THE EFFECT OF DENTOFACIAL FORM ON CHEWING EFFICIENCY IN HUMANS

by

LAURA REI IWASAKI

A thesis submitted to the Faculty of Graduate Studies
of the University of Manitoba
in partial fulfilment of the requirements for the degree of

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Abstract

When dentofacial form is deviant from the accepted norms, it is expected that the functional abilities associated with this non-ideal form are also non-ideal. Such functional differences have yet to be quantitatively established. Nevertheless, through the treatment of dentofacial "problems," particularly with surgery, large morphological changes are often achieved.

In this work a method of measuring chewing efficiency has been developed and used to quantify the functional differences between people with extremely different dentofacial form. A relationship between the efficiency and the adaptability of the masticatory system is proposed. This relationship makes it possible for the system to cope with large alterations in form.

Mechanical efficiencies for a number of chewing and biting tasks were measured by comparing the amount of mechanical work done on a bolus with the muscle energy required to carry out that work. *In vivo* tasks were simulated in a materials testing device to determine the amount of the work done on a given bolus. The muscle energy input associated with these tasks was quantified using surface electromyography [EMG] recorded from the main jaw elevating muscles. This quantitative EMG data was normalized to the EMG-isometric force relationship for the muscles in order to compare results from different individuals and recording sessions. The theoretical concepts of the applied methods were experimentally verified.

A sample of 33 untreated adults was investigated. This sample represented: 14 "long face syndrome," 13 "short face syndrome," and 6 "normal" dentofacial type individuals.

Remarkable differences in chewing efficiencies were not demonstrated between individuals with extremely different dentofacial form. In addition, the results indicated that the human chewing apparatus is not highly efficient in converting biological energy into the mechanical energy that is required to comminute a bolus.

Such "inefficiency" may be an important attribute of the chewing apparatus. An appreciation of the characteristic versatility and adaptability of the masticatory system, important at both evolutionary and individual levels, is not compatible with a high degree of specialization for efficiency. That is, the human masticatory system demonstrates that high adaptive capacity and high mechanically efficiency are entropically related. The inefficiency of the system may account for its ability to cope with the changes in form, realized through treatment, without more than transient functional penalty.

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Chapter I Introduction

1 General Intent

Philosophically, the primary goal of dental health care delivery is the maintenance and, if possible, the improvement of the functional chewing system. Beyond the basic relief of acute pain, however, much of clinical dentistry is focussed on the control of dentofacial morphology. Divergence from normal form is usually equated with divergence from ideal function, but this functional divergence has not been adequately quantified. Instead, since form is more easily measured, it has become commonplace to advocate and evaluate treatment primarily on the basis of morphological assessments. Objective, well-founded, functionally based support for or against various treatment regimens is not usually provided.

It is not at all certain whether the marked diversity in human dentofacial form, as conventionally observed or measured, is reflective of the functional abilities of the human chewing apparatus. The so-called extremes in facial type clearly demonstrate marked differences in dental and skeletal morphology and their abilities to perform contrived biting tasks. Patients who fall into these categories - those exemplifying "long face syndrome" and "short face syndrome," for example - and who seek treatment, commonly undergo surgical procedures which are very different, based on their differences in form. Functional parameters are not commonly assessed.

This raises the question: How large is the functional penalty paid by people with "poor" morphological relationships? Many people with "abnormal" dentofacial form appear to lead full, healthy lives without major, predictable impairment. In this regard, if form is significantly changed by treatment, how is the chewing apparatus able to accommodate such large changes, and how large, if any, are the concomitant changes in function?

It may be argued that the number of dental patients complaining of post-treatment functional problems is relatively small. The reasons for this may be that the function of the masticatory system is not changed significantly as a result of treatment, or that the system is adaptable and tolerant to change.

Clinical conscience related to considerations of treatment efficacy, if not scientific curiosity should demand that more be known about the function of the chewing apparatus. Only through the identification and measurement of functional parameters of the masticatory system can an improved understanding of the system be more fully realized. The overall aim of this work is to address some of these matters.

2 Reasons for Investigation

Conventional clinical diagnoses and rationales for the treatment of dentofacial relationships in otherwise healthy human beings is subject to challenge. Such treatment is usually aimed at changing the relationships of the teeth and the craniofacial structures in order to achieve "superior" esthetics and function. There is no doubt that changes in dentofacial relationships to more closely approximate conventional ideals of esthetic form can be achieved through various dental therapies (for example, orthodontics, prosthodontics, and orthognathic surgery). Furthermore, corrective measures for the esthetics of the dentofacial complex can be diagnosed, carried out, and assessed in quantitative and qualitative detail. This is not possible, at present, for the functional aspects of the dentofacial complex.

In the past, many studies that were designed to evaluate chewing have described masticatory patterns by tracking mandibular movement or recording muscle activity (Neumann, 1950; Schweitzer, 1961; Graf and Zander, 1963; Gibbs *et al.*, 1971; Bates *et al.*, 1975a), or have measured the degree-of-bolus-maceration (Hildebrand, 1931; Dahlberg, 1942; Manly and Braley, 1950; Loos, 1963). Some have attempted to match these findings with morphological characteristics of the dentition and the face (Guttleman, 1961; Beyron, 1964; Woelfel *et al.*, 1962; Sheppard, 1965; Ahlgren, 1966; Møller, 1966; Rissin *et al.*, 1978; Gibbs *et al.*, 1982; Michler *et al.*, 1987). These studies, while of merit for the description and categorization of individuals, are of limited critical and predictive value in the consideration or the evaluation of treatment.

The clinical emphasis on morphology rather than physiology stems from long-standing assumptions that form and function have a strong relationship. Generally, it has been supposed that the effect is mutually beneficial or detrimental, in that:

- good form optimizes function, and good function optimizes form, while
- poor form handicaps function, and poor function handicaps form.

Much clinical conjecture and many clinical studies have documented correlative reinforcement for these suppositions (see Chapter II). Consequently, they have formed the bases for widely-applied clinical stereotyping and "corrective" treatment of the human dentofacial complex.

Sound evidence for important improvements to masticatory function as a consequence of "successful" changes made to dentofacial form is sparse. Furthermore, earlier work (Iwasaki *et al.*, 1986a and 1986b; Iwasaki, 1987a and 1987b; Iwasaki and McLachlan, 1988) showed that the marked diversity in dentofacial form, as conventionally measured and assessed, was not necessarily reflected in the functional abilities of the human chewing apparatus in terms of the mechanics of biting. Differences in the functional characteristics of the human masticatory system exist of course, and some of these characteristics can be consistently associated with distinct dentofacial types. Maximum bite force, for example, has been found to be significantly higher in people with a short lower facial height compared to people with a long lower facial height (Sassouni, 1969; Ringqvist, 1973; Throckmorton *et al.*, 1980; Proffit *et al.*, 1983; Weijs and Hillen, 1984). However, Iwasaki (1987a and 1987b) has demonstrated that no matter what the bite force magnitude in humans, biting is handled by the masticatory system in a relatively similar way, even in individuals with extreme differences in dentofacial form, for example short- and long-lower-facial-height types. In addition, it has been shown that the relationships of the anatomical components important to the mechanics of isometric biting are remarkably similar when assessed relative to a functional reference plane (occlusal plane). This clearly contradicts assessments based on conventional analyses using standard reference planes (such as Frankfort Horizontal or Sella-Nasion) and conventional expectations about the relationship between form and function which would suggest that people who looked very different also function very differently.

The challenge raised to conventional wisdom and practice has invoked further study, particularly in light of the paucity of methods to analyze quantitatively the function of the human chewing apparatus. Analysis of the three-dimensional mechanics of isometric biting (Iwasaki, 1987a and 1987b) addressed function in a meaningful way; however, this was a static analysis and it involved only one aspect of the functional repertoire of the masticatory system. The concept of chewing efficiency, therefore, was put forth for scientific and clinical investigation in this study. Scientifically, the work presented is intended to understand better the development and possible adaptive advantages of the human dentofacial complex. Clinically, the work is intended to provide a means for the quantitative measurement and evaluation of the function of the masticatory system. Clinical information of this sort, supported by reasonable scientific arguments as the basis for interpretation and assessment, could have important implications to the understanding and management of the masticatory system. Conceptually, the clinical application of the proposed method is appealing relative to its possible use as an aid to the identification and quantification of chewing function for diagnostic purposes, and for the planning and evaluation of treatment.

3 The Concept of Chewing Efficiency

Despite the fact that chewing is one of the main functions of the masticatory apparatus, chewing efficiency has not been a commonly, or easily addressed parameter (Carlsson, 1974). Appropriate efficiency calculations involve some measure of the mechanical output (work done) divided by the energy input (to carry out the work). In the case of chewing, the work done is the mechanical preparation of ingested food for swallowing, and the cost is that of the metabolic energy input.

The amount of mechanical work done on a given bolus of food can be measured or calculated in various ways (Lucas and Luke, 1983; Olthoff *et al.*, 1984; Van der Bilt *et al.*, 1987). By having a standard food bolus of set form and size, it is assumed that the amount of work done by any individual during a relaxed, ordinary chew-until-swallow task is exactly that which is necessary to prepare the bolus to an adequate degree for swallowing. Since chewing patterns have been shown to be very consistent for an individual (Dahlberg, 1942; Yurkstas, 1951), the amount of work done for a given situation can be standardized. It is assumed further that the energy costs of carrying out the mechanical work on the bolus can be estimated using surface electromyography [EMG] recorded bilaterally from the major jaw adductor muscles. This is based on the general assumption that the recorded myoelectric activity has a strong and direct relationship to the force exerted by the muscles.

This method of evaluating the efficiency of mastication was employed. More specifically, the total muscle energy expended in carrying out work on a given standardized food bolus during its mastication was derived from the true integration of the square of the EMG recordings of the two main, paired, adductor muscles. A more detailed description of the use of integrated, squared EMG data [ISE] is presented in Appendix A. It should be noted however, that this is distinctly different from the "rectified, averaged" EMG data that is commonly referred to by the term "integrated." Firstly, and very importantly, it is not waveform-dependent, which rectified, averaged data definitionally must be. In addition, the squaring of the EMG signal:

> 1) is in accordance with the units of the relationships between energy and voltage as per basic principles of electronics (energy is proportional to voltage-squared), and
>
> 2) de-emphasizes the contribution of any unavoidable background noise to the integrated results.

A combination of *in vivo* and *in vitro* experiments allowed a quantitative comparison of the relative muscle "energy" (as indicated by EMG activity) required by different individuals in chewing the same kind of bolus in their own way.

4 The Clinical Sample

The subjects chosen for investigation were selected to represent the "extreme" categories of dentofacial morphology known as short-face (square jaw, flat mandibular plane, or brachyfacial) type [SF] and long-face (tapered jaw, steep mandibular plane, or dolicofacial) type [LF]. Such people are regarded as being very different in appearance and also very different in the functioning of their chewing apparatus. Individuals from both categories tend to demonstrate characteristic dental as well as skeletal patterns that are considered "abnormal" and, therefore, indicative of a need for treatment. These dentofacial malrelations are never life-threatening, but they have come to be regarded as "compromising" in terms of the "quality of life" expected within our society. Most commonly, treatment involves orthodontics, with or without conjunctive orthognathic surgery.

The problem of biological variability in clinical studies is often addressed through the use of large sample populations. This ensures that statements made regarding any correlative or non-correlative findings can be statistically verified, despite what is often a large degree of variation within the sample groups tested. In this study, this problem was addressed by employing specifically designed tests on people who were conventionally regarded as extremely different in form and who, consequently, were also expected to show large differences in function. That is, specific investigative experiments were used, as distinct from statistical surveys intended to identify variables that demonstrate significant correlations. This permitted the comparison of expected "extreme-case scenarios," for the evaluation of the validity of the hypothesis put forward.

5 Statement of the Thesis Hypothesis

The mechanical efficiency of the human chewing apparatus is significantly affected by the form and relationships of the dentofacial complex.

A quantifiable functional parameter of the human masticatory system was tested through this investigation. Chewing efficiencies were established by comparing the mechanical work done with the muscle energy input to carry out this work. Chewing efficiency measures were then used:

> 1) to assess human masticatory function, and
>
> 2) to compare masticatory function between individuals who were very different morphologically, and who therefore were also expected to be very different functionally.

This study was designed to effectively challenge the thesis hypothesis by assessing and comparing function in cases where relative extremes in terms of dentofacial form existed. Based on assumed relationships between form and function, individuals with large differences in form would be expected to exhibit large differences in function. Qualitatively and quantitatively, the differences were expected to be dramatic. Simple statistical analyses (Student's t-tests) were employed to aid the description of the findings.

Chapter II Literature Review

1 Facial Type Classifications

1-1 Overview

The use of facial typing in clinical dentistry has been advocated as an interpretive aid to the diagnosis and treatment of groups of people that are presumed to have distinct morphological and functional traits. The rationale supporting the conventional facial type classifications, and the functional characteristics ascribed within these, is based on the long-standing assumption of a strong relationship between form and function with respect to dentofacial growth and development. Individuals with distinct facial types, who are regarded as being morphologically very different from "normal," are regarded as being functionally very different as well. The literature on this topic is highlighted in the following sections. A more detailed review of facial types and their discernment may be found in Iwasaki (1987a).

1-2 Description of Long and Short Facial Types

Long facial type [LF] individuals are characterized generally by an excessive nose-to-chin length (lower anterior face height) and a steep mandibular plane angle. They are also reported to have: a narrow alar base and nostrils that are small and poorly developed; a poor upper lip-to-tooth relationship with inordinate exposure of maxillary teeth and gingiva upon smiling; a large interlabial gap; a short ramus;

a retruded or protruded mandible; a long, narrow, v-shaped maxillary arch with a high palatal vault; proclined upper incisors; and a large distance between the maxillary root apices and the nasal floor. Tendencies toward a skeletal anterior open bite, an open mouth posture, and a vacant facial expression have also been associated with LF (Linder-Aronson and Backstrom, 1960; Linder-Aronson, 1970; Schendel *et al.*, 1976; Radney and Jacobs, 1981; Shaughnessy, 1983). The term "long face syndrome" has been used to describe these individuals by some authors (Schendel *et al.*, 1976; Radney and Jacobs, 1981; Proffit *et al.*, 1983; Fields *et al.*, 1984). Among other terms used to describe this facial type are: high angle type (Schudy, 1966), idiopathic long face (Willmar, 1974), total maxillary alveolar hyperplasia (Hall and Roddy, 1975), extreme clockwise rotation (Schendel *et al.*, 1976), vertical maxillary excess (Schendel *et al.*, 1976), adenoid facies (O'Ryan *et al.*, 1982), leptoprosopic type (Enlow, 1982), and dolicocephalic type (Van Spronsen *et al.*, 1989).

In contrast, the opposite condition of short facial type [SF], is exemplified by a short lower anterior face height and a low mandibular plane angle. Other clinical features attributed to a typical SF individual include: an edentulous, overclosed appearance in a short, square-shaped face; a distinct chin button, deep mentolabial fold, and skin-folds lateral to the oral commissures; well-developed masseter muscles, a small vertical maxillary height, large resting interocclusal distance, and a large overbite (Van Sickels and Ivey, 1979). These features, collectively called "short face syndrome" (Bell, 1977), are said to derive from a lack of vertical maxillary growth. They are also known by such terms as: hypodivergent face (Schudy, 1965), low-angle type (Schudy, 1966), skeletal type deep-bite (Sassouni, 1969), idiopathic short face (Willmar, 1974), vertical maxillary deficiency (Opdebeeck and Bell, 1978), extreme counterclockwise rotation type (Opdebeeck and Bell, 1978), euryprosopic type (Enlow, 1982), and brachycephalic type (Van Spronsen *et al.*, 1989).

The use of the term "syndrome" has been justified by Opdebeeck and Bell (1978), since, for a given facial type, esthetic, cephalometric, and occlusal features are similar and consistent. LF and SF individuals are said to represent extreme dysplasias in terms of skeletal, dental, and facial structures. Surgical treatment to improve the hard and soft tissue relationships is often advocated for these people on the basis of compromised esthetics, function, and stability, due to extreme morphological deviations from accepted human norms (Bell, 1977; Bell and Jacobs, 1979; Van Sickels and Ivey, 1979; Piecuch *et al.*, 1980; Radney and Jacobs, 1981; Proffit, 1986).

1-3 Functional Attributes of Long and Short Facial Types

Differences in the functional demands and physical abilities that correlate with differences in appearance and morphologic measurements between LF and SF exist. Those most commonly referred to will be reviewed.

1-3.1 Breathing and Posture

Mouth-breathing due to impaired nasal respiration has often been discussed as a major etiological factor in LF (Linder-Aronson, 1979; O'Ryan *et al.*, 1982; Quinn, 1983; Tourné, 1991; Warren *et al.*, 1991). Evidence from animal experiments (Harvold, 1979; Tomer and Harvold, 1982; Miller *et al.*, 1984; Ramadan, 1984) appear to provide support for this notion. The causal relation between respiration, posture, and deformities in the dentofacial complex has yet to be substantiated by well-controlled, prospective, longitudinal human studies, however (Vig *et al.*, 1981; O'Ryan *et al.*, 1982; Warren, 1984; Vig *et al.*, 1991). Recent work by Fields and associates (1991) suggested that any differences in breathing modes between LF and normal facial type individuals may be behaviourly based rather than airway-dependent, since no significant differences could be demonstrated in tidal volumes and airway patency.

The effects of forward head posture (Solow and Tallgren, 1977; Daly *et al.*, 1982; Solow *et al.*, 1984) and forward tongue and mandibular posture (Lowe, 1980) on craniofacial morphology have also been considered in attempts to demonstrate the etiology of LF.

1-3.2 Muscles

Whether facial form is predetermined and dictates muscle strength or whether muscle strength determines the facial form remains an unanswered question. Consistent facial type-specific muscle characteristics have been demonstrated, such as increased masticatory muscle activity in SF over LF individuals for conditions of chewing, biting, swallowing, and resting (Ahlgren, 1966; Møller, 1966; Ringqvist, 1973; Ingervall and Thilander, 1974; Ingervall, 1976; Lowe and Takada, 1984).

Investigations into vertical facial dysplasias with respect to muscle morphology, activity, and mechanics have been reported (Ingervall and Thilander, 1974; Finn *et al.*, 1980; Throckmorton *et al.*, 1980). Boyd and associates (1984) carried out a histochemical study to characterize muscle fibre types and muscle fibre distribution within the deep masseter muscle from nine LF patients who were undergoing "corrective" surgery to change their dentofacial relationships. The results from this study demonstrated "normal" tissues with considerable variability in the size and distribution of the muscle fibres in the LF patients. This contradicted an earlier report from the same laboratory which suggested that LF was associated with muscle fibre hypertrophy (Finn *et al.*, 1980). The work of Boyd and associates established that the finding of hypertrophic masseter muscle fibres in the three LF patients reported on in 1980, was unusual and indicative of pathology not demonstrated in all LF people.

