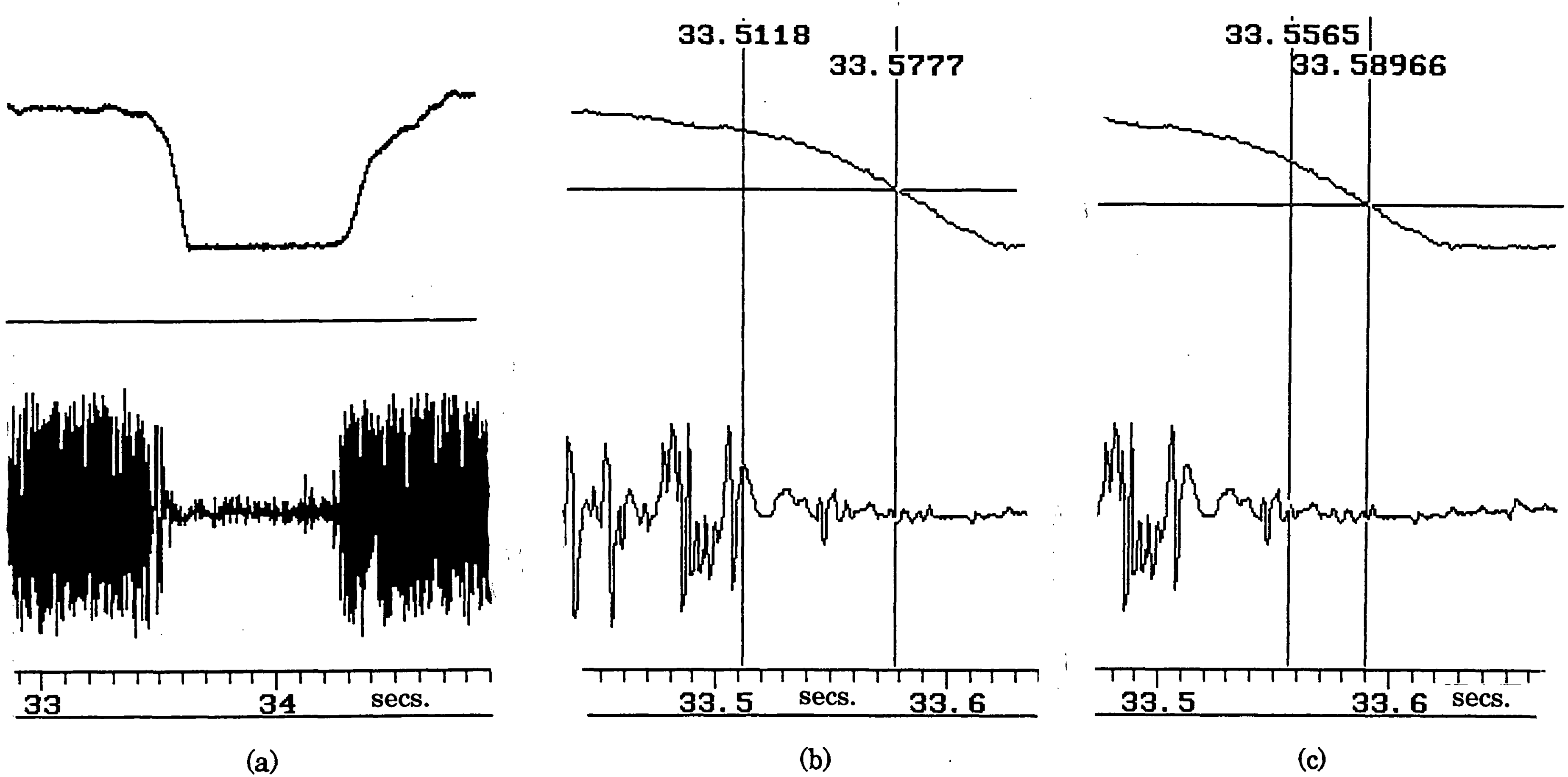


Figure 6.11 Measurement of relaxation half-time in a volunteer (JG) with some on-going EMG activity. (a) An overview of a brief relaxation (b) one possible position for measurement gives a half-time of 66 msec (c) an alternative position for measurement gives a half-time of 33 msec. The numbers on the vertical cursors indicate time in seconds.

6.6 CONCLUSIONS

In view of the small sample size and the variability of the data, the conclusions drawn from this experiment cannot be considered conclusive. The conclusions were as follows:

1. It is important to age and sex-match controls with patients.

2. The patients with myogenous CMD in this sample did not have a reduced maximum bite force compared with healthy controls.

3. The patients in this sample had less increase in relaxation half-times than controls during a sustained contraction.

4. Relaxation half-times of the patients recovered more slowly than those of the controls.

5. The patients had a reduced shift in median frequency of the power spectrum compared to the controls.

6. The patients with myogenous CMD in this sample had less measurable fatigue in their masseter muscles than the healthy controls, but recovered less quickly.

7. The patients in this sample had more on-going EMG activity after relaxation of mechanical force than did the controls.

CHAPTER 7.

GENERAL DISCUSSION AND CONCLUSIONS

7.1 GENERAL DISCUSSION

This work was undertaken to investigate the manner in which the masseter and anterior temporalis muscles withstand fatigue, and the occurrence of fatigue in patients with CMD. After a review of the relevant literature it was clear that attention had to be paid to more accurate diagnosis of CMD and more careful use of standardized terms. It was also apparent that CMD is a group of related disorders rather than one disorder. The failure of many studies to include a control group matched for age and sex was reported in Chapter 1.

There was little evidence in the literature that fatigue leads to muscle spasm, nor was the possible link between fatigue and muscle pain established. It is generally believed that localised muscle fatigue plays a central role in the complex of symptoms of CMD, but this hypothesis has not yet been proven.

The stomatognathic system has some advantages over other systems for certain physiological studies, principally because of the invariable reference point provided by the teeth. However, there are disadvantages: the medial pterygoid is a large jaw-elevator but is relatively inaccessible; the difficulty of recording the force output of an individual muscle; the inaccessibility of the motor nerve supply; and the occurrence of rotation of synergist muscle activity in particular. Activity occurs bilaterally and not in isolation, and frequently activity may change from one side to the other subconsciously. The extensive muscle compartmentalisation and the occurence of coactivation may lead to difficulty in the interpretation of results.

The stomatognathic system has special emotional significance throughout life. This is relevant when considering parafunctional activity, and bruxism in particular. Bruxism is generally considered to be a centrally induced activity enhanced by stress, but the reason for this behaviour remains unclear. A plausible explanation is that of thegosis, a phenomenon postulated by Every (1960, 1965). He proposed that in both primate and non-primate species the teeth are ground in order to maintain sharpness for defence, and that a vestige of this instinct may still be present in humans.

7.1.1 Bite Force and Endurance

The maximum bite force and endurance in bruxists was investigated in Chapter 3. It was decided to place the bite force transducer between the canine teeth because these teeth are often severely worn in bruxists and so this is presumably the position of the mandible (a laterotrusive mandibular position) in which parafunctional activity takes place. There was often a large difference in both horizontal and vertical overlap between bruxists and controls because of the degree of attrition. This meant that the mandible was in a different position (in relation to the maxilla) in the two groups, which brings into question the validity of directly comparing bite force and endurance values between these two groups.

Most volunteers found it quite uncomfortable to apply force in this laterotrusive position with the canines separated by 7 mm; this is approximately 25% of maximum opening. Heavy effort in this position induced considerable pain on the contralateral side, and it was not clear whether this was from the joint or from muscle. The most likely explanation is that protrusion of the contralateral condyle (which was beyond the parafunctional position because of the degree of opening) led to pain in the lateral pterygoid and some of the fibres of the masseter muscle on that side. The limit of endurance was pain rather than an inability of the muscles to continue the effort.

In an experiment where the bite force transducer was placed between the second premolar and first molar teeth (Chapter 5) it was found that the endurance times were slightly longer. It is true that this was a group of healthy volunteers with no history of bruxism or CMD, but in addition to the slightly longer endurance times there was also less contralateral pain. These differences could well have been due to the more centralised position of the mandible.

It was interesting that both bite force and endurance times were increased when clenching with the teeth together i.e. not using the bite force transducer; the bite force values in this case were obviously calculated values (see Section 5.5). The reasons for these increased values are clear: the condyles were centralised, the muscles were functioning at optimum length, there was no discomfort to the teeth induced by a bite force transducer, and there was probably a greatly reduced inhibiting influence from the periodontal mechanoreceptors (see Section 1.11.2).

When the bite force transducer was placed between the anterior teeth in the mid-line (Chapter 6) it was found that pain did occur, but at a later stage in the contraction. This was probably because of the brief relaxations every 10 seconds, but it is likely that some of this delay in pain onset could be attributed to the central position of effort. In this experiment (Chapter 6) pain was experienced by the patients in the area where pain had been reported before taking part, as would be expected. In the control group, and also the group of males, pain tended to predominate on either one side or the other, but was present to some degree on both sides. One of the controls (JJ) experienced considerable pain on one side for several days after the experiment, whereas all the others had no pain by the following day. The only discernable difference between this volunteer and the other controls was that she had a slightly larger horizontal overlap than the others and so required to protrude slightly more to achieve an edge-to-edge vertical relationship of her incisor teeth on the bite force transducer. This would have induced a greater effort from the lateral pterygoid muscles.

7.1.2 EMG Changes

The changes which occur in the electromyogram during localized muscle fatigue have been well documented (Section 1.4). However, because of the nature of the stomatognathic system these EMG changes have to be interpreted with care. This point is illustrated clearly in Chapter 3. An increase in EMG amplitude with time of the first dorsal interosseous muscle is regular and progressive (Figure 3.11); this increase is less easily seen in the masseter and anterior temporalis muscles, and there are greater fluctuations (Figures 3.4 and 3.10).

This variability of amplitude was also shown in Chapter 5. It was found that there was a closer correlation between the subjective perception of fatigue and median frequncy changes than between amplitude and median frequency changes. Regardless of this difference in correlation, it was clear that the volunteers were in a state of real fatigue at the end of the sustained contractions. Large fluctuations in signal amplitude are seen in many muscles in fatigue, and it may be that the masseter and anterior temporalis muscles are even more prone to this phenomenon than limb muscles.

Shift in median frequency appeared to be a better indicator of fatigue in that it correlated more closely to the subjective perception of fatigue. It has more theoretical sensitivity (Section 5.5) and is less prone to the wide fluctuations that occur in signal amplitude.

The finding in Chapter 6 that there was less shift in median frequency in the patients compared to the controls was unexpected, even though the difference was small and not statistically significant. A possible explanation was that only a small part of the muscle was affected by the disorder and that the remainder of the muscle had compensated for the small affected part. It is possible that if the electrodes had been placed in a slightly different position then the results would have been different. Surface EMG clearly does not sample the whole muscle, but 9 mm discs with a centre-to-centre separation of 20 mm are likely to sample a significant proportion of the superficial part of the masseter muscle.

7.1.3 Relaxation Rate

The magnitude of relaxation half-times was greater than expected, considering the results of Edwards et al (1972). However, the essential difference between the muscles investigated by Edwards et al (the quadriceps, first dorsal interosseous and flexor pollicis brevis) and the masseter muscles was that the masseters do not act alone to produce movement of the mandible. It is very likely that there was still some activity from either the medial pterygoid or the anterior temporalis muscles, or even deeper fibres of the masseters, to prolong the total force output. The presence of a continuing low level of EMG activity after the relaxation would have slowed the relaxation rate considerably.

In spite of this difference in magnitude there was still an increase in relaxation half-times during the course of a sustained voluntary contraction, albeit with large fluctuations. The increase was of the order of 0.5, however, not the 2 or 3 obtained by Edwards et al (1972). This could again be attributed to the number of muscles involved in any jaw movement compared to the situation in the leg or the hand where the activity of individual muscles can be isolated.

The rate of recovery was very rapid, however, with values generally returning to initial levels within 20 seconds after the end of the sustained contraction. This figure corresponded approximately to the findings of Edwards et al (1972) who found that recovery was 50% complete within 10 seconds. The rate of recovery was less likely to be affected by the number of muscles involved, and hence the closer agreement of these figures.

7.2 CONCLUSIONS

The conclusions to be drawn from this work may be summarised as follows:

1. The position of bite force transducers is important and these should be placed either in the mid-line anteriorly or on both sides posteriorly. If these are placed on one side posteriorly then contralateral pain is usually induced. This will have an effect on bite force values and endurance times.

2. Groups of patients should be age and sex-matched with control groups, and other variables such as relative jaw size and parafunctional habits should also be considered.

3. The T-Scan system is of no value in the measurement of bite force and could be misleading.

4. The changes in EMG amplitude and power spectrum median frequency during a sustained isometric voluntary contraction are closely correlated to subjective perception of fatigue; the median frequency is correlated rather more closely than amplitude change.

5. Patients with CMD have more ongoing EMG activity than healthy controls when relaxing after voluntary sustained contractions.

6. The study of jaw-closing muscle relaxation rate is complicated by the number of muscles involved, but in the small sample studied the masseter relaxation half-times were longer than has been found in studies of limb muscles; relaxation half-times also increased less in the patient group but recovered more slowly than in the control group.

7. The shift in median frequency of the power spectrum is a more useful indicator of fatigue in the jaw-closing muscles than increase in EMG amplitude or increase in relaxation half-times.

AREAS FOR FUTURE RESEARCH

The application of the twitch interpolation technique (described on page 29) to the jaw-closing muscles might be useful in the investigation of maximum bite force values and should be pursued. The recent availability of a new force-sensing material also warrants assessment for use in monitoring bite force.

Rotation of synergist activity has been demonstrated to occur between the masseter and anterior temporalis muscles (Hellsing & Lindstrom, 1983), and it would be of interest to attempt to replicate these results and to investigate the role of the medial pterygoid muscle in rotation.

The investigation of control properties of motor units perhaps provides the most promising avenue of research in the study of the jaw-closing muscles and their involvement in CMD. The use of the low frequency part of the power spectrum (below 40 Hz) may be of value in this endeavour.

APPENDIX A.

FUND RAISING

The experiment reported in Chapter 2 was carried out with equipment on loan from the Institute of Physiology, University of Glasgow. The EMG signals were amplified, filtered, integrated, and then passed directly to a chart recorder. The hard copy was then analysed manually. It was clear that funds would have to be raised to enable the purchase of EMG equipment to detect at least four channels of data and record this raw data for subsequent off-line analysis.

In November 1988 a Medical Research Travel Grant to the value of £895 from the Scottish Hospital Endowments Research Trust was obtained. The purpose of this grant was to visit Dr Gustaf Hellsing of the Department of Clinical Oral Physiology, Karolinska Institute, Stockholm, in order to learn more on frequency analysis of surface EMG signals and the application of Lindstrom's EMG Fatigue Index. The period of the visit was from the 22nd January to the 3rd of February 1989.

In January 1990 an application to the Greater Glasgow Health Board for the sum of £10,195 for non-recurring expenditure was approved. This sum enabled the purchase of a Neurolog Power Supply, NL107 recorder amplifier, NL 820 isolator, four NL125 filters, four NL705 RMS integrators, a four-channel isolating pre-amplifier, PCM-8 video adapter, video recorder, mobile rack.

A Tektronix oscilloscope and a Devices four-channel chart recorder are on long-term loan from the Institute of Physiology, and these complete the equipment required.

Disposable items have been purchased from the departmental and general research funds of the Department of Prosthodontics and the Institute of Physiology. The metal beams of the bite force transducer were constructed at no cost to the project by the West of Scotland Health Board's Department of Clinical Physics and Bio-Engineering.

APPENDIX B

SIGNAL PROCESSING THEORY

The analysis of EMG signals may be in the time domain (rectification, smoothing, integration, RMS value) which is based on the autocorrelation function, or in the frequency domain (Fast Fourier transforms are used to obtain the power density spectrum) which is based on the spectral density function. The autocorrelation function and the spectral density function are useful characteristics of random signals because they contain all the first- and second-order statistical properties of the signal (Kwatney, Thomas & Kwatney, 1970). The spectral density function describes how the variation in a time series (a collection of observations made sequentially in time) may be accounted for by cyclic components at different frequencies. This function is estimated by a procedure called spectral analysis. Spectral analysis is essentially a non-parametric statistical procedure in which a finite set of observations is used to estimate a function defined over a range (Chatfield, 1975). A non-parametric method of analysis is used for data that does not follow any recognised distribution pattern i.e. data which is non-Normal.

A new development is time-frequency analysis of the reduced interference distribution of the electromyogram. This produces high resolution which reveals details not visible when using other distributions (Widmalm et al, 1990; Shi & Hua, 1992).

The spectrum is best plotted with linear scales rather than logarithmic scales as a logarithmic scale would tend to compress the spectrum (Basmajian & De Luca, 1985). Plotting on a logarithmic scale exaggerates the visual effects of variations where the spectrum is small. When plotted on an arithmetic scale the area under the graph corresponds to power and so it is easier to assess the importance of various peaks. Logarithmic scales are often used in other disciplines, such as acoustics. The frequency scale can be measured in cycles per unit time or radians per unit time, but a spectrum is more easily interpreted if cycles per unit time are used.

The three parameters which are most often used to describe a spectrum are the mean frequency, the median frequency and the bandwidth. The median frequency was found by Stulen & De Luca (1981) to be less sensitive to noise than the mean frequency. The bandwidth is essentially a window in the frequency domain. Basmajian & de Luca (1985) state that the components of an EMG signal below 20 Hz are unstable and therefore the low frequency 3 dB point should be set at 20 Hz. The high frequency 3 dB point should be set at slightly higher than the highest frequency of the signal.

The ratio of the output voltage to the input voltage is measured as a gain andit is, like all ratios, unitless. Magnitude and gain are usually measured in dB, and a gain of $0.707 = \sqrt{0.5} = 3$dB. An octave is a doubling of the frequency and a decade is an order of magnitude. The value of the frequency where the gain decreases by 3 dB is the cutoff frequency or 3 dB point. A 3-dB drop is the same as a 50% drop in a linear scale representation of the power spectrum, and can therefore be called a half-power frequency.