Carlson and coworkers have studied the effects of altered muscle length on craniofacial growth and adaptation by reviewing the literature pertinent to this area and by conducting experiments using an animal model (Carlson *et al.*, 1982; Carlson and Poznanski, 1982). The histochemical work described by Carlson and Poznanski (1982) suggests that abnormal facial form and relapse after clinical treatment are not determined by muscle fibre structure. They concluded that muscle fibres tend to adapt to changes in habitual function rather than determine them. According to these authors, it is more likely that the neural factors which control function at least partially determine form and may contribute to relapse after treatment.

The total muscle fibre cross-sectional area has been said to be a measure of the maximal isometric strength of a muscle, and therefore has been suggested as an indication of mechanical influences on the craniofacial skeleton (Van Spronsen *et al.*, 1991). Computer tomography has been used to demonstrate a correlation between increased cross-sectional areas (Weijs and Hillen, 1986) and volumes (Gionhaku and Lowe, 1989) of the masseter and medial pterygoid muscles in subjects with tendencies towards SF characteristics.

Distortions in muscular balance appear to result in distortions in craniofacial form. In the extreme, individuals suffering with progressive disease conditions that result in muscle atrophy and/or dystrophy are reported to demonstrate LF morphology (Kreiborg *et al.*, 1978; Gazit *et al.*, 1987). Bolt and Orchardson (1986) have shown a correlation between subjects with large mouth-opening forces and LF characteristics.

1-3.3 Biting Strength

Differences in biting strength have been measured, with stronger maximum bite forces found in SF over LF individuals (Sassouni, 1969; Ringqvist, 1973; Throckmorton *et al.*, 1980; Proffit *et al.*, 1983). Studies by Ingervall and Helkimo (1978) suggest that in individuals with increased biting strength, a higher degree of tooth wear might be expected. It is important to note, however, that maximal bite force levels are not required for the ordinary maceration of foodstuffs and other normal activities (Howell and Brudevold, 1950; Anderson and Picton, 1958; Graf *et al.*, 1974; Bates *et al.*, 1975b; DeBoever *et al.*, 1978; Gibbs *et al.*, 1981).

In subjects with increased biting strength, Proffit and co-workers (1983) demonstrated that at maximum effort, LF subjects produced biting forces about half the magnitude of normal individuals. LF were also shown to use considerably less occlusal force during simulated chewing, and were found to bring their teeth together with significantly less force during swallowing than did normals. In children, Proffit and Fields (1983) found no significant difference between occlusal forces in LF and normal groups. Proffit and Fields thereby concluded that LF adults fail to develop normal levels of strength in the muscles involved in biting.

1-3.4 Dysfunction Associated with Long and Short Facial Types

Clinical impressions have suggested that Angle Class II skeletal and dental patterns with vertical dysplasias show signs and symptoms of temporomandibular joint dysfunction most frequently. Deep bites, characteristic of Angle Class II, Division 2 malocclusions have been noted in clinical temporomandibular dysfunction groups (Perry, 1969; Mongini, 1977; Williamson and Brandt, 1981), as have skeletal anterior open bite malocclusions (Perry, 1969; Williamson and Brandt, 1981; Mohlin and Thilander, 1984; Thilander 1985). Currently, there is little agreement on the association between abnormal skeletal and dental relationships and temporomandibular joint dysfunction, including internal joint pathology and abnormalities of muscle function. It has been suggested that such correlations have been greatly exaggerated (Greene and Marbach, 1982).

Although the nature of the loading of the temporomandibular joint during function is described by some authors to be different in LF than SF (Throckmorton *et al.*, 1980; O'Ryan and Epker, 1984; Moles, 1989), such differences have not been supported by mechanical analyses (Iwasaki, 1987a and 1987b; Hannam and Wood, 1989).

2 Mastication

2-1 Role in Evolution

Obtaining nourishment is of paramount importance to the existence of all life forms. In evolutionary terms, feeding and locomotion are seen as the fundamental processes responsible for the adaptive modifications in mammalian morphology (Nobel, 1979). The improvement of the functional efficiency of the jaws to ensure adequate nourishment for survival has been deemed a critical factor in many of the most important stages of vertebrate evolution (Du Brul, 1979; Noble, 1979). Many comparative studies, focussed on dentofacial structures, have been described. These provide theoretical explanations to account for the form and function of the masticatory apparatus (Crompton and Parker, 1978; Dubner *et al.*, 1978; Noble, 1979; Byrd, 1985; Gorniak, 1985; Hiiemae and Crompton, 1985; Radinsky, 1985). Since preconceived notions tend to be the basis for these morphological studies, experimental testing of the hypothesized relationships between form and function has been encouraged (Gans, 1985; Herring, 1985). Work in the area of jaw muscle fibre type and composition, for example, has provided some physiological data to support the prevailing descriptions and rationales (Pette and Vrbová, 1985; Rowlerson, 1990). The speculative nature of the comparative approach is not always acknowledged, however, and is often extrapolated upon in the interpretation of animal-model studies for the clinical evaluation of human dentofacial form and function (Ardran and Kemp, 1960; Harvold, 1968; Enlow, 1982; Crompton, 1985; Herring, 1985; De Gueldre and De Vree, 1988).

2-2 Role in Contemporary Humans

Mastication, or chewing, is the act of processing material taken into the mouth. It serves two main functions:

1) to reduce material to a condition suitable for swallowing, and

2) to increase the surface area of the material in order to facilitate the penetration of the digestive enzymes and thus expedite the rate of chemical breakdown.

2-2.1 Effect on Digestion and Gastrointestinal Function

The digestibility of many foods, particularly meats and vegetables, is increased if they are chewed before swallowing. Farrell (1956) demonstrated this by testing the effect of mastication on 29 commonly eaten foods. The human subjects in his experiments swallowed two cotton bags that were tied together, one of which contained a specimen of chewed food, and the other an equal weight of unchewed food. These bags were recovered from the faeces, then weighed and analyzed. Farrell found that 18 of the tested foods left large undigested residues if swallowed without chewing and allowed to pass naturally through the body. Many of these specimens were incompletely digested even if chewed, but chewing always increased their digestibility. Foods that were completely digested in the process, whether they were chewed or not, included meat fat, fish, eggs, rice, bread, and cheese.

In the same study, Farrell also investigated the effect of different degrees of "masticatory efficiency" on digestion, using a full-denture wearer, a partial denture wearer, and one person with natural dentition, as subjects. Farrell was able to demonstrate that only a small amount of chewing is necessary for the proper digestion of foods, even those more resistant to digestion. This is in agreement with Ardran and Kemp (1960), who reported that dividing food finely by chewing has not demonstrated marked value to digestion or general health in humans. A study by Sognnaes (1941) in rats showed that the extraction of molar teeth resulted in "reduced chewing efficiency," as evidenced by the swallowing of larger particles and impaired digestion of the samples recovered from the stomach. Compromise of the overall rate of growth and general health of the experimental animals, however, could not be demonstrated. Restoration of the dentition in humans, for the sake of proper digestion or to avoid compromising general health, does not seem to be supported by the literature.

Experiments have shown that the extent to which food is macerated can affect the rate of emptying of the stomach. In general, when food is swallowed without chewing, the passage time is prolonged. This has been shown in animal experiments (cited by: Farrell, 1956; Ardran and Kemp, 1960; Carlsson, 1974), where meat offered in chunks remained in the stomach longer and resulted in a greater production of gastric fluids than meat ingested in a ground-up form. Read and associates (1986) showed this in humans by studying the postprandial glycaemic effects of carbohydrates when chewed and swallowed versus when swallowed without chewing. They found that swallowing of the carbohydrate food resulted in decreased plasma insulin and glycaemic responses. The increased maceration of carbohydrates allowed more rapid absorption of the sugars and starches. This initiated a series of effects. That is, following a carbohydrate-rich meal, the glycaemic reactions were initiated and plasma insulin levels were high, a situation that stimulated fat synthesis and deposition. Concomitant to this, a rebound fall in blood glucose occurred, which tended to prematurely stimulate hunger. These results may in fact lend support for decreased mastication of carbohydrate foods where the tendencies to diabetes mellitus or obesity are a concern.

Compromised chewing ability does not seem to be a primary cause for pathological effects in the gastrointestinal system. The studies conducted in this area are generally correlative and the number of variables have been difficult to control (see Carlsson, 1974 for a review of this literature). This difficulty is put into perspective by considering the perplexity still associated with gastrointestinal disorders and dysfunction, in general. The most prevalent form of gastric distress, "irritable bowel syndrome," has an incidence of about 15 percent in adult humans, and appears to be more closely linked with psychological state than any other single factor (Janowitz, 1987).

The importance of the psychological state to gastrointestinal function is further supported by work done to investigate the oral digestion of complex carbohydrates. Morse and co-workers (1989) found that a relaxed state was related to increased stimulation of salivary amylase activity, and that this was more important than thorough chewing to oral digestion.

Unequivocal penalties to the digestion of an individual due to poor mastication are not evident in the literature reviewed. Studies have demonstrated that the thorough maceration of food by the teeth is not critical to good health.

2-2.2 Emotional Factors

Food and feeding also play a prominent role in the emotional and social aspects of human existence. A great deal of literature exists on this subject, particularly in the areas of food preparation, sociology, and the study of eating disorders. This literature is beyond the scope of this thesis and will not be covered herein.

The fact that reduced chewing ability may result in less satisfaction in mastication (Carlsson, 1974) deserves mention.

Many studies in the dental literature have documented the importance of this with respect to dental restorations and prostheses (Oosterhaven *et al.*, 1988). This may be linked to the perception that "proper chewing" of food is important to general health, and the social and cultural demands for such behaviour (Carlsson, 1974).

2-3 Masticatory Physiology

Physiologists have pursued explanations for the complex act of chewing in a number of ways. Neurophysiological studies have been aimed to identify the neural control mechanisms for mastication and to understand their evolution and ontogeny. Historically, the reflexive characteristics of the masticatory apparatus were isolated and studied first, since it was believed that at least some of these are involved in chewing. Theories regarding the existence of a central neural pattern generator to program mastication followed. The influences of higher centre control mechanisms and peripheral feedback have demonstrated, however, that chewing is more complicated than can be explained by reflex-responses and preprogrammmed neural activity alone.

From a different perspective, much attention has been paid to the structural and mechanical aspects of masticatory function, since this is the level most directly and effectively controlled by dental treatment. The early dental literature regarding chewing has been based largely on the observations of practitioners, and tends to be descriptive in nature, rather than experimental.

The topic of masticatory patterns has been a prominent one. In particular, the form of the chewing cycle, the rate of chewing, the velocity of mandibular movement and the forces developed during chewing, and the effect of food type and texture on the chewing pattern have been characterized. Many investigators have attempted to demonstrate how the state and arrangement of the dentition affect or are affected by these characteristics. The importance of efficiency in mastication is generally accepted, despite the fact that there is very little convincing evidence to support efficiency as an objective critical to the masticatory system.

In the following sections, the main theories of neuromuscular control of the masticatory system will be outlined, and the chewing literature will be highlighted. The subject of chewing function will be covered specifically, to exemplify how it has been described and assessed, and the factors affecting it.

2-3.1 Basic Theories of Neural Control

Traditionally, mastication was seen as the reciprocal activation of two simple brain stem reflexes (Sherrington, 1917):

> 1) the jaw-opening reflex, elicited by pressure to the teeth or various areas of soft tissue in the mouth or on the lips, and

2) the jaw-closing reflex, which occurs in response to the stretching of the jaw elevating muscles during opening.

The ingestion of food was proposed as the initiating factor and a self-perpetuating cycle resulted.

Repetitive electrical stimulation of the motor cortex was shown to evoke cyclic jaw movements that resembled mastication (Rioch, 1934). The stimulation excited jaw opening motoneurons and inhibited jaw closing motoneurons, and thus initiated the cycle of jaw-opening and jaw-closing reflexes. By inference, this accounted for the voluntary initiation of masticatory movements with or without the presence of an ingestant. Lesioning and electroneural stimulation studies led to the suggestion that a "chewing centre," or central pattern generator existed, and to evidence for its location in the brain stem (Dellow and Lund, 1971). A number of sites in the brain stem and motor cortex from which cyclic activity can be elicited have been identified, but it seems that only the reticular formation structures in the brain stem are essential for cyclic jaw movement. For a comprehensive review of central pattern generator control of masticatory movements, readers are referred to Lund and Enomoto (1988).

Although cyclic jaw function can be induced experimentally, and can be continued without sensory feedback, under most normal circumstances sensory feedback appears to play an influential role. Bosman *et al.* (1985), for example, investigated the extent to which proprioceptive feedback influenced the control of normal chewing movements and fast, goal-directed jaw-opening and jaw-closing movements. Surface EMG activity was recorded from the temporalis, masseter, and digastric muscles during undisturbed movements and when these activities were disturbed randomly by a force impulse in either the closing or opening direction. The EMG for undisturbed movements showed a reproducible and distinct pattern. For disturbances of the chewing movements, a differential existed, in that force stimuli in the closing direction caused greater alterations to the normal pattern of movement than stimuli in the opening direction. Bosman and associates concluded that this reflected a difference in the inherent stiffness of the system for closing and opening, and that a different control mechanism exists for the two directions. For the fast, goal-directed movements, disrupting force caused a change in the EMG pattern, but target positions were still reached without much error. This work suggested that these jaw movements may be "coarsely programmed" by the central nervous system, and more "precisely tuned" by peripheral feedback.

Mastication, as it occurs naturally, seems not to be a completely involuntary, or a completely voluntary act. Apparently, chewing is more elaborate than can be accounted for by a simple reflex cycle or by automatic patterning via a brain stem chewing centre (Luchei and Goodwin, 1974; Matthews, 1975; Hannam, 1979). Some of the ways in which chewing may be influenced and the factors involved will be presented in the following sections. For a more detailed discussion of the central regulation and peripheral regulation of chewing, see Dubner *et al.* (1978), Hannam (1979), and Taylor (1990).

The effective functioning of the chewing apparatus is conceptually important, particularly to clinical dentistry. The control of the masticatory system is not understood well enough to discuss neural mechanisms for efficiency, however, except to say that individuals who exhibit decreased chewing efficiency do not seem change their chewing pattern, and consequently end up swallowing large food particles (Dahlberg, 1942; Yurkstas, 1951; Oosterhaven *et al.*, 1988). Oral feedback to stimulate compensations for a decreased bolus-maceration ability (longer chewing time, for example), does not seem to be in operation.

2-3.2 Chewing Patterns

2-3.2.1 Jaw Movements

The literature on jaw movement is extensive. Unfortunately, in terms of directly assessing masticatory function, this information is of limited value. In the past, the exact measurement of jaw displacement and patterns of movement was regarded as essential for the establishment and description of "normal" and "abnormal" functional ranges.

The studies that describe and "quantify" chewing by describing the movements of the mandible range from those based on direct observations (Mills, 1955; Guttleman, 1961; Ahlgren, 1967) to technologically sophisticated methods aimed at enhanced measurement precision. The works in the latter category have employed: graphic registration methods (for example, Posselt, 1952; McMillen, 1972), photographic and cinematographic techniques (Schweitzer, 1961; Beyron, 1964; Ahlgren, 1966), cineradiographic and cinefluorescopic techniques (Jankelson *et al.*, 1953; Ardran and Kemp, 1960; Sheppard, 1965; Wictorin *et al.*, 1968), and various electronic and magnetic recording methods (Ahlgren and Öwall, 1970; Gibbs *et al.*, 1971; Gillings *et al.*, 1973; Mongini *et al.*, 1986; Michler *et al.*, 1987; Ow *et al.*, 1988).

Comprehensive reviews of the literature regarding jaw displacement studies and the form of the chewing cycle, have been published by Bates *et al.* (1975a), Dubner *et al.* (1978), and Hannam (1979). More literature regarding the topic is available and is likely to be forthcoming, due to the application of new and/or improved technologies. The exact measurement of jaw movements in three-dimensions is a difficult task, and it should be emphasized that the value of such information has definite limitations. Firstly, the interference of the methods and materials used for jaw-tracking, with normal masticatory behaviour is an inherent problem, and secondly, the description of jaw movements during chewing falls far short of explaining jaw function.

In general, the jaw-tracking work has demonstrated that each individual has a characteristic pattern of jaw movement during chewing, but that the pattern of consecutive chewing cycles is continuously changing, such that two consecutive cycles are rarely identical (Ahlgren, 1966; Mongini *et al.*, 1986). The functional pattern of jaw movement and the positioning of food in the mouth during chewing is believed to be established early in life (Jankelson *et al.*, 1953; Ahlgren, 1976), and is maintained as an involuntary process (Bates *et al.*, 1975a).

In the frontal view, the form of the chewing cycle is teardrop in shape, and usually deviated to one side, since the opening movement is rarely straight downwards. The pattern of deviation has been shown to vary greatly between individuals and to be influenced by the occlusion and by the nature (consistency, shape, size, taste) of the food bolus (Bates *et al.*, 1976; Ahlgren, 1976).

The chewing cycle may be artificially divided into three phases (Murphy, 1965; Ahlgren, 1966):

1. the opening or preparatory phase during which the mandible is depressed,

2. the closing phase or masticatory stroke, during which the mandible is elevated, and

3. the intercuspal or occlusal phase, during which the teeth come together into the habitual intercuspal position.

With increasing age, there appears to be a decrease in chewing velocity, but also a decrease in vertical displacement of the jaw during chewing. The total chewing cycle duration, therefore, remains approximately the same and tends to be consistent across all ages. Karlsson and Carlsson (1990) have suggested that the opening and occlusal phases are affected with increasing age, as a consequence of central motor impairment, whereas the closing movements, which are more dependent on muscular feedback and guiding, remain relatively consistent throughout life.

The literature regarding the relationship between particle size and jaw gape during chewing has been reviewed by Van der Bilt and co-workers (1991). These authors acknowledge a paucity of quantitative data regarding this relationship. The same group has investigated the problem by monitoring vertical changes in jaw position during chewing using an infra-red light-emitting diode system. From this system, measurements of the maximum jaw gape and the jaw gape at peak closing velocity (time derivative of the jaw position just before the jaw decelerates during a chomp on a bolus) were obtained. Variable volumes of a consistent and coherent bolus (chewing gum) and variable volumes and initial particle sizes of a non-coherent bolus (silicone rubber impression material) were tested. The maximum volume tested was 8.8 cubic centimetres and the maximum particle size tested was 9.6 millimetres [mm] (edge size of a cube). Van der Bilt and associates found that for the chewing gum boluses, the maximum jaw gape and jaw gape at peak closing velocity were consistently related to the bolus height. The bolus height was, on average, a predictable function of the volume of gum offered. For the hard, non-cohesive bolus, they found that the maximum jaw gape and the jaw gape at peak closing velocity were closely related to the height of the large-sized particles in the early phases of a chewing sequence. In the later phases of a chewing sequence and when the initial particle size was small however, the jaw gapes measured were always significantly larger than the height of the bolus particles. The maximum jaw gape and the jaw gape at peak closing velocity for a given chewing cycle, showed a close correlation when compared from cycle to cycle. This correlation was influenced by the texture and size of the bolus. In addition, these investigators found peak closing velocities to occur shortly after the teeth had begun penetrating the bolus.