For any AC wave or sine wave:

effective voltage = RMS voltage

= peak voltage X 0.707

(Wallace, 1960)

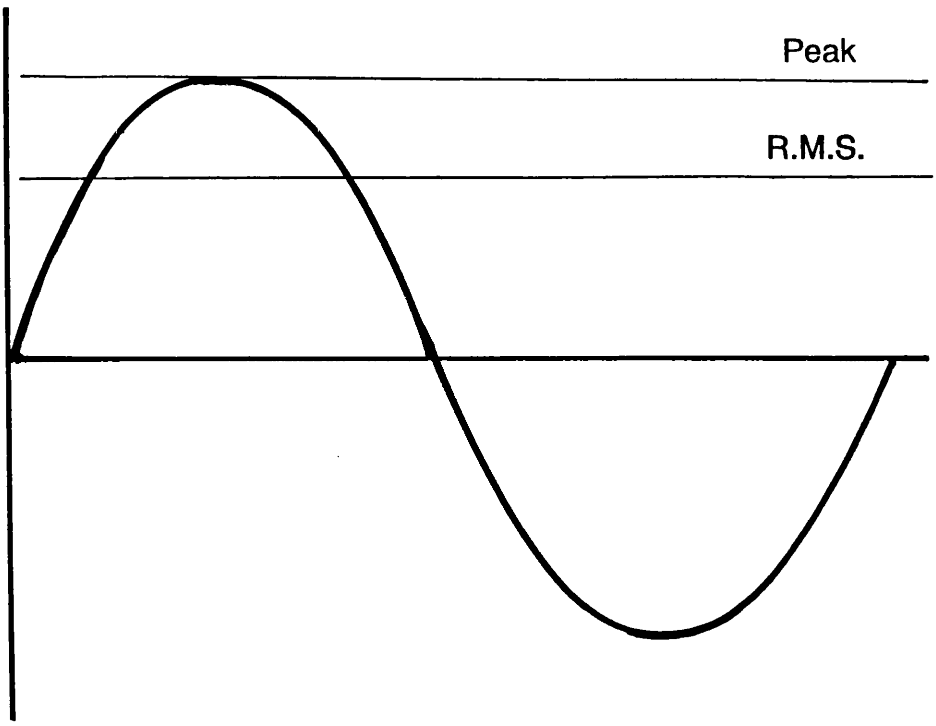


Figure B.1. A representation of the RMS value of a sine wave.

Spectral analysis (spectrum analysis) is the name given to methods of estimating the spectral density function (or spectrum) of a given time series (Chatfield, 1975). This describes how the variation in a time series may be accounted for by cyclic components at different frequencies. It is concerned with estimating the spectrum over the whole range of frequencies. Spectral analysis is a modification of Fourier analysis so that it is suitable for stochastic rather than deterministic functions of time. A deterministic time series is one that can be predicted exactly, whereas a stochastic time series is one in which the future is only partly determined by past values. Fourier transforms have long been used when dealing with a continuous waveform, and when a waveform is sampled it is the discrete version of the Fourier transform which is used. The fast Fourier transform (FFT) is a more efficient way of calculating the discrete Fourier transform (Bergland, 1969). The fast Fourier transform provides point estimates of the spectral density function at different frequencies.

The Nyquist frequency is the highest frequency about which meaningful information can be obtained from a set of data. It is the upper limit of the spectral distribution function.

There are several methods of obtaining a consistent estimate of the power spectral density function. Before carrying out an FFT on a signal, any obvious trends should be removed first otherwise they will dominate the analysis. A trend may be defined as a long-term change in the mean and will produce a peak at zero frequency. The removal of trend and tapering are achieved by performing a straight-line fit and then applying a cosine bell to the first and last 10% of the samples in each record (Barker, Wastell & Duxbury, 1989). This application of a raised cosine window to the first and last 10% of the data, with a weight of unity being applied in between, is called Tukey's "interim" data window and the objective is to reduce leakage. Another window which can be applied is the Hanning window, which is a cosine bell on a pedestal (Bergland, 1969). The procedure, then, is to de-trend, take out the pedestal, and taper.

The autocorrelation function is a valuable intermediate stage and can be calculated by performing two FFT's. To reduce the computations, zeros can be added to the mean-corrected sample record so as to increase the value of N until it is a suitable integer, and this should be accompanied by tapering (Chatfield, 1975; Godfrey, 1974).

In comparing different spectral windows, the bias, variance and bandwidth should be considered. The wider the window, the larger will be the bias. The choice of bandwidth is an important step in spectral analysis. The bandwidth is the width of the "ideal" rectangular window which would give an estimator with the same variance (Chatfield, 1975). The bandwidths that have been used with surface electrodes on the masseter muscle are 1-600 Hz (Duxbury, Hughes and Clark, 1976), 8-800 Hz (Lindstrom and Hellsing, 1983) and 10-1000Hz (Palla and Ash, 1981).

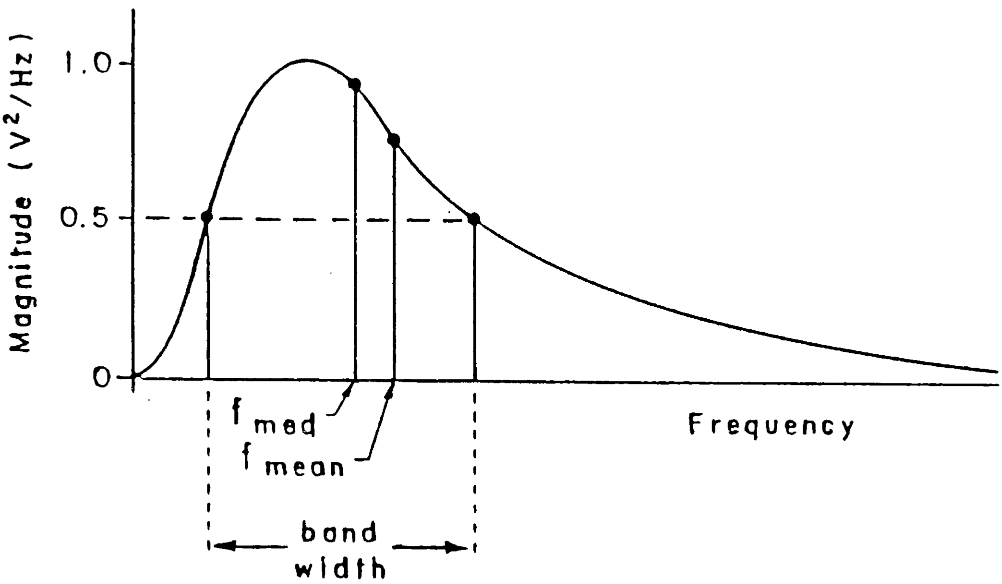


Figure B.2 The concept of band width, reproduced from Basmajian & De Luca, 1985.

A continuous time series can be converted into a standard discrete time series by taking values at equal time intervals i.e to digitize the series. The main question is how to choose the sampling interval. If the maximum frequency is known then the choice of sampling interval is straightforward. The Shannon Sampling Theorem states that at least two samples per cycle of the highest frequency of the signal must be taken (Geister, McCall & Ash, 1975). If the sampling interval is too large then aliasing may occur. This is where variation at frequencies above the Nyquist frequency will be folded back and produce an effect at a frequency lower than the Nyquist frequency. In other words, high frequency components can impersonate low frequencies if the sampling rate is too low (Bergland, 1969). The estimate of the spectrum should approach zero near the Nyquist frequency if the sampling interval is small enough.

If the spectrum is large at low frequencies it could indicate non-stationarity in the mean, as discussed previously. This is one of the factors to look for when interpreting the results of an estimation. The other two factors are peaks and general shape in the spectrum.

In summary, three important points which should be considered in spectral analysis are sampling rate, removal of trend and tapering, and the choice of bandwidth. The length of the data record is also important as it is proportional to the resolution. For masseter and temporalis muscles two seconds would be sufficient (Andrews, personal communication).

APPENDIX C.

GLOSSARY OF TERMS

This Glossary is compiled from the following sources: Dorland, 1977; the *ad hoc* Committee of the International Society of Electrophysiological Kinesiology, 1980; British Standard (BS 4492) Glossary of Dental Terms, 1983; Basmajian & De Luca, 1985; Glossary of Prosthodontic Terms, 1987; McNeill, 1990.

Alpha-Motoneuron: The neural structure whose cell body is located in the anterior horn of the spinal cord and which, through its relatively large diameter axon and terminal branches, innervates a group of muscle fibres.

3-dB Bandwidth: The difference between the upper and lower 3-dB frequencies, or half-power frequencies.

Bruxism: The parafunctional grinding of teeth.

Common-mode Rejection Ratio: A performance characteristic of a differential amplifier (used with a bipolar electrode configuration). The ability to cancel out noise. The higher the CMRR the better the cancellation. The recommended CMRR is 100 dB (Basmajian & De Luca, 1985).

Craniomandibular Disorders: A collective term embracing a number of clinical problems that involve the masticatory musculature, the temporomandibular joint, or both.

Deflective Occlusal Contact: A tooth-to-tooth contact that changes the direction of mandibular movement during closure.

Eccentric contraction: The muscle is lengthening under tension.

Eccentric: (Dental) an adjective denoting any position other than that which is a centric position.

Fasciculation: A small local involuntary muscular contraction visible under the skin, representing spontaneous discharge of a number of fibres innervated by a single motor nerve filament.

Input Impedance: A characteristic of a differential amplifier which should be above 10^{12} ohms in order to minimise wave-shape distortion and signal attenuation.