2-3.2.2 Tooth Contacts and Occlusion

Any question as to whether teeth come into contact during chewing (Jankelson *et al.*, 1953) has been resolved by telemetry studies (Graf and Zander, 1963; Pameijer *et al.*, 1969). According to these works, the teeth contact most often in the maximum intercuspation position (centric occlusion). The pattern of tooth contact is relatively haphazard, and can be quite variable within one individual. A recognizable masticatory pattern, in terms of rate of chewing and frequency and duration of tooth contacts, has been reported however, by

Graf and Zander (1963), albeit on a very small sample (five subjects). The subjects tested by Graf and Zander, demonstrated chewing contact durations ranging between less than one-eighth of a second to two-thirds of a second. Pameijer and co-workers (1969) also studied bruxism and found that the nature of the tooth contacts involved were distinctly different from those of mastication, in that they were regular, repetitive, grinding tooth contacts that were much more specific than those recorded during mastication.

Evidence for occlusal sliding during mastication has been gathered by Woda and associates (1979). Along with proof from telemetric studies, indirect evidence exists from jaw-tracking studies. For example, there is an abrupt change in the direction of jaw movement at the end of mandibular elevation when the teeth reach occlusion. In addition, the terminal part of the masticatory cycle is superimposable from cycle to cycle and on occlusal sliding patterns made during voluntary lateral mandibular movements. Apparently occlusal sliding does not occur at all times or in everyone (Graf and Zander, 1963; Gillings *et al.*, 1973), depends on the type of food being chewed (Adams and Zander, 1964), the part of the chewing cycle (since tooth sliding is more frequent at the end of a chewing act) (Adams and Zander, 1964; Møller, 1966), and may occur in any direction (Pameijer *et al.*, 1969).

The literature reviewed by Woda *et al.* (1979) was restricted to experimental work based on non-iatrogenic, nonpathological methodologies and where a concept of "ideal occlusion" was not being directly tested. From their survey, they also concluded that:

- contacts in centric occlusion do not correspond to any ideal occlusal diagram,
- during unilateral mastication, the chewing of the food is performed by working as well as nonworking contacts, which may account for evidence of wear on nonworking side cusps,
- centric occlusion is the occlusion most often used during mastication and the occlusion for which masticatory forces are greatest.

The importance of a "functional occlusion" has been emphasized by many authors in the literature (Schuyler, 1954; Beyron, 1969; Stallard, 1976; Roth, 1981). Although a number of detailed criteria are outlined by these authors, based on the goal of "avoiding dysfunction" (Roth, 1981), conclusive experimental evidence to support the application of these criteria is not provided.

In spite of this, orthodontic tooth movement is generally expected to improve masticatory function and occlusal stability. A number of authors have proposed that masticatory efficiency is dependent upon the number, size and distribution of occlusal contacts in centric occlusion (Yurkstas, 1965; Omar *et al.*, 1987). Ricketts (1966) advocated 48 occlusal stops as the ideal number for dentitions without third molars. A recent study by Sullivan and co-workers (1991) however, demonstrated that orthodontic treatment often results in a decrease in the number of tooth contacts, and even after sufficient settling time for the teeth post-treatment, orthodontic patients may not realize as many contacts as a comparable group of untreated controls.

A definite relationship between tooth morphology and occlusion, and chewing pattern in dentate humans appears to exist. In general it seems that flattened cusps encourage more lateral jaw movements during chewing. This was noted by Beyron (1964), and also demonstrated by Hannam and associates (1977) in subjects who underwent occlusal adjustment.

The same level of sensitivity to tooth morphology was not demonstrated in a group of edentulous subjects, studied by Woelfel *et al.* (1962). Three different types of posterior tooth form were tested in six edentulous subjects, to determine the effect, if any, on chewing pattern. Differences in the chewing pattern associated with the 3 different occlusal schemes in well-adjusted dentures, could be identified in only one subject. The loss of input from the periodontal receptors resultant to the loss of the teeth could possibly account for the level of insensitivity demonstrated by the edentulous group to posterior tooth morphology.

The debate over whether tooth wear is a functional or parafunctional phenomenon has been long-standing. Lucas and Luke (1983) have reviewed the main arguments for and against tooth wear, and have concluded that although the attrition of teeth is an unavoidable consequence of ageing, the external and internal structure of tooth cusps are too specific and well-designed for maintenance of form to advocate wear as imperative. This argument is supported by Shaw (1918) who described the mechanical advantages of unworn tooth cusps in causing rupture of a bolus via sheer stresses, as opposed to compressive stresses.

2-3.2.3 Food Rheology

The rheological properties of food (characteristics of deformation and flow) are considerations to the individual in all matters of food choice, and are of particular interest to the food industry. A great deal of literature is therefore available regarding the study of food rheology and texture (see Mita, 1986). The physiology of texture perception is indeed complex (Boyar and Kilcast, 1986). It involves not only the physical characteristics of the food, but the *in vivo* sensory evaluation, which includes visual, olfactory, and oral perception.

A number of instruments have been devised to objectively measure food properties. In general, these are modifications of basic material testing machines. For a description of some of the instruments commonly referred to in the literature, see Boyar and Kilcast (1986). While these instruments tend to simulate the first bite in a chewing sequence adequately, they cannot mimic the variable dynamic processes involved and the continuous changes in the physical properties *in vivo*, due, for example, to changes in temperature, and to wetting and dilution by saliva. For this reason, some investigators have advocated the use of artificial test boluses, for which the textural properties are controllable, and therefore more reliable and reproducible (Olthoff *et al.*, 1986).

The nature of the test food is known to affect the chewing pattern (see Bates *et al.*, 1976 for a review). in general it seems that harder and tough food results in a more lateral chewing stroke, while softer foods are chewed with more vertical movements (Koivumaa, 1961; Rudd *et al.*, 1969).

Plesh and associates (1986) showed that for automatic chewing, increasing the hardness of gum resulted in a slower chewing rate, with no change in gape. These effects were accounted for by adjustments in the opening and occlusal phases, while the closing phase of the chewing cycle remained approximately unchanged. These findings for automatic chewing were important to distinguish from findings from later work by the same group of investigators (Bishop *et al.*, 1990), where, during chewing involving voluntary control, the peripheral feedback effects of changing the hardness of the gum bolus appeared to be overruled. That is, for chewing gum of different hardnesses in time with a metronome, no difference in chewing pattern could be detected.

An increase in the amplitude of EMG activity has been associated with foods of increased hardness by some studies (Neumann, 1950; Horio and Kawamura, 1989), although the opposite was found by Steiner and co-workers (1974). Without a method for normalizing and calibrating the EMG results, comparisons between different muscles and different studies may not be valid. Horio and Kawamura (1989) reported that the masseter muscle EMG amplitude showed a greater increase than that of the temporal muscle when foods of increasing hardness were tested. This finding is difficult to interpret meaningfully in terms of relative muscle strengths, especially since the temporalis muscle was only recorded unilaterally in "a few subjects."

Differences in the number of chewing strokes and chewing time varied with the hardness of the test food in the majority of subjects (23/29) tested by Horio and Kawamura (1989). In a smaller group of the subjects tested (6/29), however, the number of chewing strokes and the chewing time were essentially the same for all 5 test foods. This suggested that in this smaller group of subjects, the induction to swallow was not dependent on the degree of maceration of the food, but rather on a habitual pattern of chewing. The proposal that the number of chewing strokes is the best single indicator of the sensory impression of meat texture put forth by Tornberg and associates (1985) therefore, may not always be applicable.

2-3.3 Assessments of Masticatory Function

The literature regarding masticatory function and ability has been reviewed by Carlsson (1974) and Bates *et al.* (1976).

Much of the attention to masticatory function has focussed on the ability to measure the degree of food maceration during chewing. The terminology used reflects this focus.

Efficiency, as defined by Webster's (1977), is:

> 1. effective operation as measured by a comparison of production with cost (as in energy, time, and money)
>
> 2. the ratio of the useful energy delivered by a dynamic system to the energy supplied to it.

The most common expression of masticatory efficiency follows the first of these definitions more closely, in that it is regarded as the number of masticatory strokes required to reduce a food bolus to a certain particle size. This has been distinguished from masticatory performance, which is the particle size distribution of food when chewed for a given number of strokes.

In a classic paper, Manly and Braley (1950) measured the masticatory performance of a number of subjects using a number of test foods. The subjects were asked to chew a given portion of test food for a prescribed number of strokes on one side of the mouth, and to avoid swallowing any food. The chewed bolus was recovered from the mouth and passed through a series of graduated sieves. The particles on each mesh screen were dried and weighed. The masticatory performance was expressed as a percentage of the chewed food particles that passed through a 10 mesh screen (2.0 mm mesh opening). The greater the degree of maceration of the bolus, the more particles passed through the standard screen, and the higher the masticatory performance. The masticatory efficiency was estimated by Manly and Braley by plotting a graph of the logarithm of the number of chews against the masticatory performance (that is, a designated degree of pulverization) on a probability scale representative of a standard subject. From the masticatory performance scores of a given subject, an efficiency ratio could be extrapolated from the graph and expressed as a percentage comparison to the results of the standard subject.

The approach by Manly and Braley has been criticized (Sheine and Kay, 1982) but variations of this approach have been used by a number of other investigators (Loos, 1963; Åstrand, 1974; Pancherz and Anehus, 1977; Helkimo *et al.*, 1978; Rissin *et al.*, 1978; Edlund and Lamm, 1980; Chong-Shan *et al.*, 1990a and 1990b).

As an alternative to this sense of efficiency and performance, Sheine and Kay have proposed the quantification of masticatory effectiveness, using a mathematical model and chewing task data from human and other primate subjects. This term has the advantage that it expresses the comparative abilities of different species to increase exposed food surface area during the process of chewing. It therefore takes into account particle surface-area rather than size, does not involve the drying of the test foods, allows the testing of fibrous foods (which by their nature interfere with the sieving process) and other animal species, and does not assume that every masticatory stroke has an identical effect on a given bolus.

Sheine and Kay found that the thoroughness of mastication depends somewhat on the initial size of the food. This is in agreement with the findings of Lucas and Luke (1983). They also found that in humans, the first masticatory cycle achieves the most increase in the exposed surface area of the food, and the amount of additional exposure declines thereafter. During the masticatory process the largest food particles are reduced in size selectively, and there seems to be a minimum size below which the food is not further divided (possibly a function of the particular dentition). Finally, Sheine and Kay were able to link the cuspal morphology in certain primates to high coefficients of masticatory effectiveness, that were compatible with the high fibre diet characteristics of these species.

The process of particle selection has also been studied (Lucas and Luke, 1983), and mathematical models have been devised to make predictions that describe what happens to the bolus during chewing (Olthoff *et al.*, 1984; Van der Bilt *et al.*, 1987).

A more true measure of efficiency, expressed as a ratio of forces, has been described by Anderson (1924). Although the system described is too simplified, the approach is an interesting one. Anderson has proposed a mechanical analysis of the biting system, and has solved the three-dimensional force and moment requirements for static equilibrium. According to this analysis, for a bite force produced at a specified location, the muscle effort (force) required to produce this bite force can be calculated. The ratio of the bite force to muscle effort thus expresses the efficiency of the system. Anderson calculated an efficiency of approximately 55 percent for molar biting, compared with approximately 36 percent for incisor biting, in situations requiring 20 pounds of biting force.

Three investigations using EMG to assess masticatory function deserve mention. In an early study, Neumann (1950) described a method for "objective" measurement of the energy produced from muscles in the cheek and the forehead during chewing. In this study, Neumann used a string galvanometer with two electrodes, one over a masseter muscle, and the other over the centre of the forehead. From this set-up, he was able to record the change in electric potentials during the mastication of a number of foods. These foods were selected to represent a range of "masticatory values." Neumann contended that soft foods had a low masticatory value, and contributed to "regressive processes" associated with the masticatory apparatus, in particular, to the susceptibility of the teeth to dental caries.

The efficiency of masticatory movements during gum chewing was assessed quantitatively by Ahlgren (1966), using total integration to represent all of the EMG activity recorded from the masseter and temporalis muscles. Ahlgren regarded this as a measure of the muscular work, and noted that the masseter and temporalis muscle work inputs were positively correlated during mastication. In the group of 60 children tested, no significant correlations were found between the muscular work input for gum chewing and jaw morphology, occlusion, or sex. Ahlgren reported a trend to decreasing integrated EMG values with age. Also, children with grinding, as opposed to chopping movements, appeared to develop more muscular activities during mastication. The EMG data was not normalized or calibrated in this study, and the results show a very large range of variability.

Many other studies in the literature have attempted to use EMG as some indicator of masticatory function (for example: Åstrand, 1974; Rissin *et al.*, 1978) but the lack of normalization and calibration of the EMG results makes direct comparisons questionable.

In a more recent paper, Neill and associates (1989) have used the EMG activity of the masseter muscles to assess the ability to apply force during chewing. These results were expressed relative to a calibrated scale, derived from isometric biting tasks. This calibration allowed the meaningful comparison of individuals with different dental characteristics. Neill and associates found that the applied forces in chewing were reduced in denture wearers, but were somewhat compensated for by increased time of force application. In testing different denture tooth morphologies, these investigators were able to demonstrate that tooth forms with sharper cutting edges required less applied chewing force.

3 Use of Electromyography

3-1 General Applications to the Masticatory Muscles

In the past, EMG has often been used to describe the coordination of the muscles involved with jaw movement (Moyers, 1950; Carlsöö, 1952; Ahlgren, 1966; Møller, 1966; Gay and Piecuch, 1986). EMG recording has also been advocated for use as a diagnostic and treatment aid to clinical dentistry. Such applications have recently been reviewed and criticized by Lund and Widmer (1989).

EMG recording has not commonly been applied in a true quantitative fashion. The interference pattern presented by the raw EMG signal is complex, and historically, technical limitations have made the direct, continuous activity of the EMG signal difficult to compute. A number of techniques have thus been developed to quantify certain EMG parameters (for a review of these, see Ahlgren, 1966; Møller, 1966; Bouisset, 1973). Most of these techniques involve some form of signal averaging, and therefore do not always represent the true nature of the signal.

In his 1966 work, Ahlgren advocated the use of total integration of the raw EMG signal, as a complete representation of the total electrical activity recorded from the muscles, in a measure of the efficiency of masticatory movements. He expressed this as:

$$\text{Efficiency of the Masticatory Movements} = \frac{\text{Work Output}}{\text{Work Input}} = \frac{\text{Chewing}^{*}}{\text{Electrical Activity}} = \frac{\text{Constant}}{\text{Integrated EMG}}$$

* (constant duration, speed, bolus, and range of motion).

Ahlgren assumed that the integrated EMG could be used as a reliable index of the muscular work developed during chewing. The rationale for this sort of proposal is summarized in the following section.

3-2 Electromyography-Muscle Characteristics

The EMG activity represents the major changes in the currents and voltages that occur when the muscle fibres are activated by their motor neuron. The depolarization of the surface membrane of the muscle caused by release of acetyl choline at the neuromuscular junction spreads down the length of a muscle fibre and results in the release of calcium ions through the sarcotubular system. This triggers events leading to the hydrolysis of adenosine triphosphate, which provides energy for the activation of the muscle contractile processes. In this way the electrical activity of the muscle initiates the mechanical activity (Møller, 1966) at the cost of muscle energy.

EMG gives some idea about the start and end of muscle activity, and the number of active motor units and the frequency at which they fire (Gottlieb and Agarwal, 1971; Basmajian and De Luca, 1985; Loeb and Gans, 1986). By all indications, single motor units located in the muscles of mastication follow an orderly pattern of recruitment, as seen in other muscle systems (Goldberg and Derfler, 1977; Yemm, 1977; Desmedt and Godaux, 1979). That is, low threshold units show longer twitch contraction times and smaller twitch tensions, and are activated first. As the muscle tension (force) levels increase, there is an orderly increase in recruitment, firing rate, and eventually, in the synchronization of firing.

A linear relationship between tension and integrated EMG of isometric and isotonic contractions has been demonstrated by several investigators (Inman *et al.*, 1952; Lippold, 1952 Bigland and Lippold, 1954, Close *et al.*, 1960; Komi, 1973; Pruim *et al.*, 1978). Other investigators have reported nonlinear behaviour: 1) where a range of high force magnitudes were tested, and increased motor unit synchronization likely occurred with the increased muscle tension (Zuniga and Simons, 1969; Milner-Brown and Stein, 1975); 2) where tension was measured over a wide range of shortening velocities (Fenn and Marsh, 1935; Devlin and Wastell, 1985); 3) where muscle length was varied (Manns *et al.*, 1969); and 4) where fatigue effects were introduced (Vrendenbregt and Rau, 1973).

In conditions where fatigue is avoided and isotonic contractions are regulated with respect to load, velocity, and range of movement (Close *et al.*, 1960; Ralston, 1961), the integrated EMG can be a suitable measure of the mechanical qualities that characterize muscle contraction (Bouisset, 1973; Winter, 1979a).

The influence of velocity on EMG has been further investigated by a series of anterior biting experiments (Appendix C; Iwasaki and McLachlan, 1990). These experiments monitored the effects on the masseter muscle EMG activity during biting on the anterior teeth at different velocities of closure. (The anterior temporalis muscles were essentially shut down for this task.) For closing velocities of less than approximately 10 mm per second, the velocity of closure had relatively little effect on the masseter muscle EMG activity. Above this threshold velocity, the EMG activity of the masseter muscle showed a consistent exponential increase. For most normal-paced masticatory activity, it therefore appears that the applied-force effects are the dominant influence on the masseteric EMG recorded.

All muscle systems are not alike, however, and in particular they differ in orientation relative to joints or other movable parts, cross-sectional area, and fibre type (Buchthal and Schmalbruch, 1970; Pette and Vrbová, 1985; Sjöström *et al.*, 1986). The masseter and temporalis muscles have been characterized to demonstrate fibre-type differences

(Erkisson and Thornell, 1983; Stålberg *et al.*, 1986). Fatigue studies have demonstrated these muscles to be relatively resistant to fatigue (Van Steenberge *et al.*, 1978; Naeije and Zorn, 1981; Lindstrom and Hellsing, 1983; Clark and Carter, 1985; Clark and Adler, 1987).

The slope of the EMG versus muscle tension (force) relationship has gained the attention of a number of investigators (De Vries, 1968; Kawazoe *et al.*, 1979). This slope is said to reflect the "efficiency of electrical activity" (De Vries, 1968), and may be decreased with muscle training. Kawazoe and associates found that the slope of the masseter muscle on the preferred side was lower than that on the non-preferred side in 18 of the 20 subjects studied.