Isometric Contraction: The muscle maintains a fixed length.

Isotonic Contraction: The muscle maintains a constant force.

Integration: The calculation of the area under a signal or curve. An EMG signal has an integrated value of zero, and so this calculation can only be applied to the rectified signal.

Motor Unit: The smallest controllable muscular unit. It consists of a single α-motoneuron, its neuromuscular junction, and the muscle fibres it innervates (between 3 and 2000).

Motor Unit Firing Rate: The average firing rate of a motor unit over a given period of time. The estimate should include a calculation of at least six consecutive inter-pulse intervals.

Myositis: A painful generalised inflammation, usually of the entire muscle. May also occur in tendinous attachments of the muscle.

Occlusal Device (Splint): Any removable artificial occlusal surface used for diagnosis or therapy regarding the relationship of the mandible to the maxillae. It may be used for stabilization, for TMJ dysfunction therapy, or to prevent wear of the dentition.

Overlap, vertical: The projection in a vertical direction of teeth in one arch beyond their antagonists.

Rate Modulation: The control of force output of a muscle by variation of motor unit firing rate.

Recruitment: The involvement of additional motor units to contribute to muscle force output.

Rectification: Including only the positive waves of a signal. Can have half-wave or full-wave rectification, the latter inverting the negative part of the signal.

Rectified Integrated EMG: The EMG signal is full-wave rectified and then integrated over a fixed time period.

Spasm: A sudden, violent, involuntary muscular contraction.

Synchronization: The tendency for a motor unit to discharge at or near the time that another motor unit discharges.

Synergist Muscle: One which actively provides an additive contribution to a particular function during a contraction.

APPENDIX D.

CONSTRUCTION OF THE BITE FORCE TRANSDUCER

The bite force transducer was constructed from 3mm stainless steel sheet, cut to form two stiff beams and separated by a stainless steel spacer (Figure D.1). The three parts were held together by two 4mm stainless steel bolts. The dimensions were finalised by trial-and-error, as the instrument had to be as thin as possible and yet stiff enough to resist maximum biting forces without permanent deformation.

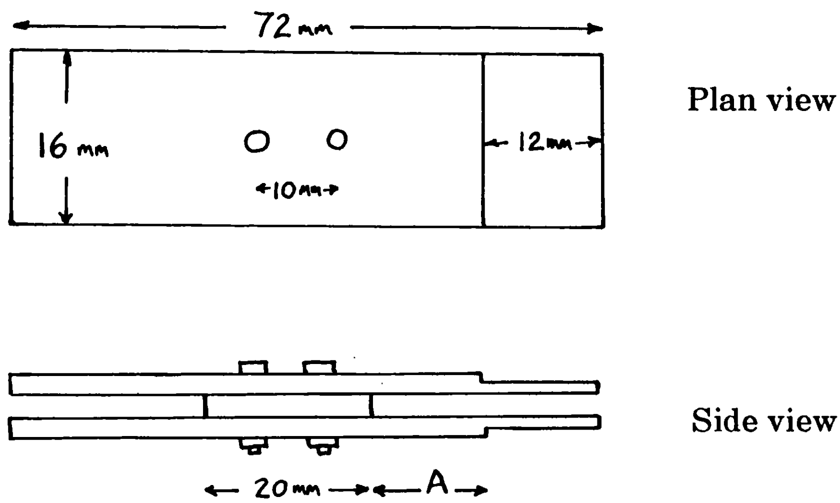


Figure D.1 Drawings of the stainless steel elements of the bite force transducer.

Two strain gauges were attached to each side of one of the beams, so that two were in tension and two in compression when the beams were loaded (Figure D.2). The strain gauges were compensated for mild steel, 8mm long, and with a resistance of 120Ω (RS Components Ltd, stock number 308-102). They were attached to the metal beam with rapid setting epoxy resin (Araldite Rapid) and wired to form a Wheatstone bridge circuit (Figure D.3 and D.4). A Wheatstone bridge circuit is commonly used for the rapid and precise measurement of resistance. The strain gauges were connected to a 2m four-core braided cable (NL953, Digitimer Ltd). This cable is supplied with a Lemo F00304 male connector on one end, and this mates with the input socket of the recorder amplifier (NL107, Digitimer Ltd). The part of the beam with the strain gauges attached was coated with a proprietary silicone rubber compound in order to effect a watertight seal (Figure D.5).

Calibration of the instrument was carried out against known weights prior to the experiment reported in Chapter 3, but a NENE universal testing machine was used for calibration prior to later experiments. The response of the bite force transducer was found to be linear in the range tested (50-300N) and consistent between sessions.

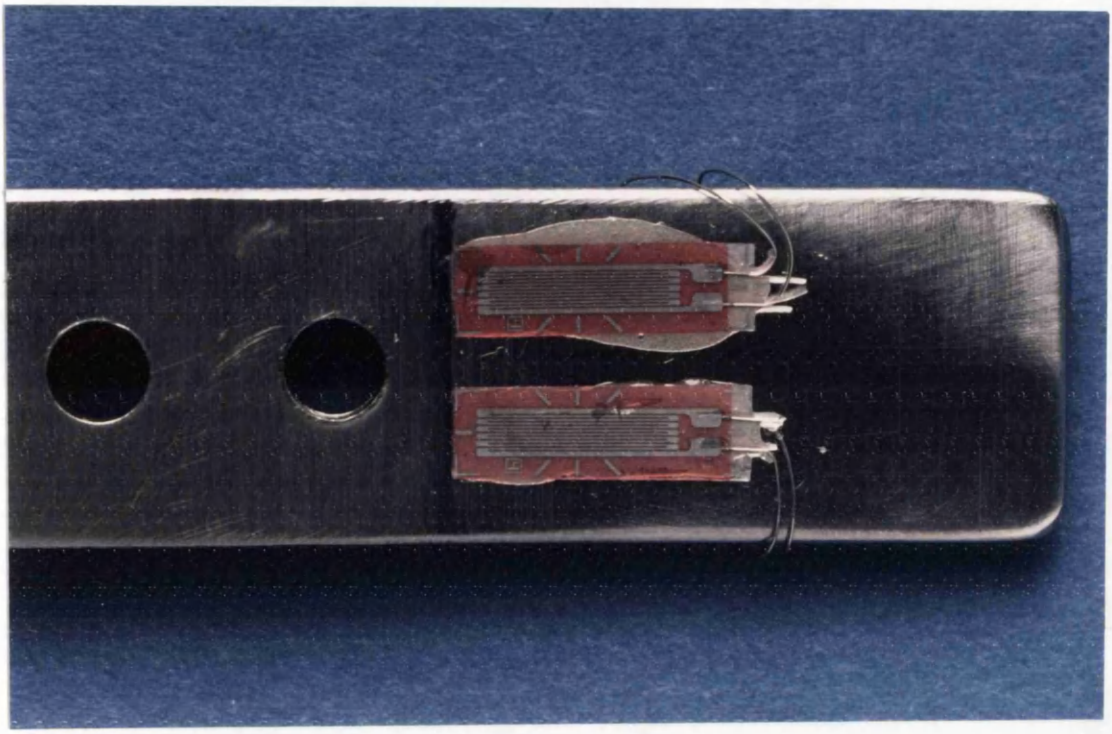


Figure D.2 Two strain gauges attached to one beam of the bite force transducer.

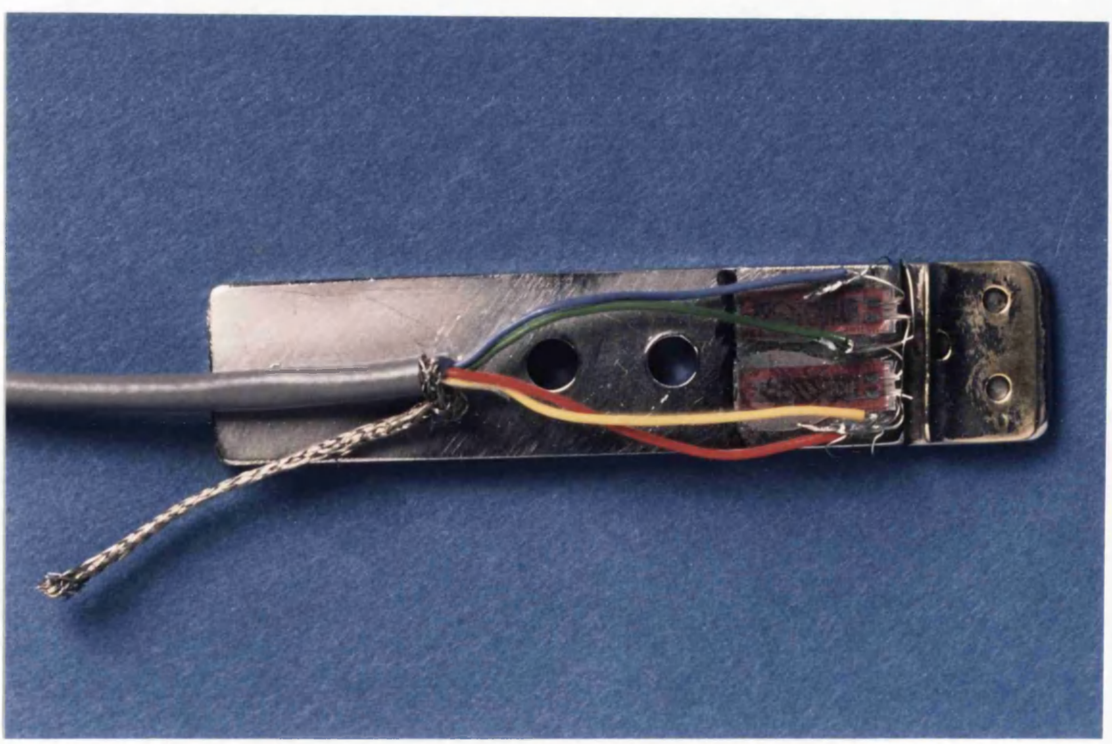


Figure D.3 The cable attached to the strain gauges.