4 Energy Cost Measurements

Muscles convert chemical energy into mechanical work. For an overview of the relationships between muscles and energy, readers are referred to Goldspink (1978). Of particular note is the difficulty in measuring the energy used by the muscle contractile system during dynamic activity. Most commonly, estimates must be made from *in vitro* muscle preparations and extrapolated to the *in vivo* situation. Methods of measuring the metabolic heat given off by muscles (which represents the muscle energy not converted into external work), and of measuring oxygen consumption (which is made more complex by the fact that muscles can operate anaerobically as well as aerobically), have been applied in the past. With respect to the efficiency of muscle contraction and the transduction of energy into work, however, these are not regarded as very accurate (Goldspink, 1978).

Because the normal metabolic system is so well-equipped for the replacement of hydrolysed adenosine triphosphate, energy costs at the biochemical level are difficult to measure, particularly *in vivo*. Some indications of the energy supplies and metabolite levels involved in muscle contraction can be gained from fatigue studies (Roberts and Smith, 1989).

A predictable link between EMG activity and oxygen-consumption has been demonstrated by Kuroda and co-workers (1970). This was found to have a "linear plus exponential" relationship, that would describe the increase in EMG observed during a sustained contraction. This finding offers more direct support for the application of muscle EMG as a measure of muscle energy costs.

5 Efficiency Measurements in Other Systems

Muscle efficiencies in relation to internal and external work done have been investigated in other muscle systems (Starr, 1951; Whipp and Wasserman, 1969; Gaesser and Brooks, 1975; Kaneko and Yamasaki, 1978; Winter, 1979b). Studies have shown that the energy costs of doing positive work (work done while the muscle is shortening) are more than those of doing negative work (work done while the muscle is stretching)

(Abbott *et al.*, 1952; Hill, 1960). Experiments by Komi (1973) have demonstrated that the EMG amplitudes associated with doing positive work are more than those for doing negative work. This also supports EMG as a relative measure of muscle metabolism (Winter, 1979a).

Chapter III Materials and Methods

1 Subjects

1-1 Selection Criteria

Healthy adults with complete permanent dentitions and without previous orthodontic or orthognathic surgical treatment were invited to participate in this study. Other criteria for the selection of subjects were based on clinical standards for three distinct facial types: long face [LF], short face [SF], and "normal." Qualitative clinical assessments of facial type were verified quantitatively by means of two measurements: the anterior facial height proportions, and the steepness of the mandibular plane. These measurements were made using standardized photographic slide transparencies of each subject.

The investigator provided volunteer subjects with verbal and written information about the study. All subjects completed a brief history form in order to document personal, medical health, and dental health information. Signed consent was also obtained from all subjects. Copies of the written information provided and the forms employed may be found in Appendix B.

1-2 Dentofacial Records

Permanent records were made of each of the subjects in order to verify and quantify the selection criteria and to characterize the dentition. As mentioned, photographs of the face and head were obtained. Dental models and records of the right and left biting positions were also made.

Plaster replicas of the dentition of each subject were assessed with respect to form by two independent and experienced investigators. The models were judged on the basis of steepness of cuspal inclines (sharpness of the teeth), and degree of interdigitation (occlusion). The dental models were also assessed with respect to function by *in vitro* measurements of work done in isolated "chomps" on various boluses. These form and function analyses are described in more detail later in this chapter.

For the dental record-making procedures, as well as for the experimental data-recording sessions, the subjects were seated upright in a dental chair, without external neck support.

1-2.1 Dental Models

1-2.1.1 Impressions and Castings

Standard impression-making techniques were employed to attain life-sized plaster replicas of each subject's maxillary and mandibular dentitions. An irreversible hydrocolloid impression material (Jeltrate^R Alginate Impression Material, Type I - Fast Set: L.D. Caulk Division, Dentsply International Incorporated, Milford, Delaware) was used as per the manufacturer's directions, in impression trays sized to fit the subject's dental arches. Soft rope wax (Modern Materials^R

Wax Square Ropes - white 94491: Miles Incorporated Dental Products, South Bend, Indiana) was adapted to the rim of each impression tray in order to further customize the fit of the tray and to help to retain the set impression material during removal from the mouth. Upon removal, the impressions were rinsed, sprayed with a disinfectant (Virocidin-X:^{R} ABI Bioventures Incorporated, Winnipeg, Manitoba), and stored at high humidity until they could be cast in buff-coloured gypsum dental plaster. All of the impressions were cast soon after removal from the mouth.

Once solidified, the gypsum castings were recovered from the impression material and inspected. Any small nodules of plaster not representing anatomical structures were removed. The bases of the maxillary and mandibular castings were then trimmed to be parallel with one another and to the plane of occlusion. This plane of occlusion was defined by the posterior teeth with the maxillary and mandibular teeth in a maximum intercuspation position ("centric occlusion").

Molds for duplication of the trimmed castings were made from sheets of clear plastic (Bioplast^R 2.0 mm x 125 mm square: Scheu-Dental, Burgberg, West Germany), by heating and vacuum-adaptation of the plastic to the original castings in a dental appliance fabrication machine (Biostar:^{R} Great Lakes Orthodontics Limited, Tonawanda, New York). The original castings were retained for reference and for the assessment of tooth morphology and occlusion. At least three sets of duplicate plaster models were made. One set was used for the customization of the isometric bite force measuring devices for each of the subjects. The other two sets were trimmed further, to obtain quadrant models of the left and right posterior teeth. The resulting paired, right and left maxillary and mandibular quadrant models had bases that were parallel to one another and to the plane of occlusion, and measured approximately 25 to 35 mm in total base-to-base height.

The tooth surfaces of the quadrant models were painted with a coat of clear lacquer (Cover Girl Nailslicks:™ Noxell (Canada) Corporation, Mississauga, Ontario), in preparation for use in the *in vitro* experiments described in Section 2 of this chapter.

1-2.1.2 Occlusal Assessment

A set of gypsum maxillary and mandibular dental models were used to describe quantitatively the dental morphology and occlusion of a given subject. This was a limited, static analysis, in which the factors considered were not weighted in terms of their functional importance.

Two individuals with advanced dental training[1] assisted in this portion of the study by performing independent inspections of the model sets representing the sample

---

[1] D.M.S., a specialist in prosthodontics
J.C.N., a specialist in orthodontics

population. The complete group of model sets were reviewed in random order, at one sitting. At this time, the inspector completed an occlusal assessment form (Table 1) for each set of models. Each individual carried out the occlusal assessments a second time, on another day.

All assessments were made with the models in "centric occlusion," a centred, full-tooth contact position. This position was noted clinically (and recorded in wax in some cases) by the principal investigator during the record-making procedures, and was transcribed to the subject's dental models. Reference markings for this position were made on the right and left sides, by drawing a vertical line through the buccal cusp tip of a maxillary bicuspid, extended on to the corresponding area of the mandibular cast. The dental characteristics assessed were divided into anterior and posterior categories, with the right posterior and left posterior sides evaluated separately.

The anterior characteristics measured were:

> Overjet - the horizontal distance between the labial surface of the lower incisors and the lingual surface of the upper incisors, measured near the incisal edges (to the nearest 0.5 mm), and

> Overbite - the vertical overlap of the incisors (measured as a percentage of the clinical crown height of the lower central incisors).

The posterior characteristics measured were divided into three subcategories:

> Angle Classification (Moyers, 1979) - the conventional orthodontic system of classifying

Table 1. Occlusal Assessment Form

Occlusal Assessment for Models:			
Investigator (initials):		Date:	
I Anterior Relationship Assessment:			
a) Overjet (mm):		b) Overbite (percent):	
II Posterior Relationship Assessment:			
A) Right		B) Left	
a) Angle Class:	mm	a) Angle Class:	mm
b) Cusp Inclines		b) Cusp Inclines	
c) Interdigitation		c) Interdigitation	
Total b) + c) Right		Total b) + c) Left	
Overall Total b) + c):			

the anteroposterior first molar relationships; this describes the position of the mesiobuccal cusp of the maxillary first molar relative to the buccal groove of the mandibular first molar: if they coincided, the relationship was termed Class I; if the maxillary cusp was ahead of the buccal groove, or behind the buccal groove, the relationship was termed Class II or Class III, respectively. The relative position of the maxillary cusp ahead (+) or behind (-) the mandibular groove, was quantified to the nearest 0.5 mm.

Cusp Inclines - the steepness of the inclined planes that formed the cusps of the teeth were evaluated and a general assessment was made of the right and left sides. The so-called "working" cusps (usually, the buccal cusps of the lower teeth and the lingual cusps of the upper teeth) were the main focus of this evaluation. The cusp inclines were scored as: 0, 1, or 2, which represented flat, moderately steep, and steep classifications.

Interdigitation - how well the teeth interdigitated was also scored, as either 0, 1, or 2, which represented the range between: open contacts (0) and the tight, inter-locking of adjacent and opposing tooth surfaces (2).

The anterior and Angle molar relationship measures provided information for the characterization of the dental occlusion in a conventional manner. According to a detailed list of criteria for "ideal" occlusion that has been formulated by Roth (1981), overjet and overbite should both measure 2.5 mm, and the molar relationships should be Angle Class I.

The cuspal inclines and interdigitation scores on one side were summed to provide an evaluation of these characteristics on that side, for a given subject. These scores were totalled for an overall evaluation of these occlusal aspects for each of the subjects.

1-2.2 Bite Registrations

Interocclusal records of a right-side and a left-side biting position were made for each subject. The ends of a wooden tongue blade were wrapped, once around, with a strip of pink denture base-plate wax (NeoWax^{R} Baseplate Wax, 0.050 inch thick: Dentsply/York Division, Dentsply International Incorporated, York, Pennsylvania), approximately 25 mm in width. Warm water was used to soften the wax for adaptation to the tongue blade, and to prepare it for the recording of the bite position. One end of the modified tongue blade (about 5 mm in total thickness) was positioned by the investigator, between the subject's posterior teeth on one side, and the subject was instructed to simply "bite down" through the softened wax. The wax records obtained were chilled in cold water, labelled, and later used to mount the dental models in the positions of left posterior biting, and right posterior biting, in a plasterless dental articulator (Galetti^{R} 21-0000: Silverman's Dental Supplies, King of Prussia, Pennsylvania). The relative positions of the teeth in the two representative biting situations were noted, and the respective set-ups were used to construct customized acrylic biting surfaces for devices employed to measure bite force on the left and on the right (see Section 3-1.1).

1-2.3 Photographic Slide Transparencies

1-2.3.1 Equipment and Set-up

A 35 mm, single-lens reflex camera (Pentax^R 'Asahi' (K1000 SE): Pentax Canada Incorporated, Vancouver, British Columbia), with a side-mounted rotatable point flash unit, and colour film (Kodak^R 'Ektachrome' 100HC (EC 135): Kodak Canada Incorporated, Toronto, Ontario) were employed to make slide transparencies of the head and face of each subject in the study. Processing and developing procedures were carried out by a local commercial laboratory. A minimum of two slides were made per subject: one full frontal view of the head and face, and one lateral view of the right side of the head and face, perpendicular to the midsagittal plane.

In preparation for photographing, the unobstructed view of the following anatomical structures was ensured: the external ear, the forehead, the eyes (opened, with a straight-ahead gaze), the inferior orbital area, the chin, the throat, and the upper part of the neck. Eyeglasses and large pieces of jewelry were removed, and if necessary, the hair was pinned back.

The subjects were seated upright on a stool. The head was oriented so that the plane marked by the level of the inferior orbital rims and the external auditory meati, known as the Frankfort Horizontal plane [FH], was approximately parallel with the floor. One frontal view facial photograph was made with the subject relaxed, the teeth in light contact in centric relation position, the lips in repose, and the gaze straight ahead. One lateral view photograph of the right side of the subject was made under similar conditions, with the addition of a marker for the orientation of the mandibular plane [MP]. For this, the flat surface of a wooden tongue blade was positioned against the inferolateral border of the mandible and held to place by the subject, using light, superomedially-directed finger pressure (Figure 1). If the posture appeared to be altered to accommodate the MP marker, a second sagittal view slide was made without the MP marker.

1-2.3.2 Measurements to Determine Facial Type

For each subject, the frontal view slide was projected and assessed for bilateral facial symmetry. The sagittal view slide was also projected and a drawing was made by tracing the soft tissue profile and the anatomical structures relevant to the facial type analysis (Figure 1). On the drawing of each individual, the following landmarks were identified:

Porion (Po) - the junction of the superoposterior part of the tragus of the ear with the external auditory meatus

Soft Tissue Orbitale (Or') - the most inferior point of the soft tissue crease below the eye, overlying the inferior orbital rim

Glabella (G) - the most prominent point of the forehead, in the midsagittal plane, determined by a tangent to the forehead from a line passing through Subnasale (Burstone, 1958)

Subnasale (Sn) - the point at which the nasal septum between the nostrils merges with the upper cutaneous lip in the midsagittal plane

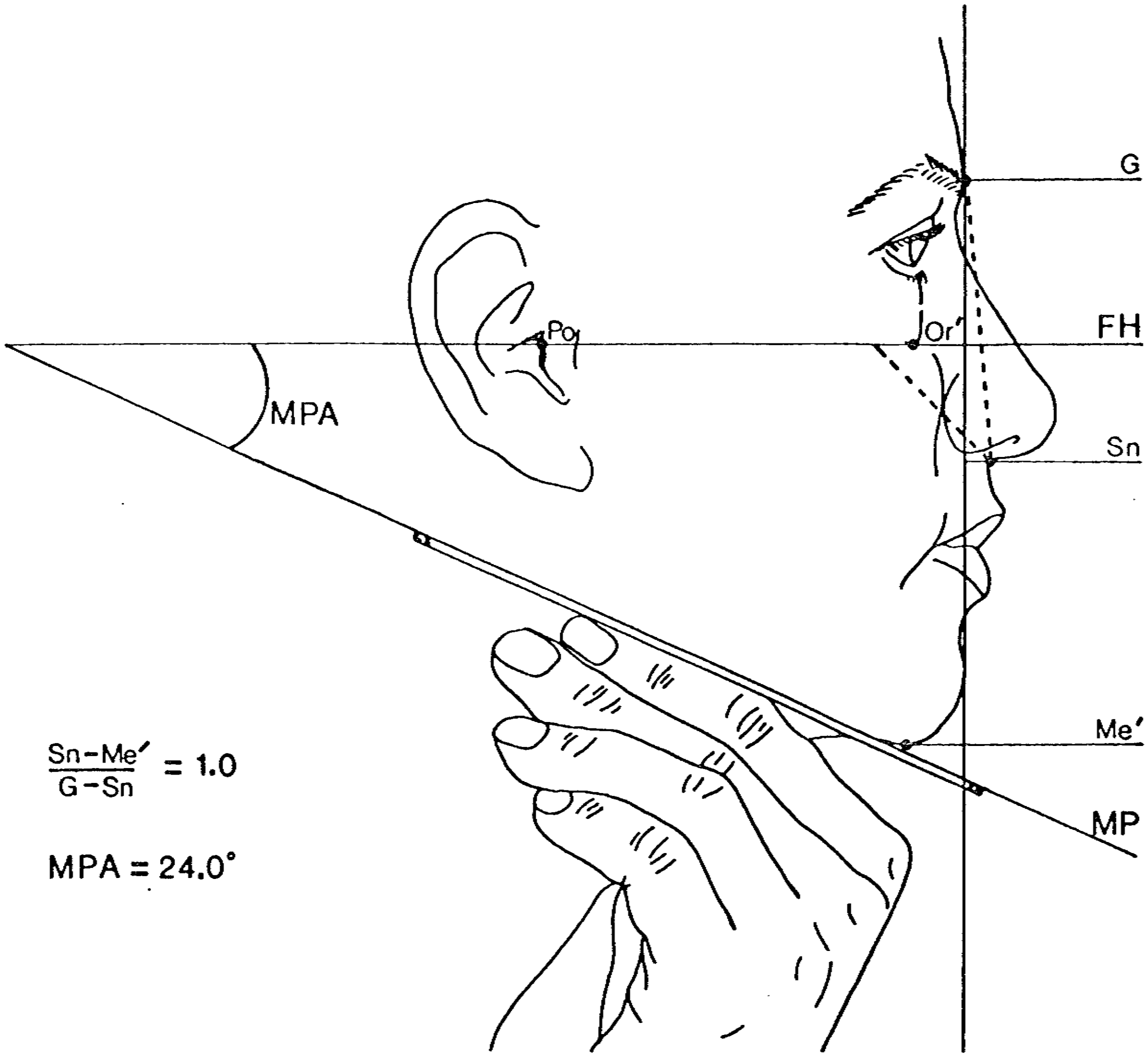

Figure 1. Sagittal view tracing of a subject showing the soft tissue profile and anatomical structures relevant to the facial type analysis. The marker that was held in place to demonstrate the mandibular plane, is also illustrated. (Po = Porion, G = Glabella, Or' = Soft Tissue Orbitale, FH = Frankfort Horizontal Plane, Sn = Subnasale, Me' = Soft Tissue Menton, MP = Mandibular Plane, MPA = MP-FH Angle) The anterior facial height proportions (Sn-Me'/G-Sn) and the MPA for this subject were consistent with the normal standards used in this study.

> forming a definite angle (If the depression is a gentle curve, Sn is interpreted as the most concave point relative to a line angled at 45 degrees from the horizontal reference plane, that passes through this area.) (Engel *et al.*, 1979)
>
> Soft Tissue Menton (Me') - the lowest point on the contour of the soft tissue chin, on a line perpendicular to the horizontal reference plane (Legan and Burstone, 1980).

The vertical dimensions of the face, that is, the anterior facial height proportions, were assessed according to Legan and Burstone (1980). The ideal ratio of the lower-third facial height (Sn-Me') to the middle-third facial height (G-Sn), measured perpendicular to the horizontal reference plane, was 1.0 (Figure 1).

In this study, the line joining points Po and Or' represented the horizontal reference plane, FH. It may be noted that the horizontal reference plane used by Legan and Burstone (1980) was represented by a constructed line through radiographically determined anatomical landmarks. That is, it passed through Nasion (the junction of the frontal and nasal bones in the midsagittal plane), seven degrees superior to the Nasion-to-Sella (Nasion-to-the centre of the pituitary fossa) line. The constructed horizontal reference used by Legan and Burstone and FH are expected to be parallel (Beaton, 1973; Burstone *et al.*, 1978).

The superior lengthwise edge of the tongue blade, marking the border of the mandible, represented the MP. The angle between the FH and MP, the mandibular plane angle [MPA], was measured to quantify the steepness of the inferior border of the mandible. According to cephalometric standards of "normal," appropriate to the population investigated, the mean for this parameter is 25.3 degrees, with a range of 20.6 to 30.0 degrees.[2]

2 Measurement of the Mechanical Work Done on a Bolus

2-1 Standard Test Boluses

The mechanical work done on a bolus can be standardized by the use of a specific amount of material that is the same for all subjects. In the case of foodstuffs, a standardized bolus would be expected to be prepared by chewing in a manner and to a degree of maceration that is acceptable for swallowing by the individual. The amount of mechanical work applied to a given type and amount of food is expected to be quite consistent for, and characteristic of, an individual (Carlsson, 1974). The work described herein also permitted investigation of this. That is, in addition to quantifying elevator muscle activity, the raw electromyographic [EMG] data was used to determine the time-taken, the number of chomps,

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[2] The "Manitoba Analysis" is a set of standard values for commonly used cephalometric measurements based on a selected sample of individuals with Class I "normal" skeletal and dental patterns, from the city of Winnipeg, Manitoba, Canada (Beaton, 1973). These norms were felt to be appropriate for the clinical sample group described in this thesis. The value of the angular measurement, MPA, should be comparable whether derived from a radiograph, or from a photograph.

and therefore, the chewing rate per chewtest.

Two types of test boluses were used. The standard food bolus, when chewed, changed in consistency and prepared it for swallowing. A second, non-food bolus, softened to a relatively consistent state when chewed, and was expected to remain in this state without being swallowed.

The standard food bolus used was a 10 mm cube of raw yellow turnip.[3] This provided a relatively consistent, brittle bolus that was broken down in a series of chomps, before being swallowed. Chewing gum was used as the non-food standard bolus. Commercially available gum in the "unprepared" and the "prepared" state were tested. The unprepared bolus began in the form of a 10 mm cube of sugarless, peppermint-flavoured gum (Cristal:™ Warner-Lambert Company, Adams Brands Manufacturing Authorized User, Scarborough, Ontario) made from a stack of three, one-quarter-stick pieces. The prepared bolus was the same amount of gum, after chewing. This was fashioned into a rectangular sample approximately 10 mm high and 8 mm in both width and length, to begin any test. During the course of the experiments, the unprepared gum bolus was worked to a relatively consistent mass. When the work required to deform the bolus was approximately the same for each chomp, it was

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[3] *Brassia napobrassica*, commonly called rutabaga and also known as "Swedish turnip," is a roundish, yellow root vegetable, with a crisp texture and sweet taste.

said to have reached the "prepared" state. The gum was not swallowed.

2-2 *In vitro* Test Chomps

A materials testing apparatus and two displacement transducers allowed force and distance measurements for the calculation of the mechanical work done in a simulated chew (single chomp) situation. That is, life-sized dental models were mounted in the materials testing apparatus and were used to crush standard test boluses. These *in vitro* simulations of *in vivo* bolus positions and compressive loading between the teeth, were recorded using a cartesian coordinate plotter to represent the force and distance outputs from the displacement transducers.

The force versus distance plots were then digitized for the computation of the work done, expressed in Newton-meter [N-m] units.

2-2.1 Equipment

2-2.1.1 Materials Testing Apparatus

A Hounsfield Tensometer universal testing machine (Hounsfield Tensometer™ (Type W): Tensometer Limited, Croydon, England), was employed for this part of the study (Figure 2). The testing machine was fitted with a compression cage attachment that had two opposing plane tables, one movable and one stationary. The load was applied by the

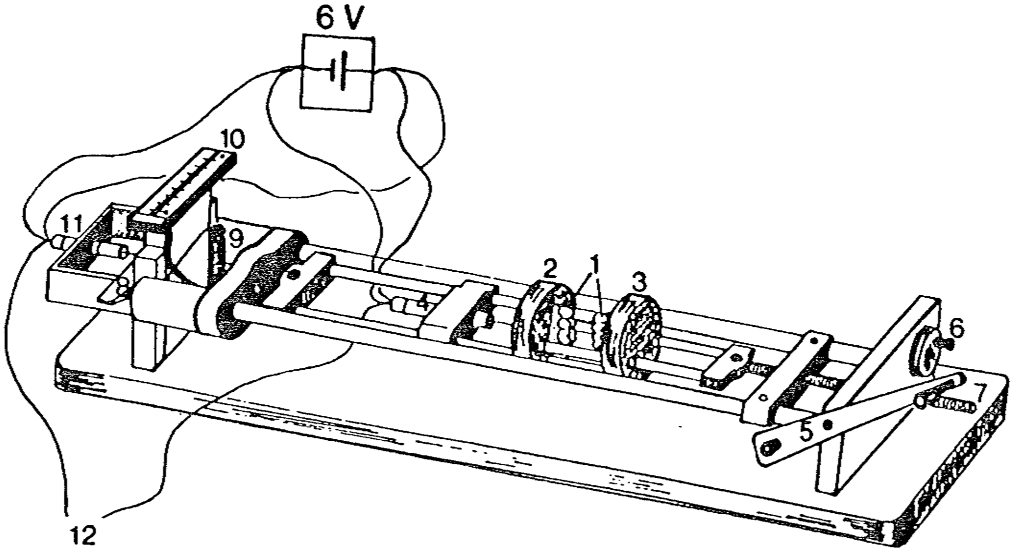

Figure 2. The materials testing apparatus showing dental models (1) mounted for simulated-biting tests. The maxillary quadrant model is attached to a movable table (2), and the opposing mandibular quadrant model is attached to a stationary table (3). The position of the movable table is monitored through a linear voltage displacement transformer [LVDT] (4), and determined by turning the handle (5 or 6) of the operating screw (7). The stationary table is linked to a spring beam (8), the deflection of which is transmitted to a mercury piston system (9) for a force-scale (10) reading of the applied load. The force output is monitored through a second LVDT (11) in contact with the spring beam. The LVDT output leads (12) were connected to an x-y plotter for recording of the applied force versus distance.

movable table, and was measured through the stationary table. The load application was controlled manually by turning the handle of the operating screw connected to the movable table. The stationary table was connected through a tension head and bridge to the centre of a precision spring beam, supported on rollers. The deflection of the spring beam was transmitted through a simple lever system to a mercury piston, which displaced mercury through a glass tube for a scale reading of the applied load. The spring beam stiffness and scale corresponded to a range of 0 to 556 Newtons [N]. According to the manufacturer, the accuracy of the apparatus, was expected to be better than ± 1 percent. This was verified for the set-up used, with a spring of known spring constant.

2-2.1.2 Force and Distance Transducers

Two linear variable differential transformers [LVDT] (7DCDT Displacement Transducer: Hewlett-Packard, San Diego, California) were used to record and measure force and distance outputs from the materials testing apparatus. The LVDT used to measure force had a full-scale displacement range of ± 2.54 mm. This LVDT monitored the force applied by the movable table of the materials testing apparatus, through the displacement of the spring beam. This force-sensitive LVDT was positioned opposite the tension head, normal to the centre of the spring beam.

The LVDT used to measure the distance travelled by the movable table had a full-scale displacement of ± 12.70 mm. After the dental models were mounted (see Section 2-2.1.4), this LVDT was secured in a position normal to the centre of the movable table, so that the working range was between zero (full-intercuspation of the models) and greater than 10 mm of clearance between the occluding surfaces of the models.

Each LVDT was connected to a 6 volt [V], direct current [DC] power source, and their DC outputs were measured via the cartesian coordinate recorder described in the following section. A linearity error of less than 0.5 percent of full-scale was to be expected, according to the manufacturer. The accuracy of the LVDTs and their readings through the recorder were tested using a spring of known constant and a calibrated ruler.

2-2.1.3 Plotter

A laboratory recorder (Model 7044A X-Y Recorder: Hewlett-Packard, San Diego, California) designed to plot cartesian coordinate graphs from DC electrical information was used to record the force and distance outputs from the materials testing apparatus. The force output was plotted along the y-axis (ordinate) against the distance output along the x-axis (abscissa). Each curve recorded the force applied and the position (distance) through the bolus at which it was applied, for an *in vitro* test chomp. Each of these plots was later digitized (see Section 2-2.3) to convert these results to measures of mechanical work done in N-m.

2-2.1.4 Dental Models

The trimmed and lacquered quadrant models described in a previous section (1-2.1), were mounted in the materials testing apparatus using double-sided tape (Scotch^{TM} Double Stick Tape: Home Products Division, 3M Canada Incorporated, London, Ontario). The mandibular model was attached to the centre of the stationary table. The opposing maxillary model was then positioned in maximum intercuspation, and the movable table was approximated to receive the tape-covered base of the upper model. The original castings, which were trimmed to the centric occlusion (maximum intercuspation) position, were used as a guide for the orientation of the quadrant models.

2-2.2 Test Chomp Protocol

A series of *in vitro* test chomp experiments were carried out with each of the *in vivo* recording sessions for a given subject. These *in vitro* experiments were done on the same day as the corresponding EMG recording session, either just prior to, or immediately following the *in vivo* experiments. The turnip boluses used for both the *in vitro* and the *in vivo* experiments, therefore, came from the same batch of sample cubes, and were always from the same turnip. Similarly, the gum boluses for one experimental session all came from the same sealed package.

Each test bolus was centred over the mandibular first molar tooth to begin the *in vitro* chomp. The bolus was positioned by the left hand of the investigator, while the right hand wound the operating screw handle of the materials testing machine at a steady rate. The table with the maxillary dental model attached was thereby moved into approximation with, and then through the bolus towards the mandibular dental model. The pen recorder simultaneously mapped out the force-distance relationships as the dental models were brought into full intercuspation, slicing and/or crushing the test bolus. The test chomps were terminated once a designated force level of 222 N was reached (Figure 3).

Before beginning each set of *in vitro* experiments, the recorder set-up was checked for hysteresis error and the zero-force baseline for the force-distance plots was established. As well, the force level of 222 N and the distance scale in mm were indicated along the y- and x-axes, respectively, for each set of *in vitro* results. These indicators were necessary to calibrate the axes of the plots for the digitizing and work done calculations.

One set of *in vitro* experiments consisted of test chomps on the turnip [T], the unprepared gum [UPG], and the prepared gum [PG] boluses. These were carried out between the right-side dental models and repeated for the left-side dental models. The test chomps on the turnip were repeated five

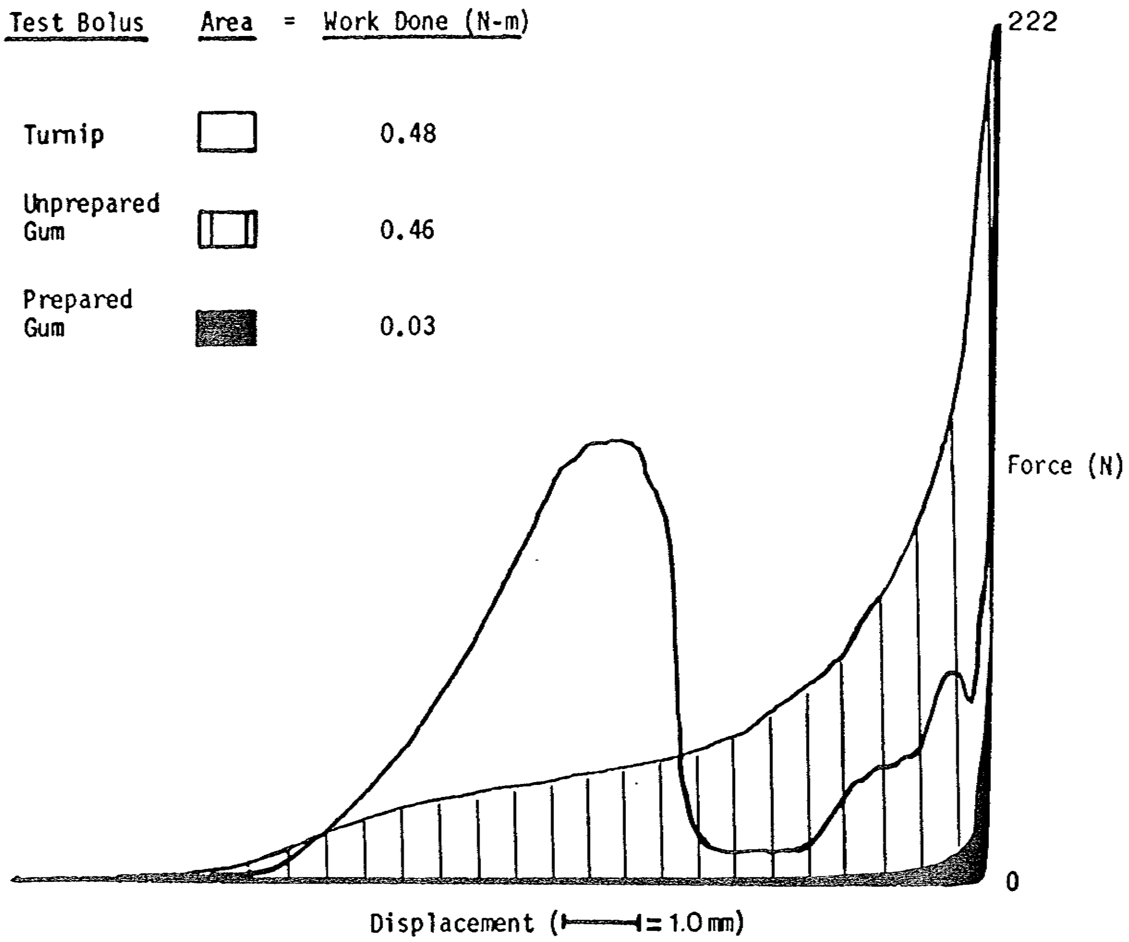

Figure 3. Force versus displacement plots showing an *in vitro* "chomp" of the Test Boluses, centred over the mandibular first molar. The corresponding work done calculations are also shown, in Newton-meters [N-m]. (Subject JH1, right)

times on each side, per set of experiments, while the gum boluses were tested once on each side (since they were expected to be of a more consistent nature).

2-2.3 Work Done Computations

The plots of force versus distance for the *in vitro* test chomps were digitized using a digitizing pad (HiPad:^{TM} Houston Instrument, Austin, Texas). An integration program (designed in house) was employed in a computer (IBM^{R} Personal Computer: IBM Personal Computer, Boca Raton, Florida) to carry out the calculations necessary to convert the information from the digitized plots to work done measurements in terms of N-m units. Each digitization and work done computation was repeated, and was expressed as a mean value. If there was a large discrepancy between the results from two measurements, the process was repeated until satisfactory agreement between the measurements was obtained. The repeatability of these measurements was generally high. Any discrepancies of significance could be attributed to operator error.

3 Measurement of Muscle Energy Costs in Chewing and Biting

The effective part of chewing and biting, in mechanical terms, involves the jaw elevator muscles. Four of the main jaw elevating muscles, the bilaterally paired superficial masseter and anterior temporalis muscles, which are accessible to surface EMG recording, were used to estimate the "energy costs" associated with the mechanical work done in chewing. For the quantitative evaluation of the results from different recording sessions and/or different individuals, it was necessary to address the potential for variability in the raw EMG signal strength and quality and the need for a calibrated scale. This was accomplished by normalizing the EMG data from chewing by expressing it relative to the EMG data from isometric biting for a given individual and recording session. Standard bipolar surface EMG recording techniques were employed.

3-1 Isometric Bite Force Measurements

3-1.1 Bite Force Transducers

Bite force measuring transducers [BFT] were designed and constructed for use in the mouth. The BFT for right biting and those for left biting were mirror-images of one another. The main components of the BFT were a thin, pressure-sensitive pad (Force Sensing Resistor,™ part numbers 150 - 1/4 inch square and 151 - 3/8 inch circle: Interlink Electronics, Santa Barbara, California), which was mounted between two opposing stainless steel plattens that formed the ends of a long-handled, forceps-like device (Figure 4). This pad was a polymer thick film device that exhibited a decreasing resistance with increasing, perpendicularly-applied force. The pad was attached to the inside surface of the lower platten. Attached to the pad, and also sitting between the two

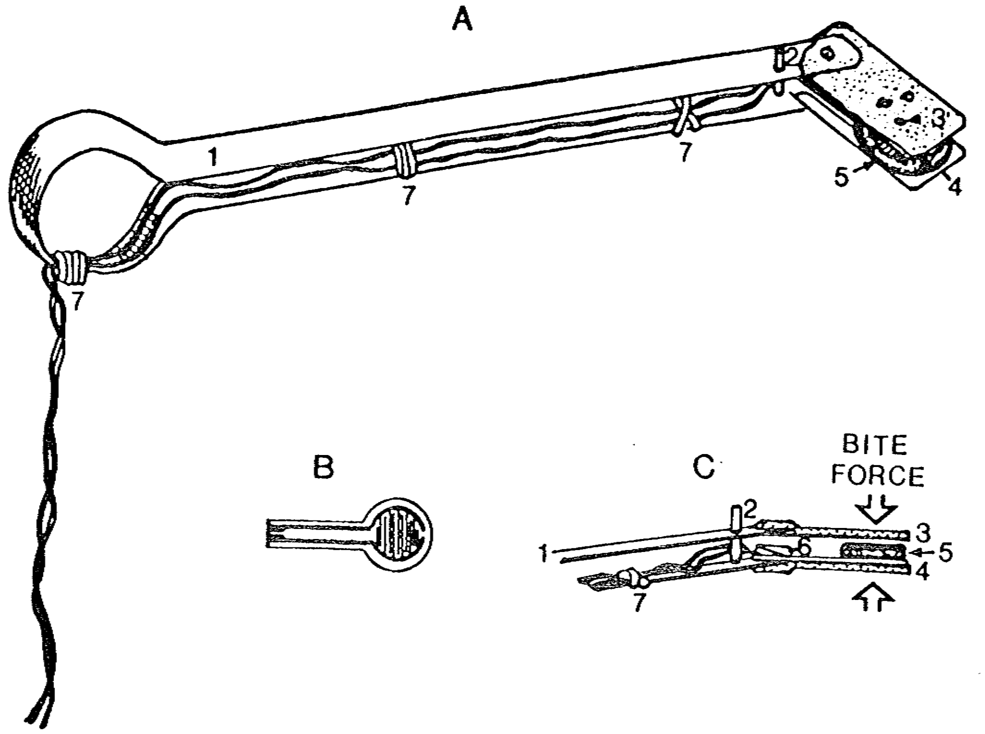

Figure 4. The Bite Force Transducer Device [BFT] in superolateral view (A) shows a stainless steel handle (1) with guide pin (2), and acrylic-covered upper (3) and lower (4) biting plattens. The upper platten has indentations in the acrylic biting surface to receive the maxillary first molar of a particular subject. A pressure-sensitive resistor pad (B, superior view) with a rubber o-ring (5) overlying it, is between the plattens, attached to the inner surface of the lower platten. The biting end of the BFT is also shown in a lateral view (C). Lead wires, cold soldered to the resistor pad and encased in protective epoxy (6), are secured to the handle by elastics (7), and permit connection of the BFT to an output recorder (x-y plotter).

plattens, was a small rubber o-ring. The o-ring served to distribute the applied bite forces over the pressure-sensitive pad, so that the force range and linearity were satisfactory. The outer, biting surfaces of the plattens were covered with a thin layer of cold-cured orthodontic acrylic resin (Lang's Jet^{R} Acrylic: Lang Dental Manufacturing Company, Chicago, Illinois). The acrylic on the superior-facing platten was customized to fit the cusp tips of the maxillary left or right first molar of a particular subject. This ensured that the force delivered was in approximately the same place each time. A biting position centred on the maxillary first molar was chosen, because, in most intact dentitions, it would be expected to be the average or most frequent point of contact of the teeth with the bolus during chewing on one side of the mouth.