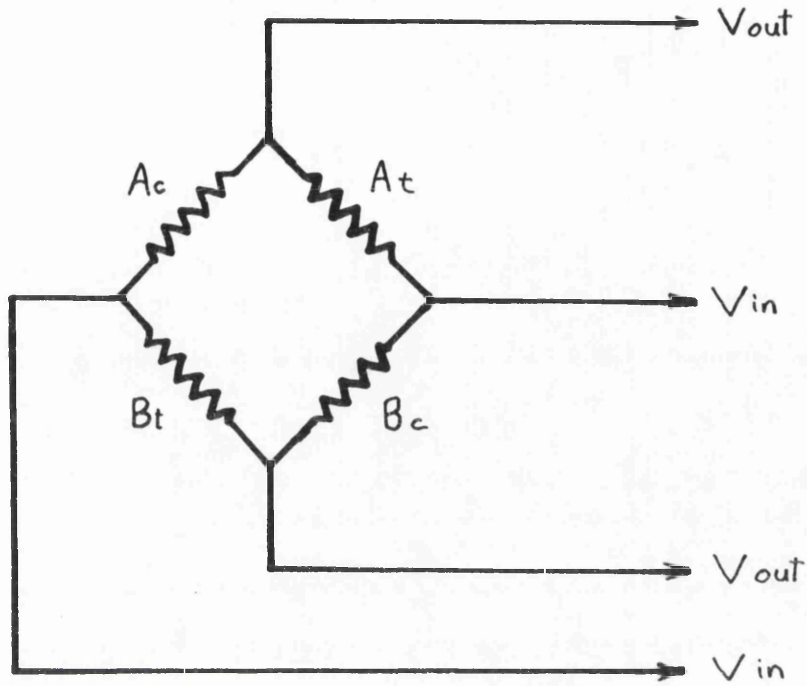


Figure D.4 The manner in which the strain gauges were wired to form a Wheatstone bridge circuit. c = compression, t = tension.

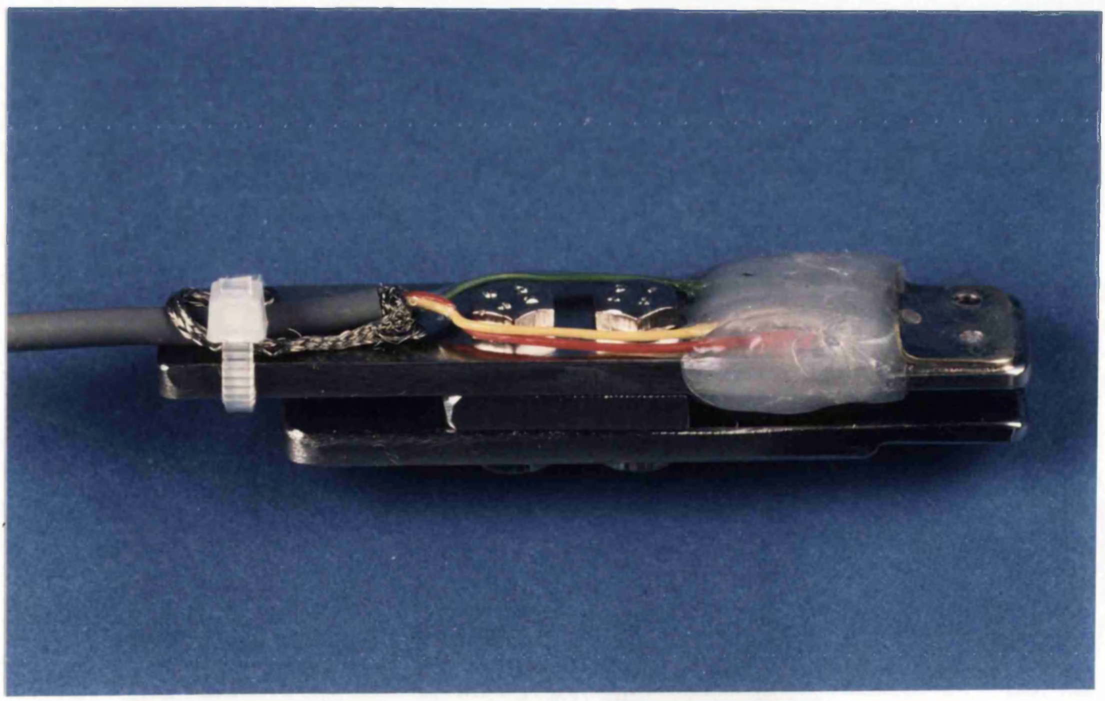


Figure D.5 The completed bite force transducer, showing the covering of silicone rubber.

APPENDIX E.

NAMES AND ADDRESSES OF COMPANIES SUPPLYING EQUIPMENT AND MATERIALS

Digitimer Limited
14 Tewin Court
Welwyn Garden City
Hertfordshire AL7 1AF

Specialised Laboratory Equipment Limited
15 Campbell Road
Croydon
Surrey CRO 2SQ

Medical Systems Corporation
One Plaza Road
Greenvale
NY 11548, USA

Link 51 (Storage Products) Limited
5/7 Colvilles Road
Kelvin Industrial Estate
East Kilbride G75 ORS

Radio Spares
P.O. Box 99
Corby
Northamptonshire NN17 9RS

Stag Instruments Limited
16 Monument Industrial Park
Chalgrove
Oxon. OX9 7RW

Tektronix Incorporated
Beaverton
OR 97077, USA

Cambridge Electronic Design Limited
Science Park
Milton Road
Cambridge CB4 4FE

Tekscan Incorporated
237 Lewis Wharf
Boston, MA 02110
USA

Cottrell and Company
15-17 Charlotte Street
London W1P 2AA

APPENDIX F

PROFORMA USED IN THE EXAMINATION AND DIAGNOSIS OF PATIENTS WITH CRANIOMANDIBULAR DISORDERS

The following proforma was initiated and developed by the author, with constructive comments from Professor Iven Klineberg and Dr I.B. Watson. This proforma was used in the examination and diagnosis of the patients who participated in this research project. It was considered essential that all relevant information was collected and an accurate diagnosis made to ensure the validity of the project.

GLASGOW DENTAL HOSPITAL AND SCHOOL

DEPARTMENT OF PROSTHODONTICS

CRANIOMANDIBULAR DISORDERS

Name:________________________________ D.o.B.:____________

Address:______________________________

____

______________________________ Postcode:__________

Occupation:___________________________

Consultant:____________________________ Date:______________

Clinician:_____________________________

Referred by:___________________________

Primary referral: Yes ☐ No ☐

Reason for referral:

Main complaint (patient's own words):

History of complaint:

Previous treatment:

Relevant Medical History:

Parafunctional Habits:

None ☐

Clenching ☐
Grinding ☐
Gum-chewing ☐
Biting soft tissues ☐
Biting objects ☐

Nocturnal ☐
Diurnal ☐
Both ☐

Headache:

None ☐

Frontal ☐
Ant temporal ☐
Post temporal ☐
Occipital ☐

Left ☐
Right ☐
Mid-line ☐

Morning ☐
Evening ☐
Any time ☐

Occurs every day ☐ every few days ☐

every few weeks ☐

Occurs only at times of stress ☐

CLINICAL EXAMINATION

Muscle Palpation (0= none, 1= mild, 2= moderate, 3= severe)

Date:								
	R.	L.	R.	L.	R.	L.	R.	L.
Temporalis - ant:								
post:								
Masseter:								
Lat. pterygoid:								
Med. pterygoid:								
Sternomastoid:								
Trapezius:								
Tongue:								
Total score:								

TM Joint Signs
(0= none, 1= mild, 2= moderate, 3= severe)

Date:								
	R.	L.	R.	L.	R.	L.	R.	L.
Pain on palpation - lat:								
post:								
Click - opening:								
closing:								
Closed lock:								
Crepitation:								
Subluxation:								
Total score:								

"End feel": elastic and painless ☐
stiff or limiting ☐

Joint play: smooth ☐
rough ☐

Mandibular Movement

Date:								
	mm	pain	mm	pain	mm	pain	mm	pain
Opening (inter-incisor distance)								
Maximum protrusion:								
Maximum Laterotrusion Right:								
Left:								
Total score:								

Deviation on opening: to R. ☐
to L. ☐

Occlusion

Jaw relationship: Cl 1 ☐ Cl 2 div 1 ☐
Cl 2 div2 ☐ Cl 3 ☐

Teeth present:

8	7	6	5	4	3	2	1	1	2	3	4	5	6	7	8
8	7	6	5	4	3	2	1	1	2	3	4	5	6	7	8

Dentures: No ☐ Yes - partial upper ☐ partial lower ☐
complete denture in one arch ☐
complete dentures ☐

Degree of attrition: ☐

(0= nil, 1= enamel only, 2= dentine, 3= dentine extensively, 4= secondary dentine.
Score the most severely involved tooth)

Buccal mucosa ridging: yes ☐ no ☐
Tongue ridging: yes ☐ no ☐

Freeway space (mm): ☐

RCP - ICP slide: mainly vertical ☐
mainly horizontal ☐
nil ☐

Non-working side contacts: none ☐
yes, on L. excursion ☐
yes, on R. excursion ☐

Special Tests

Study casts: yes ☐
no ☐

Radiographs taken: no ☐
OPT ☐
Zone arc ☐

Other special tests:

DIAGNOSIS

1.Muscle disorder	- myogenous pain (myofascial pain, myositis)	☐
	- spasm	☐
	- reflex splinting	☐
	- hypertrophy	☐
2. Joint disorder	- deviation in form	☐
	- disc displacement:	
	with reduction (reciprocal click)	☐
	without reduction (closed lock)	☐
	- hypermobility	☐
	- dislocation	☐
	- inflammatory conditions: synovitis/capsulitis	☐
	- arthritides:	
	osteoarthrosis	☐
	osteoarthritis	☐
	polyarthritis	☐
	- ankylosis	
	fibrous	☐
	bony	☐
3. Combined joint and muscle disorder		☐
4. Psychological factors:		

TREATMENT PLAN

SUMMARY OF ATTENDANCES

Date	

APPENDIX G.

LETTERS OF APPROVAL FROM THE ETHICS COMMITTEE

Letters of approval from the Area Dental Ethics Committee of the Greater Glasgow Health Board are reproduced on the following pages. These letters of approval relate to the experiments carried out in preparation for this thesis.

GREATER GLASGOW HEALTH BOARD

Royal Beatson Memorial Hospital
132 Hill Street, Glasgow G3 6UD
Tel: 041-332 2600 - Health Board
041-332 2525 - Personnel/
Supplies/Information Services

Our Ref.: RMcK/EMcG

Your Ref.:

If 'phoning ask for:— Mr R. McKechnie

30 January 1989

All communications must be addressed to
Chief Administrative Dental Officer
Glasgow Dental Hospital and School
378 Sauchiehall Street
Glasgow G2 3JZ

Telephone: 041-332 7020
Ext. 280/325

Mr Mervyn F. Lyons
Lecturer/PhD Student
Hon. Dental Surgeon
Dept. of Prosthodontics
Glasgow Dental Hospital and School
378 Sauchiehall Street
Glasgow
G2 3JZ

Dear Mr Lyons

AREA DENTAL ETHICS COMMITTEE

I write to inform you that your application of 29th November 1988 for clinical research has now been approved by the Area Dental Ethics Committee at their meeting on 5 December 1988, the title of the project being:-

> "A preliminary investigation into masticatory muscle function in human subjects exhibiting advanced tooth wear"

I apologise for the long delay in informing you of the Committee's decision.

The Committee would be grateful if you would inform them of the results of your project and any ethical problems encountered whenever the project is complete.

Yours sincerely

R. McKechnie

R. McKECHNIE
Chief Administrative Dental Officer

c.c. Mr H.A. Critchlow, Chairman
Mr G. Lewis, Secretary

Greater Glasgow Health Board

GLASGOW DENTAL HOSPITAL AND SCHOOL

378 SAUCHIEHALL STREET, GLASGOW, G2 3JZ
TELEPHONE No. 041-332 7020

RMcK/EMcG

15 September 1989

Mr Mervyn F. Lyons
Dept. of Prosthodontics
Glasgow Dental Hospital and School
378 Sauchiehall Street
Glasgow G2 3JZ

Dear Mr Lyons

AREA DENTAL ETHICS COMMITTEE

I write to inform you that your application of 16 May 1989 for clinical research was considered by the Area Dental Ethics Committee at their meeting on 5 June 1989, the title of the project being:

> "An investigation of the mechanisms of fatigue in the muscles of man"

The Committee decided to withhold approval of the project pending confirmation from yourself that an information sheet and a consent form would be used and also clarification was required on the source of volunteers for your project. Your letter of 29 June 1989 covers the points raised and you may proceed with your research although the decision will not be minuted until the next formal meeting of the Area Dental Ethics Committee.

The Committee would be grateful if you would inform them of the results of your project and any ethical problems encountered whenever the project is complete.

I apologise for the long delay in replying to you.

Yours sincerely

R. McKechnie

R. McKECHNIE
Chief Administrative Dental Officer

Greater Glasgow Health Board

GLASGOW DENTAL HOSPITAL AND SCHOOL

378 SAUCHIEHALL STREET, GLASGOW, G2 3JZ
TELEPHONE No. 041-332 7020

RMcK/EMcG

15 September 1989

Mr Mervyon F. Lyons
Dept. of Prosthodontics
Glasgow Dental Hospital and School
378 Sauchiehall Street
Glasgow G2 3JZ

Dear Mr Lyons

AREA DENTAL ETHICS COMMITTEE

I write to inform you that your application for clinical research has now been considered by the members of the Area Dental Ethics Committee, the title of the project being:

> "An investigation into the efficacy of the T-Scan computerised system for occlusal analysis"

The project has been approved subject to the provision of a simple information sheet for patients who will be participating describing, in lay terms, the purpose of the investigation and the procedures involved.

You may proceed with your research although the decision will not be minuted until the next formal meeting of the Area Dental Ethics Committee.

The Committee would be grateful if you would inform them of the results of your project and any ethical problems encountered whenever the project is complete.

Yours sincerely

R. McKechnie

R. McKECHNIE
Chief Administrative Dental Officer

APPENDIX H.

PUBLISHED PAPERS

Reprints of papers which have been published on some of the material presented in this thesis are reproduced on the following pages.

Journal of Oral Rehabilitation, 1990, Volume 17, pages 311–318

A preliminary electromyographic study of bite force and jaw-closing muscle fatigue in human subjects with advanced tooth wear

M.F. LYONS *and* R.H. BAXENDALE* *Department of Prosthodontics, Dental School and *Institute of Physiology, University of Glasgow, Glasgow, Scotland, U.K.*

Summary
The maximum bite force was recorded in five experimental volunteers with advanced tooth wear and five control volunteers who showed no abnormal wear. All subjects were then asked to maintain a force of 50% of the maximum for as long as possible while surface electromyograms from the masseter and temporalis muscles were recorded. The bite force and endurance time were found to be slightly increased in the experimental group, but no conclusions could be drawn regarding the state of fatigue. Two significant problems with regard to fatigue studies of the jaw-closing muscles emerged from the study, namely the use of the canine position for recording of the force, and the thickness of the force meter.

Introduction
The problem of advanced tooth wear or, perhaps more correctly, tooth surface loss, is observed with increasing frequency in Departments of Fixed and Removable Prosthodontics. There are many reasons for this, not least being the fact that a higher percentage of the population now retain their teeth into their middle years and beyond. Patients' expectations are rising, and general dental practitioners are increasingly recognizing the process and referring such patients to specialists for an opinion or, more usually, for treatment. The latter is invariably time-consuming and expensive.

The term 'tooth surface loss' refers to the loss of surface tooth tissue as a result of attrition, erosion or abrasion, or often a combination of all three. The process of attrition was of particular interest in this study, being the loss by wear of tooth substance or a restoration caused by mastication or contact between occluding or approximal surfaces (Watson & Tulloch, 1985).

In cases of attrition, where no obvious dietary factor is involved, there is usually a history of bruxism. The forces exerted during bruxing activity have been reported to be between 30% and 60% of a maximum voluntary contraction (Clarke, Townsend & Carey, 1984), which is a large force compared to normal chewing forces. Up to 11

Correspondence: Mr M.F. Lyons, Department of Prosthodontics, Glasgow Dental Hospital and School, 378 Sauchiehall Street, Glasgow G2 3JZ, Scotland, U.K.

The subject matter of this paper was presented at the Annual Conference of the British Society for the Study of Prosthetic Dentistry 1989.

bruxing episodes during a night's sleep were also reported, with an average duration of 11 s. In addition, bruxism may occur during the day, particularly at times of stress.

It would seem reasonable to suggest that the jaw-closing muscles of bruxists might have benefited from a 'training effect' as a result of all this activity, resulting in muscles that are stronger and possibly more resistant to fatigue. The picture is not entirely clear, however, as it is likely that such activity may often occur in one particular eccentric position.

A view which is generally held regarding the aetiology of bruxism is that it is a centrally induced activity, and perhaps peripheral factors, such as occlusal irregularities, play a precipitating role. It was pointed out by Chaffin (1973) that limb muscle fatigue results in a reduced ability to perform accurate movements and to judge the exertion of light forces — it is possible that this may also have some relevance in bruxists. Furthermore, Chaffin defined localized muscle fatigue, stating, that it results in discomfort and decreased performance. The ability to perform precise coordinated movements decreases, and there is an increase in muscle tremor, as well as subjective feelings of pain and a 'desire to abandon the task'. A better understanding of fatigue in the jaw muscles of human subjects is necessary in order to advance our understanding of parafunctional activity.

One of the problems associated with the study of the jaw closing muscles is that the force output of each individual muscle cannot be measured, only their collective force. Furthermore, it has been shown by Hellsing and Lindstrom (1983) that there is a rotation of activity among the synergist muscles which is quite beyond voluntary control, and serves to complicate the situation further.

Metabolic fatigue, as opposed to fatigue resulting from an excitation failure, is a relatively gradual biochemical process that eventually results in an inability to maintain a contraction (Basmajian & De Luca, 1985). This gradual process can be detected by EMG even before a reduction of force output has occurred, as during a sustained isometric contraction the surface-detected signal has been shown to increase in power. Thus the EMG/force ratio increases, whereas during an excitation failure this ratio remains constant. The increase is due to recruitment of additional motor units in an attempt to maintain the force output (Edwards & Lippold, 1956).

In this investigation the maximum bite force, and then the integrated EMG during a sustained isometric contraction, were recorded in order to determine the strength, endurance and resistance to fatigue of the masseter and anterior temporal muscles in bruxists compared to those of normal control volunteers.

Methods

Ten volunteers participated in this study, five of whom showed advanced attrition and five of whom showed no abnormal wear. All were males aged 32–60 years. The experimental volunteers had a history of bruxism, they were partially dentate, and showed a degree of attrition corresponding to a score of 3 or 4 on the Smith and Knight Tooth Wear Index (Smith & Knight, 1984) for the occlusal or incisal surfaces. They were selected as being representative of the tooth surface loss patients referred to the Glasgow Dental Hospital and School, and were clearly the victims of attrition rather than a detectable dietary or other abnormality. The controls were also partially dentate, but did not have a history of bruxism, and showed no abnormal tooth wear. The controls and experimental volunteers were age-matched. Ethical Committee approval was obtained for the project, and informed consent was obtained from each participant.

The bite force was measured using a stainless steel bite fork with two strain gauges* attached to each side of one arm of the fork to form a Wheatstone bridge circuit. This was calibrated with standard weights before each session and checked again afterwards. The force level was displayed on an oscilloscope screen† and then fed to a 4-channel chart recorder‡.

The EMG was recorded using Copeland-Davis stainless steel surface electrodes, which are designed to maintain a constant impedance, placed in a bipolar configuration over the masseter muscle and the anterior fibres of temporalis. The electrodes were positioned with their centres 2 cm apart and parallel with the main direction of the muscle fibres, the earth electrodes being placed either on the ear lobe or on the back of the neck. The signal was amplified ×1000, optically isolated and integrated with a time constant of 200 ms. The data was stored on a 4-channel chart recorder with the paper speed set at 10 cm min^{-1}. The preferred chewing side was used for the experiment.

Small autopolymerizing acrylic resin indexes were fabricated with the canine teeth in contact with the metal faces of the bite fork. These indexes protected the teeth against the possibility of enamel fracture during heavy biting, and ensured closure in the desired position. The total thickness of the bite fork and the acrylic indexes was 7 mm.

The procedure was explained to the volunteers, and they were allowed to familiarize themselves with the bite fork and the oscilloscope screen that provided the visual feedback. The volunteers were then asked to carry out a maximum voluntary contraction (MVC) several times, with intervening rest periods, until the maximum had clearly been obtained. Each volunteer was then requested to sustain a force equal to 50% of the MVC for as long as possible. This force level was determined by observing the marker on the oscilloscope screen.

Results

The maximum bite force achieved by the attrition group was generally higher than that achieved by the controls (Fig. 1), the mean bite force being $26 \pm 2{\cdot}59$ kg ($\pm$ SE) compared to a mean value of $22 \pm 4{\cdot}81$ kg for the control group. However, two members of the control group had very large bite forces of 32 kg and 35 kg, respectively.

The time period for which each volunteer was able to sustain a contraction was termed the endurance time (Fig. 2). The mean endurance time of the attrition group was $2{\cdot}0 \pm 0{\cdot}3$ min, slightly longer than the value for the controls, which was $1{\cdot}6 \pm 0{\cdot}15$ min.

However, when these two parameters, namely bite force and endurance time, were subjected to an unpaired Student's *t*-test, no statistical differences were found between the means of the experimental and control groups.

The change in the level of the integrated EMG signal during the sustained isometric contraction, i.e. the measure of fatigue, was expressed as a percentage of the initial increase from the resting level to the level at a force of 50% MVC (Figs 3 and 4). It was observed that there was a slightly greater change in the EMG level from the temporalis muscles than from the masseters, but apart from this no particular pattern emerged. Two volunteers showed a decrease of EMG level in the masseter. There was

* RS Components Ltd, Corby, Northants, U.K.
† Tektronix 5103N, Tektronix Inc., Beaverton, OR 97077, U.S.A.
‡ Devices, Digitimer Ltd, Welwyn Garden City, Herts, U.K.

such wide variation in the levels of change of EMG activity, and with a relatively low number of volunteers, that it was considered that statistical analysis of these data would not serve any useful purpose.

Discussion

The fact that a greater change in activity levels was observed for the temporal muscles than for the masseter muscles was to be expected since the anterior fibres of temporalis

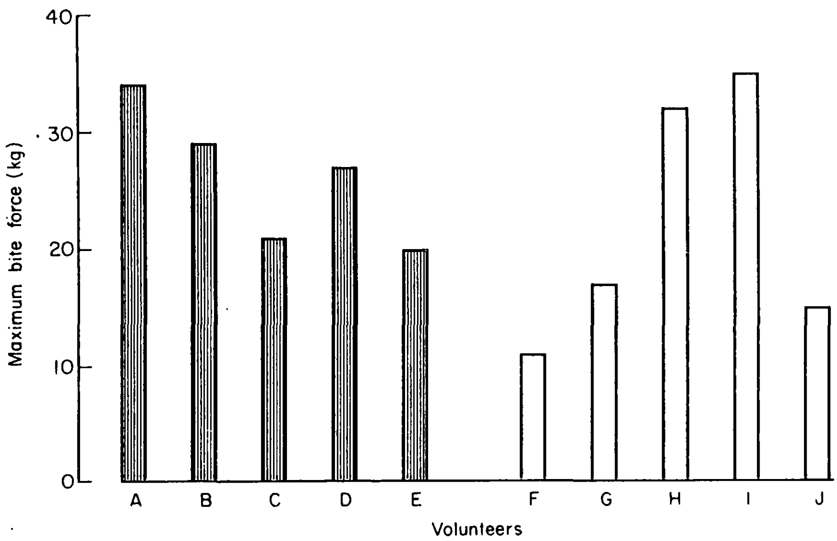


Fig. 1. The maximum bite force obtained for each volunteer; individuals showing tooth wear (▥) and those showing no abnormal wear (□).

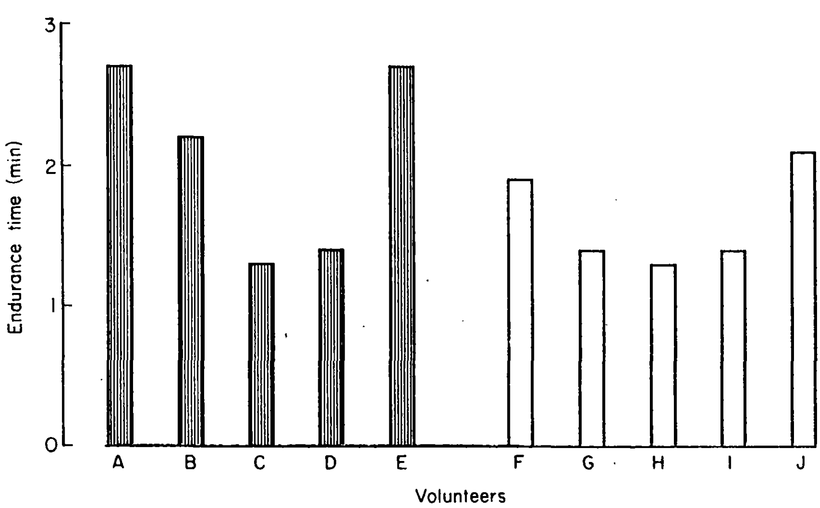


Fig. 2. The time period for which each volunteer was able to sustain a contraction at 50% MVC; individuals showing tooth wear (▥) and those showing no abnormal wear (□).

are more active than the masseter muscle in this laterotrusive canine position, and thus a greater degree of fatigue would be anticipated.

A possible explanation for the decrease in EMG activity observed in two volunteers

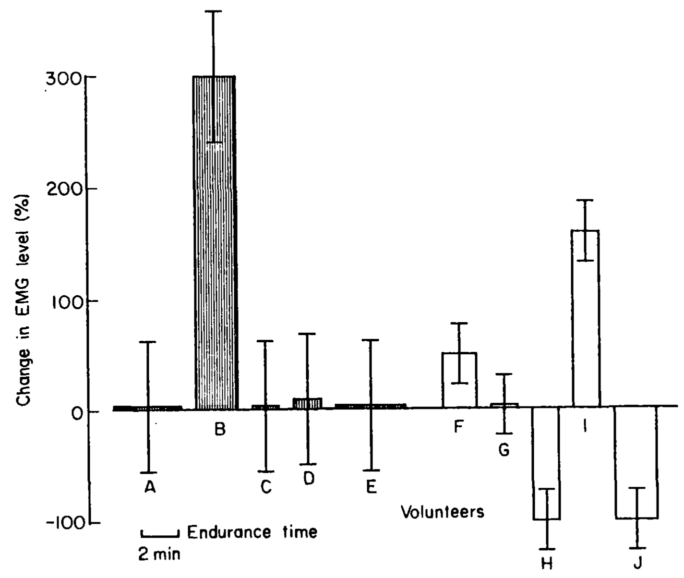


Fig. 3. The change in masseter muscle EMG level (±SE) for each subject; individuals showing tooth wear (▥) and with no abnormal wear (□). The width of each bar represents the endurance time, i.e. the time period during which the change in EMG occurred.