The repeatability of the biting position was critical to the BFT since the accurate measurement of force by the resistor pad was position-dependent. The acrylic on the inferior-facing platten was smooth and polished, and did not restrict the biting position of the mandibular teeth. This allowed some freedom to achieve a stable biting position on the BFT between the maxillary first molar and the opposing mandibular teeth. The bite opening required to accommodate the BFT was approximately 4 mm to 6 mm.

The pressure-sensitive resistor pad and the interdigitating electrode array within it had an overall thickness of 0.33 mm. For consistent activation, the pad had requirements for a firm backing, and the application of loads to its upper surface. When a load was applied, the interdigitating electrodes were shunted to a degree dependent upon the magnitude of the load. This load could be measured as a resistance output. Lead wires were cold soldered (Hysol^{R} Epoxy Conductive Cement: Hysol Electronic Chemicals, Industry, California) to the poles of the electrode array. These connections were then encased in a protective binding material (Lepage's^{TM} 5 Minute Epoxy Glue: Lepage's Limited, Bramalea, Ontario) to keep them moisture-resistant.

All component parts were washed and disinfected or cold sterilized before and after assembling and customizing a BFT for use by a given subject. Double-sided tape (Scotch^{TM} Double Stick Tape: Home Products Division, 3M Canada Incorporated, London, Ontario) was used in the assembly to attach the o-ring to the upper surface of the resistor pad, and to attach the pad to the BFT forceps.

Since the position of the applied force was critical to the pressure-sensitive resistor pad, steps were taken to keep the biting position on the BFT as consistent as possible for a given *in vivo* and *in vitro* experimental session. The wax bite registrations of right and left biting between the maxillary first molar and the opposing mandibular teeth, described in a previous section (1-2.2), were used to record the relationships of the teeth in this position during a relatively natural bite. These bite registrations were then used to mount the dental models in this position, for the making of the customized acrylic biting surfaces of the BFT (one for the right biting situation, and another for the left biting situation).

3-1.2 Bite Force Transducer Calibration

The resistance output from the BFT was recorded on the y-axis of the x-y plotter, versus an x-axis time base (sweep speed: 2.5 centimetres/second), during a series of *in vitro* isometric bites. The set-up used was the same as for the *in vitro* chomps on the test boluses. That is, the quadrant models of a given subject's teeth were mounted in the materials testing apparatus. For the calibration of the BFT however, only the force-measuring LVDT was employed. The BFT was correctly positioned between the plaster dental models, according to the maxillary first molar, and the resistance outputs were recorded for measured, systematically increased isometric force magnitudes. The applied force was increased in steps of 19.7 N over a range of zero to 394 N or more. These measurements were repeated at least once for each BFT, for a given experimental session. From a mean of the measurement trials, a scale was thus developed to determine the relationship between the resistance measured and the magnitude of the applied force. The calibrated BFT was then used to measure the force associated with *in vivo* isometric biting tasks.

3-2 Electromyographic Recording

3-2.1 Conditions and Equipment

All *in vivo* experimental sessions were conducted in a designated EMG recording and data analysis room (Room 411, Department of Civil Engineering, University of Manitoba). Subjects were seated upright in a dental chair, facing away from the recording and signal-viewing equipment. During a recording session the doors were kept shut and the window shaded, in order to minimize exposure of the subject to extraneous stimuli.

The standard surface EMG techniques and equipment that were utilized in this study were approved by the Ethics Committee of the Faculty of Dentistry, University of Manitoba. Silver cup electrodes (E5S Silver Cup Electrodes, 48-inch length: Grass Instrument Company, Quincy, Massachusetts) were paired to form a bipolar electrode unit for recording from each of the masseter and anterior temporalis muscles. A single ground electrode was attached to a distant site, the right ear lobe. Adhesive-backed sponge pads (Reston™ Self-Adhering Foam Pads, 1560M: 3M Medical-Surgical Division, St. Paul, Minnesota) were used to secure the electrodes in position on the subject's skin. The centre-to-centre interelectrode distance of the bipolar units was approximately 25 mm. Each electrode cup was filled with a water-soluble conducting cream (Liqui-Cor,^{TM} 007886: The Burdick Corporation, Milton, Wisconsin) before being applied to the skin.

A four channel, battery operated, amplification system (Biological Amplifier System: BioSys, Winnipeg, Manitoba) enhanced the low-power electrical signals transmitted from the muscles by the EMG electrodes. The electrodes were linked to the preamplifier portion of the amplification system through a grounded socket assembly that was mounted on the wall behind the subject. The four preamplifiers were also attached to this wall unit. The preamplifiers were differential input, single-ended output and had a common mode rejection ratio of 100 decibels, an input resistance of 44 mega-ohms, a root-mean-square noise level of 1 microvolt, and a frequency band width of 0.1 Hertz to 10 kilo-Hertz. Each had a set gain of 100 times (± 5 percent).

Insulated cables connected the preamplifiers with the main amplifier. Adjustable low and high bandpass filters, set at 1 kilo-Hertz and 10 Hertz, respectively, were part of this system. The main amplifier provided an additional, adjustable gain of up to 100 times more for a maximum system gain of 10,000 times. The continuous gain controls were adjusted for each channel to maximize the signal-to-noise ratio without exceeding the output limit, which was ± 5 volts.

An oscilloscope (Model 1200A Dual Trace Oscilloscope, Hewlett-Packard Company, Colorado Springs, Colorado) was used to monitor the quality and strength of the EMG signals from the amplification system. The amplified signals were then stored on magnetic tape (3M Recording Tape, 809-1/4-1800 PR7: 3M Magnetic Media Division, St. Paul, Minnesota) by a four channel frequency-modulated tape recorder (Model 3960 Instrumentation Tape Recorder: Hewlett-Packard Company, Mountain View, California), run at a tape speed of 95.25 mm per second.

A known signal, provided by a function generator (Model 3310B Function Generator: Hewlett-Packard Company, Loveland, Colorado), was passed through the amplification system and recorded at each recording session, once the amplifier gain settings had been established, and again if any adjustments were required during the session. This permitted the calculation of the gain for each channel.

3-2.2 Protocol for EMG Recording

3-2.2.1 Preparation of the Subject

In preparation for a recording session:

- each male subject was asked to shave his face, prior to the session, and
- all subjects were asked to refrain from applying facial ointments or cosmetics on the day of the session, until the recording was completed.

The subject was first seated upright in a dental chair, in a comfortable position. The muscles of interest were then palpated to locate the major component of each of these muscles. That is, the fleshy portions of the superficial masseter muscles and anterior temporalis muscles were manually located by the investigator. The centre of the most active portion of these was determined as the subject contracted the muscles by gently clenching the teeth together.

The skin over these areas was prepared to receive a bipolar electrode unit, by being wiped with 70 percent isopropyl alcohol, and then being rubbed vigorously for ten to fifteen seconds with a disposable cotton gauze sponge. The skin was wiped again with alcohol and allowed to dry. The bipolar electrode unit was positioned over the prepared area of the skin, in line with the direction of muscle pull (Figure 5).

Similarly, an area of skin on the subject's right ear lobe was prepared to receive a single ground electrode. This ground electrode was fixed to the ear with an adhesive-backed sponge, and was additionally secured with a plastic ear clip.

The impedance at each set of bipolar electrode-prepared skin interfaces was measured and recorded before the electrode leads were connected to the preamplifier. Low impedance readings were desirable. If the impedance exceeded 30 kilo-ohms, the electrode unit was removed, the skin reprepared, and the electrodes were checked and cleaned, if necessary. The unit was then reassembled and replaced. This was repeated until a lower reading was achieved, as long as the subject's comfort was not compromised. The signal-to-noise ratios for each EMG set-up were checked and the

Figure 5. A subject prepared for electromyographic recording, illustrating bipolar surface electrode units attached to the skin by adhesive pads over the right anterior temporalis (1), right masseter (2), left anterior temporalis (3), and left masseter (4) muscles. A single ground electrode is similarly attached to the right ear lobe (5), and secured with a plastic clip. The position of the electrode cups along the direction of the muscle pull is shown schematically for (1) and (2), as if the pads were transparent.

amplifier gains adjusted as required. The minimum acceptable peak-to-peak signal-to-noise ratio was 10:1 for the ipsilateral muscles involved in a moderately hard unilateral molar bite on a wooden tongue blade.

3-2.2.2 *In vivo* Chewing and Biting Tasks

The EMG activity of the main jaw elevating muscles was recorded while a standard series of tasks was performed by the subject. This comprised one recording session and took approximately 45 minutes to complete. In a second recording session, the series of tasks was repeated by the subject on another day, and was recorded in the same fashion. The tasks involved the chewing of standard samples of turnip and gum, and isometric biting on the BFT. The tasks are described in detail according to the chewing or biting material, in the following paragraphs. The tasks were always carried out in a particular order, however, and this protocol is outlined in Table 2.

The term "natural chewing" refers to chewing in an ordinary fashion, that is, chewing in the subject's habitual manner without marked conscious effort. The term "unilateral chewing" refers to chewing on one side, the side of the first chomp, for the duration of the chewing task.

A turnip "chewtest" was defined as the chew-until-swallow of a standard turnip cube. The end of the task was indicated by a hand wave from the subject. The natural chewing turnip

Table 2. *In vivo* Chewing and Biting Task Protocol

Task Label	Chewing/Biting Material*	Task Description**	Number per Session
A-	Turnip	Natural Chewing	4
R-	Bite Force Transducer	Isometric Biting, Right	3
L-	Bite Force Transducer	Isometric Biting, Left	3
BR-	Unprepared Gum	Unilateral Chewing,Right	1
BL-	Unprepared Gum	Unilateral Chewing, Left	1
CR-	Prepared Gum	Natural Chewing, starting Right	1
CL-	Prepared Gum	Natural Chewing, starting Left	1
DR-	Turnip	Unilateral Chewing,Right	3
DL-	Turnip	Unilateral Chewing, Left	3
ER-	Turnip	Unilateral Chewing,Right starting at bicuspids	1
EL-	Turnip	Unilateral Chewing, Left starting at bicuspids	1
FR-	Turnip	Unilateral Chewing,Right starting at second molar	1
FL-	Turnip	Unilateral Chewing, Left starting at second molar	1
N	-	Relaxed and Resting	1
r	Impression Material	Isometric Biting, Right	1
l	Impression Material	Isometric Biting, Left	1

* Refer to the text for a description of the standard size and form of the material.

** Refer to the text for a complete description of the tasks.

chewtests (A tasks in Table 2) were always carried out at the very start of the EMG session. For these, one turnip cube was offered at a time, which the subject delivered by hand for ingestion, without any restriction regarding the chewing side.

Turnip samples were also chewed unilaterally by the subject for trials carried out alternately on the right and on the left. On each side, three different starting positions were used, beginning with the turnip cube between the teeth, centred over: the mandibular first molar (D tasks in Table 2), the mandibular bicuspids (E tasks in Table 2), and the mandibular second molar (F tasks in Table 2).

The gum chewing tasks were of two general types: an unprepared gum cube chewed unilaterally for trials on the right and on the left (B tasks in Table 2), and a prepared gum cube chewed naturally after a starting chomp on the right side for one trial, and the left side for another (C tasks in Table 2). The EMG activity was recorded during the gum chewing tasks for between 45 and 60 seconds per trial. To start a trial, the gum boluses were always positioned between the teeth, centred over the mandibular first molar of the designated side in the unilateral chewing tasks, or of the starting side in the natural chewing tasks.

An isometric biting task involved biting on the BFT at three bite force levels, sustained for approximately three seconds each. That is, once the BFT was correctly positioned, the subject bit down, beginning with a "medium" bite force (as perceived by the subject), and then increased the bite force twice more so that the final bite force magnitude was relatively "hard." This task was repeated three times on the right and three times on the left. A minimum of 30 seconds rest was taken between each task.

At the same time that the EMG activity was recorded on tape during these biting tasks, the resistance of the BFT was recorded on the y-axis of the x-y plotter versus a time base on the x-axis (run at 2.5 seconds/centimetre) (Figure 6). A sustained isometric bite force level could thus be identified, and the force magnitude derived from the force-resistance calibration curves established *in vitro*.

The x-y plotter was set-up behind the subject, so that no visual feedback was provided to the subject. Verbal feedback in terms of increasing the bite force and holding a bite force was provided to the subject by the investigator, who monitored the bite force (as indicated by the resistance output) as it was plotted by the recorder pen during the task. The objective was to obtain a variety of sustained isometric bite force levels in the range where the BFT was most linear (generally, 90 N to 440 N).

The subject was informed that maximum effort biting was not desired. Positioning of the BFT relative to the maxillary first molar on the side of biting was aided by the investigator, however, the subject freely positioned the mandible to achieve a stable bite. The subject was asked to

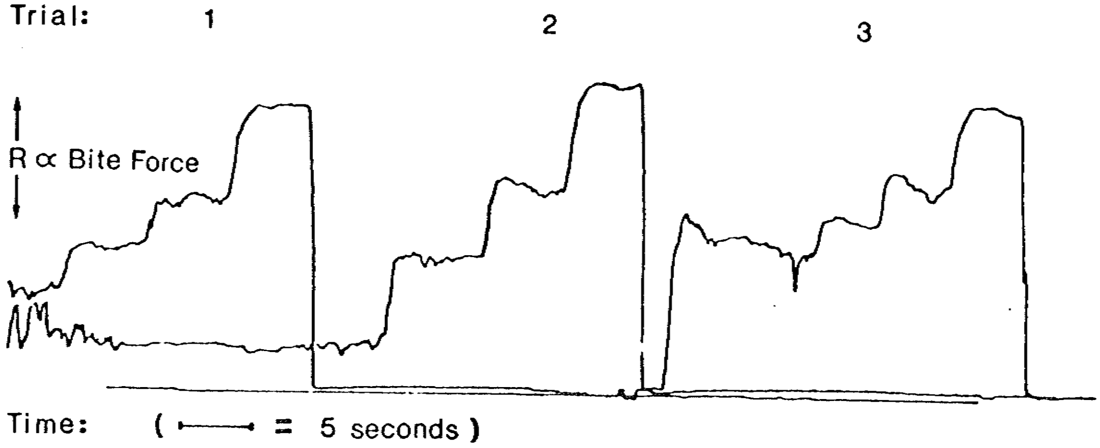

Figure 6. Isometric Biting Tasks: Plots of Resistance (R) versus Time for three trials (with a minimum of 30 seconds rest between trials, not shown on the time scale). The R-output from the Bite Force Transducer *in vivo* was calibrated by *in vitro* experiments to obtain the corresponding bite force magnitude.

bite down a few times on the BFT, without recording, to test this situation for comfort.

Before each chewing and biting task, the investigator gave the subject simple verbal instructions regarding the particular task. No mention was made of how many tasks of one sort would be performed. Feedback, if required, was always verbal, and of an encouraging nature. For instance, the placement of the bolus required for some of the tasks was first described by the investigator, sighted by the investigator, and adjusted as necessary through verbal instructions (for example: "position the cube over the first big teeth on the lower right," and "please move the cube forward about 3 mm"). The sighting of the position of the cube was important for these specific tasks since these positions were simulated by the investigator for the *in vitro* test chomps. If the performance of a task was unsatisfactory, this was not indicated directly to the subject, but the task was repeated with instructions as appropriate.

3-2.3 Notations and Observations

A microphone auxiliary to one channel was used to label the tape at the start of each EMG session. A verbal identification of the tape reel number, the counter position, the date, the name of the subject, and the session number were recorded on to the tape.

A written record of the procedures done and the data collected for each EMG session was kept. The tape counter positions before and after each task were written down so that they could be located and identified for future analysis. Any noteworthy observations regarding the experimental conditions, and EMG signals, or subject behaviour were also written down.

At the conclusion of an EMG session, all the equipment was switched off or disconnected, and the electrodes were removed. The prepared areas of the subject's skin were wiped free of any residual conducting cream and moisturized with a lanolin towellette (Moist wipes: Zellers Incorporated, Montreal, Quebec). During this clean-up period, the subject was informally questioned as to whether they had a preferred side for chewing and a dominant side in terms of chewing "strength." These responses, as well as any comments offered by the subject regarding the study were noted and recorded.

3-3 Data Analysis

3-3.1 Data Transfer, Data Display, and Calculations

The EMG activity of the four muscles during the chewing and biting tasks were recorded simultaneously and stored on tape. Subsequently, the tapes were replayed and the signals converted to digital form, and stored on the hard disk of a computer. Special programs (designed in house), permitted the raw EMG data to be visually displayed against a time scale (Figure 7), and computations to be performed. From the time scale and the visual display, measurements of the time-taken

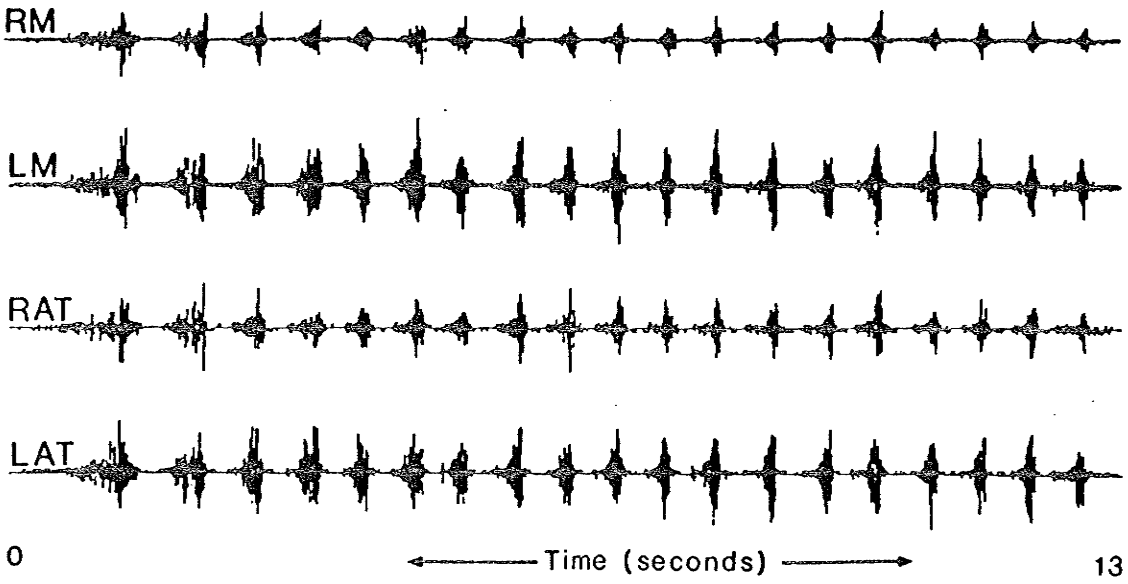

Figure 7. Raw EMG data from the right masseter (RM), left masseter (LM), right anterior temporalis (RAT), and left anterior temporalis (LAT) muscles for a left unilateral turnip chewtest (total number of chomps = 19). (Subject: CG1)

for any task, the number of chomps (muscle activity bursts) and the chewing rate per chewtest, could be obtained. In addition, calculations of the root-mean-square [RMS] and the integrated-square values of selected sequences of the raw EMG data were performed through the computer.