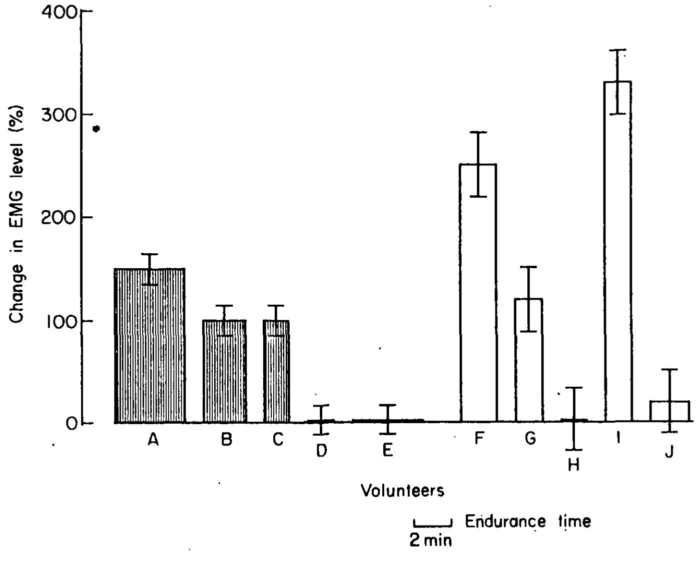


Fig. 4. The change in temporalis muscle EMG level for each subject with (▥) or without (□) tooth wear. The width of each bar represents the endurance time, i.e. the time period during which the change in EMG occurred.

might be the occurrence of a rotation of activity, perhaps to the medial pterygoid. This is a good illustration of the problem of rotation of synergist muscle activity.

The canine position was used to record force in this pilot study because many individuals with attrition show considerable wear on their canines, indicating heavy functional or parafunctional contacts. Helkimo and Ingervall (1978) found that clenching or grinding resulted in an increased bite force when measured at the incisors, but not when measured at the molars, and they suggested that there could have been muscular training at eccentric positions. They also observed that the bite forces ranged widely, from 3–45 kg at the incisors. The range in this preliminary study was 11–35 kg in the canine area.

A difficulty encountered with volunteers showing attrition is that the canine overjet is often zero, while it is invariably greater than this in individuals without attrition. Consequently, different degrees of opening are found between the two groups when closing on the bite fork. The use of the incisor position would not eliminate this problem, as worn incisors are often also involved in an edge-to-edge relationship.

The measurement of bite force is fraught with difficulties, the most obvious of which is the inability to tell whether or not a volunteer is really applying full effort. A possible solution to this problem would be to employ the twitch interpolation technique, as described by Bigland-Ritchie, Furbush & Woods (1986), which involves the delivery of a transcutaneous sub-maximal electrical stimulus to the muscle under investigation. However, because of the anatomy of the region and the discomfort involved, this approach has some disadvantages.

Secondly, when using any eccentric position it is impossible to achieve the same degree of protrusion and laterotrusion in all volunteers — this will vary according to the relative size of their skeletal bases and the occlusal patterns.

Another problem with bite force studies is that it is difficult to reduce the thickness of the bite fork to less than 7 mm, as the beams become too weak to resist the forces involved. This is a large opening, and is in marked contrast to the situation that occurs in either normal or para-function. Although this type of bite force meter is very accurate, the extrapolation of data obtained with this degree of opening to the normal contact position in endurance and fatigue tests should be carried out with caution. It must be pointed out that although the thickness of the force meter is only 7 mm, if any overbite is taken into account the total extent of opening will be considerably greater than this value. In addition to the effect of muscle lengthening, as the jaws open the angle at which the muscles are applying the force changes, and changes to different degrees. If a lateral movement is incorporated, the contribution of different muscles changes, and the situation becomes even more complex. It seems clear that a much thinner device is required. The use of piezzo-electric foil of the order 60 μm thick, which is now commercially available, would represent an enormous step forward in obtaining accurate information about bite force, if the technique could be developed sufficiently.

Fatigue studies, as well as those of bite force, also present the difficulty of volunteer cooperation. Some individuals might well try harder than others to endure the discomfort of a prolonged contraction. Some might experience more pain than others; some individuals may be able to tolerate the same level of pain better than others. It is certainly true that all of the participants in this study ceased to maintain the contraction because of pain, and not on account of an inability of the muscles to continue. There is no obvious answer to this problem, except to point out that the number of experimental volunteers needs to be larger than would otherwise be the case, and that the control volunteers should be matched as closely as possible to the experimental volunteers, perhaps even more closely than might be required for other experiments.

An alternative solution might be to test pain tolerance and then to normalize the endurance time to the pain tolerance, but this approach adds yet another unpleasant procedure to the experimental session. On the other hand, alternative methods for quantifying fatigue, such as power spectral analysis, would be simpler and probably more meaningful in clinical research.

The most significant problem is that, by using the canine position, and thus introducing a lateral movement of the mandible, the lateral pterygoid and masseter muscles on the contralateral side must exert a relatively large force in order to maintain the position, and in several subjects pain in the contralateral side was the reason for abandoning the sustained contraction. This means that the endurance of the jaw-closing muscles was not fully tested on the ipsilateral side, which highlights a significant complication with the use of the canine position. The phenomenon of pain on the contralateral side during unilateral biting has also been observed by other workers (Kydd, Choy & Daly, 1986).

It has been shown that resistance to fatigue varies between muscles. The processes which may contribute to this difference are recruitment and firing rate differences, the proportion of slow twitch to fast twitch fibres, cross talk from adjacent muscles, and agonist/antagonist muscle interaction (Lawrence & De Luca, 1983). The latter phenomenon is particularly relevant where joints must be stabilized, as in the case of the masseter and temporalis. It is likely that this relationship takes a different form in the mandible because of the stability provided by the teeth, or contact with the force meter, and that the contralateral lateral pterygoid muscle assumes the role of a partial antagonist to the contralateral masseter.

Conclusions

Bruxists do appear to demonstrate increased bite force at the canines, even though the difference between the means is not statistically significant. They are also apparently able to maintain a given force over longer periods than non-bruxists, although again this is not statistically significant. However, no conclusion can be drawn regarding possible differences in resistance to fatigue between the two groups.

The most important conclusions are that the recording of bite force between the canines presents complications in jaw muscle fatigue studies, and that the use of bite force meters of a thickness greater than what might be considered a normal functional limit (perhaps 0·5 mm) may also present complications in fatigue and endurance studies.

Acknowledgements

We would like to thank Professor R. Yemm and Dr J.P. Newton of the Dundee Dental School and Hospital, Park Place, Dundee, Scotland, for kindly providing details of their design for the bite force meter.

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Fatigue and EMG changes in the masseter and temporal muscles during sustained contractions

M.F. LYONS, M.E. ROUSE *and* R.H. BAXENDALE *Department of Prosthodontics and Institute of Physiology, University of Glasgow, Glasgow, U.K.*

It has been shown that the muscles of mastication are more resistant to fatigue than the limb muscles, but the mechanisms by which they deal with fatigue require further investigation. The aim of this study was to evaluate the direct measurement of RMS-integrated EMG during an isometric contraction as a measure of fatigue, and to compare it with the changes observed by spectral analysis. These parameters were also related to the subjective quantification of fatigue by the use of visual analogue scales.

Eight volunteers with no signs or symptoms of TMD were asked to clench on a bite force meter several times to obtain their maximum voluntary contraction force. They were then asked to maintain 50% MVC for as long as possible, using the force display for visual feedback. During the course of this sustained contraction they were presented with a fresh visual analogue scale at approximately 15-s intervals and directed to mark the scale while maintaining the contraction. After resting, the experiment was repeated without the use of a force meter, this time using integrated EMG from the right masseter muscle as visual feedback. EMG was recorded with surface disc electrodes from the masseter muscles and intra-dermal hook electrodes from the anterior temporal muscles, both bilaterally. The data were recorded on video tape via a multiplexing and digitizing adapter for subsequent analysis.

During the isometric contraction the mean EMG level for all four muscles typically increased from around 40% MVC at the beginning to around 70% MVC at the end, with a large inter-individual variation. There was, of course, no increase for the masseter muscle when EMG was used as feedback, but fatigue certainly occurred. The VAS scores increased by relatively even increments during both contractions. Endurance times varied greatly between subjects. The mean frequencies of the power spectra decreased during the sustained contractions. *The use of amplitude increase of RMS-integrated EMG is not as useful as power spectral analysis as a measure of fatigue in the jaw-closing muscles.*

This study was supported by grant number RSG/END/8990/J from the Greater Glasgow Health Board Research Support Group.

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