3-3.2 Normalization and Calibration Factors

3-3.2.1 EMG Activity and Bite Force Relationships

From the force-calibration of a given, customized BFT, the bite force magnitudes corresponding to the EMG activities recorded during the isometric biting tasks, were calculated. The time scales of the x-y plotter recording of the BFT output during an *in vivo* biting task, and the computer display of the raw EMG activity during that task, were matched. The RMS value of the EMG activity corresponding to a sustained bite force of known value was thus determined for the four muscles for the situation of right biting and left biting. Plots of RMS EMG activity versus bite force were expected to be reliable, reproducible, and quantitatively sensitive with respect to muscle function (Lindauer *et al.*, 1991).

3-3.2.2 Normalization and Calibration Factor Derivation

From the plots of RMS EMG activity versus bite force, the normalization and calibration factor values were established for each of the four muscles in the situation of right biting and in the situation of left biting. These normalization and calibration factors had units of (EMG activity)^2/N, and were employed to express the integrated square of the raw EMG data [ISE] from chewing on a given side relative to the EMG of isometric biting on that side.

In the derivation of a normalization and calibration factor, the RMS EMG value corresponding to a bite force of 133 N was used. This value of bite force was deemed an appropriate standard to use to establish these factors for three reasons:

1. This bite force magnitude was well-within the range of expected human bite force capabilities (see Chapter II Literature Review, for details).

2. From *in vitro* chomps of the standard turnip boluses, it was established that the peak force reached before initial failure of the bolus ranged between 110 N and 150 N, with the mean around 133 N.

3. The BFT device was least accurate in the low ranges of applied force (approximately less than 90 N).

For a given muscle, and a given biting side (right or left) then, the RMS EMG value corresponding to a bite force of 133 N was squared and divided by 133 to obtain the normalization and calibration factor value expressed in the desired units (EMG activity^2/N). A set of eight factors were derived to analyze the data obtained for an individual at a recording session.

3-3.2.3 Normalization and Calibration Factor Check

The basis of the established normalization and calibration factor for a given subject and recording session was indirectly checked in most cases. That is, the accuracy of the bite force magnitudes measured by the BFT and the relative mix of muscle activity elicited were checked by having the subject carry out an additional biting task on the right and left sides.

A small rectangular sample of set vinyl polysiloxane impression material (Cutter^R Perfourm Putty - Type I: Columbus Dental, Toronto, Ontario) approximately 10 mm long, 10 mm wide, and 5 mm high, was positioned between the first molars on one side. The subject was asked to bite down and maintain this position in a steady fashion for a short period of time (2 to 3 seconds). The EMG activity of the four muscles was recorded during this time and the displacement of the bolus (gauged by the vertical distance between the teeth) was measured and noted. This displacement of the bolus was repeated *in vitro* for the same biting conditions, again using the dental models mounted in the materials testing machine, to measure the approximate applied force. The EMG data for the *in vivo* biting conditions for this force were then compared with the EMG data corresponding to the same bite force magnitude measured by the BFT, as determined from the plots of RMS EMG versus bite force.

3-3.3 Normalized and Calibrated EMG Data

The EMG values recorded during chewing tasks performed at a given recording session were normalized and calibrated relative to the EMG output for isometric biting recorded at the same session. Experiments designed to test the effects of velocity and force on EMG are described in Appendix C (see also: Iwasaki and McLachlan, 1990; Chapter II Section 3-2). These experiments established that for the range of normal-paced chewing, the velocity effects can be considered negligible as compared with the force effects.

The ISE recorded from the four main jaw elevating muscles during a given chewing task gave a running summation of the EMG activity over the time taken to complete the chewing task. The ISE was representative of the raw data itself, as discussed in the Introduction and in Appendix A.

Because the relative activity was different for a given muscle depending on whether it was involved with biting on the ipsilateral side or the contralateral side, the normalization and calibration factor appropriate to the side of the biting or chewing situation was applied. The identification of relative muscle patterns associated with a chewing side in the analysis of the unilateral chewing task data facilitated the identification of the chewing side for the analysis of the natural chewing task data.

The ISE for each muscle from a given task was divided by the normalization and calibration factor of the same muscle acting in the same capacity relative to the side of chewing or biting, with the time for the task taken into account. For example, the ISE from the right masseter muscle during a right chewing sequence would be normalized with the factor for the right masseter muscle from right isometric biting. In addition, the normalization and calibration factor, which was the squared EMG output per unit of isometric bite force for each muscle, was integrated over the same time as the *in vivo* chewing task. That is, the factor was multiplied by the length of time taken to complete the chewing task to be analyzed. This represented the "energy cost" of isometric biting at a bite force magnitude of one N, for the designated length of time. (Fatigue effects were not considered here.) Measured in this way, the EMG activity ratio used to express "energy costs" was independent of time. This ratio had units of N-equivalents of bite force [N-eq BF]. The individual muscle ratios were summed to obtain a quantitative value that was normalized and calibrated for the comparison of results from different subjects and recording sessions.

All the turnip chewtest data were analyzed and the EMG data expressed as energy cost ratios. The first ten chomps of the unprepared and prepared gum chewing tasks were analyzed and also expressed as energy cost ratios. (These were compared, as were the energy cost ratios of the first ten chomps for the chewtests.) Similarly, the data from the initial chomps in a chewing sequence involving the turnip or gum boluses were analyzed.

3-3.4 Presentation and Description of the Data

The measurements made of the individuals studied are presented in tabular form in Chapter IV Results. The data for each parameter measured were grouped according to the facial type of the individual: long [LF], short [SF], and "normal" [NF]. The group results for a given parameter are also expressed as the mean value and standard deviation [s.d.] about the mean.

Some elementary statistics were used to help further describe the results of this investigation (Kitchen, 1987). Student's t-test was employed to evaluate whether the LF group and SF group means for a given parameter differed significantly. The 95 percent confidence level was used unless otherwise stated. Student's t-test was also employed to test for significant differences between the mean results of a parameter for the LF group versus the NF group, and the SF group versus the NF group.

Chapter IV Results

1 Characterization of Subjects

1-1 Age

A total of 33 healthy, adult Caucasians participated in this clinical study. The mean age (and standard deviation) of this group was 29.3 years (7.2 years) with a range of 16.8 years to 48.2 years. The sample population was primarily intended to represent two very different facial types. Of the people who were willing to participate, those who exemplified relative extremes in terms of long facial type [LF] and short facial type [SF] were selected for study. The results from 14 LF subjects (eight females, six males) and 13 SF subjects (five females, eight males) are reported on herein. The results from six subjects (four females, two males), who were classified as belonging to the "normal" facial type [NF] category by conventional standards, are also presented.

People with medical or dental problems that compromised the reasonable and comfortable function of the chewing apparatus were not accepted (for example, those who reported current tooth or jaw pain were not accepted).[4] None of the

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[4] One subject, SK, reported a history of non-painful joint noises during chewing. Ten months prior to her participation in the study, she had experienced a period of jaw pain and dysfunction, presumed to be related to sustained, wide mouth-opening for dental treatment. The subject underwent occlusal splint therapy under the direction of her dentist, and the acute pain and discomfort were apparently relieved. The joint noises persisted and were quite marked.

Two other subjects, FK and RC, reported a history of periodic nocturnal bruxism. Both subjects wore a customized subjects had undergone orthodontic treatment involving the permanent teeth, nor had they had any form of orthognathic (jaw) surgery.[5]

The subjects were also screened for intact permanent dentitions. However, those with missing or unerupted teeth, but where the dental arch was continuous (without gaps between the teeth), were accepted. With one exception,[6] people who had spaces due to missing dental units were not accepted.

1-2 Facial Type Classification

The anterior facial height proportions and mandibular plane angle were used to verify the subjects as long, short, or "normal" facial types. The subject population is presented according to these conventional groupings in Tables 3 to 5. These tables indicate the sex and the age of each subject as well as the quantitative data regarding the aforementioned facial type parameters.

The results of the statistical analysis showed that in terms of each facial type parameter, anterior facial height proportions and mandibular plane angle, the groups were

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occlusal splint, *pro re na'ta*, to decrease muscle tension and tooth wear during these periods.

[5] One subject, TM, reported a jaw fracture during childhood, but this was deemed to have healed without obvious penalty to the masticatory apparatus.

[6] In the case of JH, spaces were present in the lower right dental arch, mesial and distal to the first bicuspid tooth. These probably developed as a result of the extraction of the mandibular right second bicuspid.

significantly different (p<0.01). There were no differences shown between the groups in terms of age however.

Table 3. Long Facial Type Subjects: Sex, Age, Facial Height Proportions [Sn-Me'/G-Sn], and Mandibular Plane Angle [MPA].

SUBJECTS	SEX	AGE (Years)	MPA (Degrees)	$\frac{\text{Sn-Me'}}{\text{G-Sn}}$
FH	Female	33.0	28.0	1.10
FK	Female	31.9	30.0	1.10
GAM	Female	30.5	46.0	1.20
GJ	Female	34.6	27.0	1.10
JA	Female	28.1	34.0	1.17
MD	Female	24.7	31.0	1.15
MI	Female	27.6	38.0	1.13
SD	Female	34.7	41.0	1.23
Mean ± s.d.	Females	30.6 ± 3.6	34.4 ± 6.7	1.15 ± .05
DB	Male	20.7	31.0	1.11
DT	Male	18.0	30.0	1.10
JM	Male	28.5	44.0	1.15
JW	Male	26.5	32.0	1.08
MM	Male	41.3	39.0	1.12
RM	Male	17.0	39.0	1.09
Mean ± s.d.	Males	25.3 ± 9.1	35.8 ± 5.6	1.11 ± .02
OVERALL MEAN ± s.d.	Females and Males	28.4 ± 6.8	35.0 ± 6.1	1.13 ± .04

Table 4. Short Facial Type Subjects: Sex, Age, Facial Height Proportions [Sn-Me'/G-Sn], and Mandibular Plane Angle [MPA].

SUBJECTS	SEX	AGE (Years)	MPA (Degrees)	Sn-Me' / G-Sn
CG	Female	34.8	22.5	0.77
JH	Female	27.3	13.0	0.83
MG	Female	29.4	11.0	0.86
RW	Female	32.7	18.0	0.76
ST	Female	21.8	20.0	0.74
Mean ± s.d.	Females	29.2 ± 5.0	16.9 ± 4.8	0.79 ±0.05
CH	Male	27.2	10.0	0.84
DO	Male	25.0	11.0	0.82
KL	Male	32.6	16.5	0.81
ML	Male	27.1	9.5	0.74
MP	Male	28.5	19.0	0.90
RC	Male	46.1	11.0	0.89
TG	Male	16.8	17.0	0.82
TS	Male	22.8	19.0	0.88
Mean ± s.d.	Males	28.3 ± 8.5	14.1 ± 4.1	0.84 ±0.05
OVERALL MEAN ± s.d.	Females and Males	28.6 ± 7.2	15.2 ± 4.4	0.82 ±0.05

Table 5. Normal Facial Type Subjects: Sex, Age, Facial Height Proportions [Sn-Me'/G-Sn], and Mandibular Plane Angle [MPA].

SUBJECTS	SEX	AGE (Years)	MPA (Degrees)	$\frac{\text{Sn-Me'}}{\text{G-Sn}}$
AM	Female	29.8	23.0	0.99
KN	Female	29.1	27.0	0.99
NH	Female	48.2	20.0	1.00
SK	Female	34.6	22.0	1.00
TAI	Male	31.4	22.0	1.00
TM	Male	23.4	23.0	0.99
OVERALL MEAN ± s.d.	Females and Males	32.8 ± 8.4	22.8 ± 2.3	1.00 (±0.005)

2 Occlusal Analysis

The results of the occlusal analysis carried out independently by two clinical dental specialists are presented for the subjects, grouped by facial type, in Tables 6 to 8. These data represent the mean values of measurements made on two separate occasions by each of the experts. Of the 264 measured values in total (8 occlusal factors for 33 subjects, measured twice, by two people), there was complete agreement in 105 instances (40 percent). There was agreement between the results from the two assessors for both sessions in at least three out of the four measurements for each occlusal factor, in 174 instances (66 percent).

In the following tables, the Overbite and Overjet measurements are presented descriptively as the "Anterior Relationships." Only those anterior relationships that represented large deviations from the "ideal" are indicated. Additional terminology, commonly used in dentistry has also been applied, and in some cases, abbreviated; that is:

ETE = ("end-to-end") overbite and overjet measurements of zero
Open bite = negative overbite measurement; a vertical distance between the incisal edges of the upper and lower teeth
Cross bite = (anterior cross bite) negative overjet measurement
Deep bite = large overbite measurement (≅100 percent)
Div. 1 = (Division 1) large overjet
Div. 2 = (Division 2) large overbite ("deep bite")
Sd. = (Subdivision) the class designation applies to the side indicated; the side not mentioned is Class I
r = right side
l = left side.

All subjects exhibited some degree of deviation from conventionally-accepted standards for ideal occlusion, and therefore, strictly speaking, all could be classified as having "malocclusions." Of the group, the records of subjects JA and JW demonstrated occlusal relationships that were most nearly ideal.[7] On the other hand, a number of subjects demonstrated occlusal relationships that were remarkably

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[7] The occlusal relationships of subject JA could be discriminated from ideal, by a small amount of mandibular anterior tooth crowding, while JW showed a minor discrepancy in the transverse positions of the upper and lower right posterior teeth (this compromised the congruency between these teeth slightly in the maximum intercuspation position).

different from accepted standards. The most notable relationships are acknowledged in the following subparagraphs:

1. As noted in Tables 6 and 7, extremes of overbite relationships were demonstrated within the sample. That is, anterior open bites, where there is a gap between the upper and lower teeth when the posterior teeth are in occlusion (negative overbite), were seen in LF subjects: GJ, MD, MI, DB, and JM. Subject DT may also be included in this group, since the overjet measurement was - 7.0 mm, and hence the anterior teeth could not be brought together to carry out incision effectively. Subject FH showed a mild form of anterior open bite, where the maxillary and mandibular incisal edges met approximately end on.

SF subjects CG, MG, RW, DO, KL, ML, MP, and TS, in contrast, all demonstrated extremely large vertical overlap between the upper and lower anterior teeth. In these cases, the lower incisal edges touched the soft tissues palatal to the upper incisors, when the posterior teeth were in occlusion.

2. Dental models from two subjects showed an exceptional amount of localized tooth wear. This loss of tooth structure seemed likely to be due to abrasion, through heavy contact between particular teeth, during jaw movements other than those involved in mastication. For subject RC, both overjet and overbite measurements were zero. This appeared to be a result of the loss of a substantial amount of incisal tooth structure. The cusp tips of the canine and the posterior teeth also showed a significant amount of wear, but relatively less than the incisors. Dental models of subject DO also showed marked localized tooth wear. That is, the mandibular left canine showed a large incisovestibular facet and the incisogingival height of this tooth was about half that of the mandibular right canine.

3. The following LF subjects demonstrated bilateral posterior cross bites (where the vestibular surface of at least one mandibular tooth was lateral with respect to the vestibular surface of the opposing maxillary tooth or teeth): FH, GAM, MI, and DT. LF subjects SD, DB, and RM and NF subject KN demonstrated a posterior cross bite on one side only.

Table 6. Occlusal Analysis for Long Facial Type Subjects: Conventional "Angle" Classification and an Evaluation of the Functional Posterior Occlusion.

SUBJECTS	"ANGLE" CLASS - Anterior Relationships	FUNCTIONAL OCCLUSION RATING: Cuspal Inclines		Interdigitation		Total Score
		r	l	r	l	
FH	III-ETE	0	1	0	0	1
FK	II, Sd. r	0	0	1	1	2
GAM	III, Sd. r	1	1	0	0	2
GJ	I-Open bite	0	0	2	1	3
JA	I	1	1	2	2	6
MD	III-Open bite	2	1	1	0	4
MI	I-Open bite	0	0	0	0	0
SD	II, Div. 1	0	1	1	0	2
DB	III, Sd. r - Open bite	1	1	0	0	2
DT	III-Cross/ Deep bite	1	1	0	0	2
JM	III-Open bite	0	1	1	2	4
JW	I	1	1	1	1	4
MM	II	0	0	1	2	3
RM	II, Sd. l	2	2	0	0	4
		OVERALL MEAN FUNCTIONAL OCCLUSAL RATING ± s.d.				3*± 2

See text (Chapter IV Section 2) for an explanation of the terms and abbreviations used.

Dashed line separates females [above], from males [below].

* Significantly different from NF group.

Table 7. Occlusal Analysis for Short Facial Type Subjects: Conventional "Angle" Classification and an Evaluation of the Functional Posterior Occlusion.

SUBJECTS	"ANGLE" CLASS - Anterior Relationships	FUNCTIONAL OCCLUSION RATING: Cuspal Inclines		Interdigitation		Total Score
		r	l	r	l	
CG	II, Div. 2	1	1	2	2	6
JH	II, Div. 1	1	1	0	1	3
MG	II, Div. 1 - Deep bite	1	1	1	1	4
RW	II, Div. 2	1	1	0	0	2
ST	II, Sd. r	1	1	2	2	6
CH	II, Sd. r	2	2	0	1	5
DO	II, Div. 2	2	2	0	0	4
KL	II, Div. 2	2	2	2	1	7
ML	II, Div. 2	0	1	1	0	2
MP	II, Div. 1 - Deep bite	1	0	0	0	1
RC	II, Sd.l -ETE	0	0	0	0	0
TG	II, Div. 2	2	2	0	0	4
TS	II, Sd. l - Deep bite	2	2	1	0	5
		OVERALL MEAN FUNCTIONAL OCCLUSAL RATING ± s.d.				4 ± 2

See text (Chapter IV Section 2) for an explanation of the terms and abbreviations used.

Dashed line separates females [above], from males [below].

Table 8. Occlusal Analysis for Normal Facial Type Subjects: Conventional "Angle" Classification and an Evaluation of the Functional Posterior Occlusion.

SUBJECTS	"ANGLE" CLASS - Anterior Relationships	FUNCTIONAL OCCLUSION RATING:				
		Cuspal Inclines		Interdigitation		Total Score
		r	l	r	l	
AM	II	1	1	2	2	6
KN	I	1	1	1	1	4
NH	I	1	1	2	2	6
SK	II, Sd. l	1	1	0	2	4
TAI	I	1	0	1	2	4
TM	III, Sd. r	1	1	1	1	4
		OVERALL MEAN FUNCTIONAL OCCLUSAL RATING ± s.d.				5*± 1

See text (Chapter IV Section 2) for an explanation of the terms and abbreviations used.

Dashed line separates females [above], from males [below].

* Significantly different from LF group results.

The functional posterior occlusion ratings, as described in Chapter III Section 1-2.1.2, potentially ranged from a minimum total score of zero to a maximum total score of eight. The means and standard deviations [s.d.] for these scores for the three groups were: LF 3 ± 2, SF 4 ± 2, and NF 5 ± 1. The variability in this rating shown by the LF and SF groups is reflected in the relatively large standard deviations about the group means. Nevertheless, a comparison of the mean total scores for the LF and NF groups revealed a significant difference for this parameter. No significant differences were demonstrated between the LF and SF groups, or between the SF and NF groups.

3 Plots of Isometric Bite Force versus EMG Data

The magnitude of the isometric bite force exerted on the BFT was plotted against the root-mean-square [RMS] of the simultaneously recorded EMG activity. Plots for the left and right masseter and temporalis muscles were made for the situations of molar biting on the right side, and molar biting on the left side. Thus, eight plots were obtained to describe the relationship of the EMG activity and bite force magnitude, for each subject, for each recording session. These plots were then used to derive the normalization and calibration factors employed to express the chewtest and chewing gum EMG data.

Since the BFT was least accurate at measuring bite force magnitudes below 90 N, the exact characterization of the plots was not reliable near the origin. For force magnitudes above 90 N, however, the plots could be represented by a straight-line relationship which, by extrapolation, passed near the origin. Data points from repeated biting trials (up to three per side) were used to construct a line representing the EMG-isometric force relationship for a given muscle, on a given side of biting, for a given recording session. Linear regression coefficient (r^2) values of at least 0.72, but in most cases above 0.90, demonstrated the strength of these relationships.

Figure 8 illustrates example plots of the EMG activity versus bite force magnitude for one muscle during two isometric biting situations. In this example, the EMG activity of the right masseter muscle of subject CG (Session 2) is shown plotted against bite force for the situation where it is acting as the ipsilateral masseter muscle (right side biting), and for the situation where it is acting as the contralateral muscle (left side biting). Data points from three trials for each side of biting are represented. The figure illustrates the scatter typical of the plotted results for the sample population. The y-intercepts of both plots pass very close to the "resting" RMS EMG activity for the muscle, recorded during a short period when the subject was asked to "relax and sit quietly." To further demonstrate example data, the plots used for EMG normalization and calibration for subject CG in Sessions 1 and 2, are described by their slopes (corrected for differences, if there were any, in amplifier gain settings) and r^2 values, in Table 9.

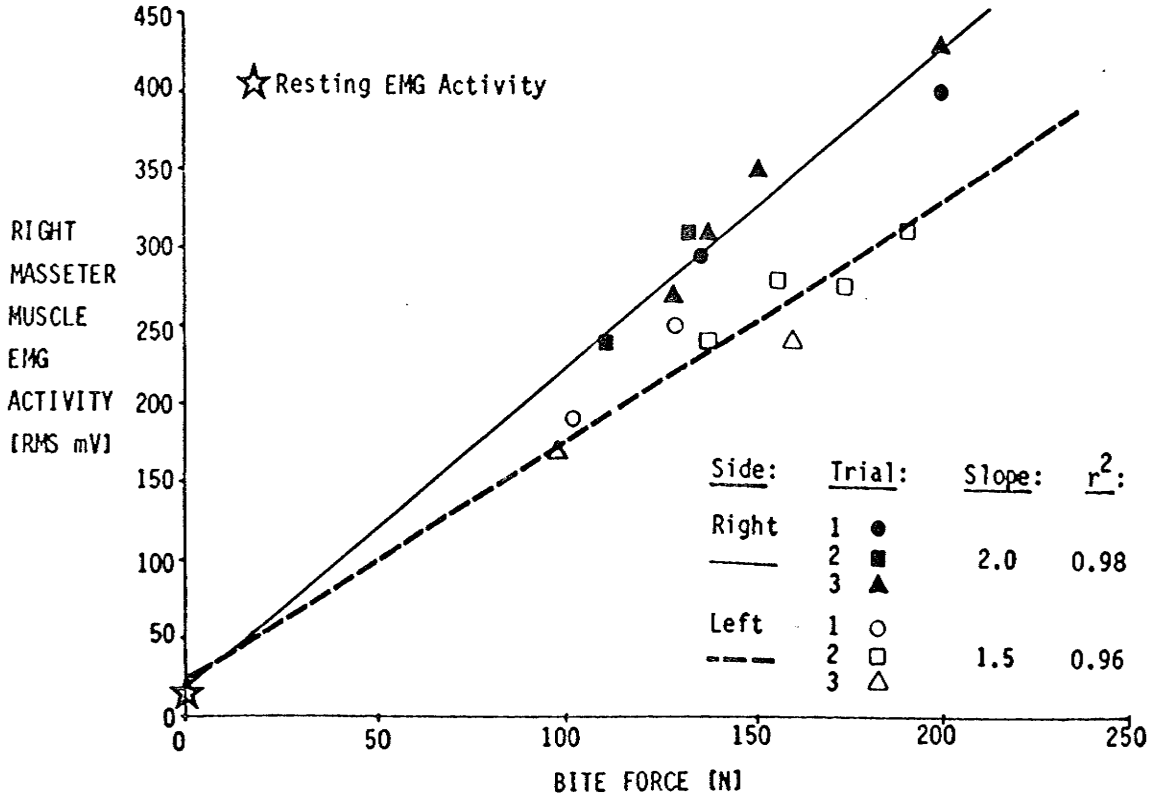

Figure 8. EMG Activity [RMS mV] versus Bite Force Magnitude [N] for the Right Masseter Muscle, in repeated trials of Right and Left Isometric Biting - Subject CG, Session 2.

Table 9. EMG Activity versus Isometric Bite Force Plots: Example of Slopes* [RMS mV/N] and Linear Regression Coefficients [r^2] - Subject CG.

SUBJECT/ SESSION	EMG ACTIVITY [RMS mV] VERSUS BITE FORCE MAGNITUDE: Slope* (r^2) Right Biting			
	IM	IT	CM	CT
CG1	0.48 (0.95)	0.43 (0.93)	0.21 (0.98)	0.09 (0.96)
CG2	0.45 (0.99)	0.27 (0.97)	0.23 (0.92)	0.13 (0.83)
SUBJECT/ SESSION	Left Biting			
	IM	IT	CM	CT
CG1	0.31 (0.88)	0.40 (0.90)	0.43 (0.92)	0.18 (0.90)
CG2	0.23 (0.88)	0.16 (0.83)	0.36 (0.94)	0.12 (0.95)

Key: r^2 = Linear regression coefficient
IM = Ipsilateral Masseter Muscle
IT = Ipsilateral Temporalis Muscle
CM = Contralateral Masseter Muscle
CT = Contralateral Temporalis Muscle

* Gain-corrected values in RMS mV/N.

4 Chewing Characteristics

4-1 Chewing Side Preference, Number of Chomps per Chewtest, and Chewing Rate for Turnip

The results for the following parameters are presented in Tables 10 to 12; once again the subject population has been grouped according to facial type, as established in Chapter IV Section 1 (Tables 3 to 5):

- the "preferred" side for chewing, according to the opinion of the subject
- the mean number of chomps per chewtest for "natural" chewing (with the percentage of chomps carried out on the right side during the natural chewing trials indicated in parentheses), unilateral right [RT] chewing, and unilateral left [LT] chewing of a turnip bolus
- the chewing rate for "natural" chewing, unilateral RT chewing, and unilateral LT chewing of a turnip bolus (chomps per second).

The key to the abbreviations and notations used in Tables 10 to 12 is as follows:

np = no awareness of a preferred chewing side
r = right side
l = left side
N = Natural chewing [mean of $\geq$ 4 chewtests]
(%r) = percentage of chomps on the right side during N
RT = unilateral chewing, right
LT = unilateral chewing, left
Dashed line separates females [above], from males [below].

The means and standard deviations for the number of chomps used to chew the standard turnip bolus and the rate at which this was done were calculated for the three groups. These means were calculated from the averaged results of the

Table 10. Side Preference, Number of Chomps, and Chewing Rate for the Turnip Chewtests: Long Facial Type Subjects.

SUBJECT/ SESSION	CHEWING SIDE	NUMBER OF CHOMPS CHEWTEST			RATE (Chomps Second)		
		N (%r)	RT	LT	N	RT*	LT*
FH1	np	15 (74)	19	20	1.7	1.6	1.7
FH2		13 (49)	18	20	1.7	1.7	1.7
FK1	r	22 (62)	33	35	1.6	1.7	1.6
FK2		14 (74)	21	21	1.6	1.7	1.7
GAM1	np	27 (22)	40	39	1.8	1.9	2.1
GAM2		41 (30)	53	54	1.8	1.8	2.0
GJ1	l	14 (54)	12	16	2.0	1.8	2.0
GJ2		16 (24)	15	18	2.0	1.7	2.0
JA1	np	13 (57)	17	23	2.0	2.1	1.8
JA2		18 (64)	28	24	1.7	2.1	2.0
MD1	np	18 (72)	22	24	1.8	2.1	2.1
MD2		18 (79)	22	21	2.0	2.2	2.4
MI1	np	22 (67)	17	16	1.4	1.4	1.4
SD1	l	14 (43)	19	19	1.8	1.9	1.9
SD2		17 (19)	24	23	1.8	1.9	1.9
DB1	l	16 (24)	21	20	1.6	1.6	1.7
DB2		20 (17)	23	24	1.7	1.7	1.9
DT1	np	20 (59)	52	53	1.6	1.5	1.4
DT2		33 (44)	60	60	1.4	1.2	1.2
JM1	l	23 (24)	28	34	1.5	1.7	1.6
JW1	np	19 (0)	20	23	1.9	1.7	1.8
JW2		17 (64)	17	15	1.9	1.9	1.9
MM1	r	26 (52)	30	24	1.4	1.5	1.5
MM2		21 (49)	23	21	1.6	1.6	1.7
RM1	r	19 (68)	19	22	1.4	1.4	1.4
RM2		19 (70)	21	26	1.5	1.4	1.4
OVERALL MEANS ± s.d.		20 ±5	26 ±12	26 ±11	1.7 ±0.2	1.7 ±0.2	1.7 ±0.3

See text for key to table (Chapter IV Section 4-1).
* [mean of ≥ 4 chewtests, except JA1: mean of 2 chewtests, and MI1: mean of 3 chewtests].

Table 11. Side Preference, Number of Chomps, and Chewing Rate for the Turnip Chewtests: Short Facial Type Subjects.

SUBJECT/ SESSION	CHEWING SIDE	NUMBER OF CHOMPS CHEWTEST			RATE (Chomps Second)		
		N (%r)	RT	LT	N	RT*	LT*
CG1	l	20 (55)	21	17	1.4	1.7	1.6
CG2		16 (45)	20	18	1.6	1.8	1.7
JH1	l	22 (54)	26	22	1.4	1.5	1.5
JH2		18 (75)	24	22	1.6	1.6	1.7
MG1	r	14 (75)	20	23	1.5	1.3	1.3
MG2		20 (76)	24	25	1.2	1.1	1.1
RW1	np	16 (89)	22	24	1.6	1.5	1.6
RW2		18 (82)	23	23	1.7	1.7	1.7
ST1	r	22 (50)	31	27	1.6	1.8	1.8
ST2		22 (36)	31	29	2.0	2.0	2.0
CH1	np	24 (71)	35	40	1.4	1.5	1.5
CH2		38 (42)	36	49	1.6	1.5	1.6
CH3		25 (34)	26	32	1.9	2.0	1.9
DO1	np	12 (26)	17	16	1.6	1.5	1.5
DO2		15 (36)	18	18	1.5	1.6	1.6
KL1	r	9 (100)	11	10	1.5	1.5	1.4
KL2		11 (93)	12	11	1.6	1.6	1.6
ML1	np	34 (94)	35	41	1.8	1.7	1.9
ML2		51 (70)	52	60	1.6	1.8	1.9
MP1	l	24 (0)	19	17	1.8	1.7	1.6
MP2		22 (22)	18	16	2.0	1.9	1.9
RC1	r	13 (65)	16	15	1.4	1.4	1.3
RC2		13 (20)	-	-	1.3	-	-
TG1	r	26 (100)	21	24	1.8	1.8	1.8
TG2		12 (81)	18	17	2.0	2.0	2.0
TS1	np	48 (71)	36	54	1.8	1.9	1.9
TS2		57 (41)	45	68	1.8	1.8	1.9
OVERALL MEANS ± s.d.		21 ±10	25 ±10	26 ±15	1.6 ±0.2	1.7 ±0.2	1.6 ±0.2

See text for key to table (Chapter IV Section 4-1).
* [mean of ≥ 3 chewtests, except RC2: RT, LT not done].

Table 12. Side Preference, Number of Chomps, and Chewing Rate for the Turnip Chewtests: Normal Facial Type Subjects.

SUBJECT/ SESSION	CHEWING SIDE	NUMBER OF CHOMPS CHEWTEST				RATE (Chomps/Second)		
		N	(%r)	RT	LT	N	RT*	LT*
AM1	l	22	(49)	25	25	1.4	1.6	1.6
AM2		21	(42)	28	23	1.6	1.6	1.7
KN1	l	30	(12)	62	42	1.7	1.9	1.7
KN2		28	(0)	55	39	1.8	2.0	1.8
NH1	r	16	(16)	16	14	1.5	1.5	1.4
NH2		17	(54)	17	17	1.6	1.5	1.5
SK1	r	15	(72)	16	19	1.4	1.2	1.3
SK2		15	(66)	16	18	1.7	1.6	1.5
TAI1	np	18	(54)	22	24	1.4	1.6	1.5
TAI2		25	(39)	27	24	1.8	1.5	1.4
TM1	np	18	(75)	22	26	1.3	1.4	1.4
TM2		22	(65)	26	30	1.4	1.5	1.5
OVERALL MEANS		21		27	24	1.6	1.6	1.5
± s.d.		±5		±16	± 8	±0.1	±0.2	±0.2

See text for key to table (Chapter IV Section 4-1).
* [mean of ≥ 5 chewtests, except NH1: mean of 4 chewtests].

recording sessions for each subject. A comparison of the means showed no significant difference in the number of chomps used or the chewing rate between natural, unilateral right, and unilateral left chewing within the groups, or between the groups for any of these parameters.

4-2 Chewing Rates for Gum Chewing Tasks

For the gum chewing tasks, chewing rate analyses were carried out on the data from the first ten consecutive chews in a given sequence. Chewing rates (chomps per second) during the unprepared gum and prepared gum tests, for the three subject groups, are presented in Tables 13 to 15. The means and standard deviations for these results are also presented. The rate of initial unprepared gum chewing on the left was significantly faster in the LF group as compared to the NF group, otherwise, a comparison between the groups revealed no significant differences.

The key to Tables 13 to 15 is as follows:

RUG = unilateral chewing, unprepared gum, right
LUG = unilateral chewing, unprepared gum, left
rPG = natural chewing, prepared gum, beginning on the right
lPG = natural chewing, prepared gum, beginning on the left
Dashed line separates females [above], from males [below].

Table 13. Rates for the First Ten Consecutive Chews in Unprepared Gum [UG] and Prepared Gum [PG] Chewing Tests: Long Facial Type Subjects.

SUBJECTS/SESSION	CHEWING RATES (Chomps per second)			
	RUG	LUG	rPG	lPG
FH1	1.1	1.3	1.2	1.3
FH2	1.5	1.4	1.8	1.5
FK1	1.0	1.1	1.5	1.4
FK2	1.3	1.2	1.4	1.7
GAM1	1.4	1.6	1.8	1.8
GAM2	1.5	1.6	2.0	2.2
GJ1	1.1	1.6	1.6	1.8
GJ2	1.0	1.3	1.6	1.4
JA1	1.5	1.6	1.6	1.3
JA2	1.9	1.8	2.0	2.0
MD1	1.1	1.6	1.8	2.0
MD2	1.5	1.7	1.8	1.4
MI1	1.3	1.0	-	1.3
SD1	1.2	1.3	1.4	1.6
SD2	1.4	1.4	1.4	1.7
DB1	1.4	1.5	1.4	1.5
DB2	1.4	1.5	1.6	1.6
DT1	1.1	1.2	1.5	1.4
DT2	1.1	1.2	1.3	1.2
JM1	1.1	1.0	1.5	1.4
JW1	0.9	1.4	1.5	1.7
JW2	1.4	1.5	1.8	1.6
MM1	1.0	1.3	1.2	1.1
MM2	1.2	1.3	1.4	1.1
RM1	1.0	1.0	1.2	1.1
RM2	1.2	1.3	1.4	1.2
OVERALL MEANS ± s.d.	1.3 ± 0.2	1.4* ± 0.2	1.5 ± 0.2	1.5 ± 0.2

See text for key to table (Chapter IV Section 4-2).

* Significantly different from NF group, LUG.

Table 14. Rates for the First Ten Consecutive Chews in Unprepared Gum [UG] and Prepared Gum [PG] Chewing Tests: Short Facial Type Subjects.

SUBJECTS/SESSION	CHEWING RATES (Chomps per second)			
	RUG	LUG	rPG	lPG
CG1	1.1	1.2	1.2	1.2
CG2	1.0	1.2	1.4	1.4
JH1	1.4	1.4	1.4	1.5
JH2	1.6	1.7	1.8	1.7
MG1	1.2	1.1	1.5	1.4
MG2	1.1	1.2	1.4	1.4
RW1	1.2	1.3	1.4	1.3
RW2	1.5	1.4	1.4	1.4
ST1	1.1	1.2	1.4	1.3
ST2	1.6	1.6	1.6	1.7
CH1	1.2	1.1	1.5	1.5
CH2	1.2	1.3	1.5	1.7
CH3	1.5	1.6	1.8	2.0
DO1	1.2	1.7	1.2	1.2
DO2	1.2	1.3	1.5	1.3
KL1	1.2	1.2	1.3	1.3
KL2	1.3	1.2	1.2	1.7
ML1	1.0	1.4	1.5	1.5
ML2	1.4	1.1	1.8	1.5
MP1	1.2	1.1	1.6	1.7
MP2	1.5	1.3	1.8	1.9
RC1	1.0	1.0	1.0	1.0
RC2	1.1	0.8	1.1	1.0
TG1	1.2	1.2	1.4	1.4
TG2	1.7	1.6	1.7	1.6
TS1	1.5	1.4	1.6	1.6
TS2	1.5	1.6	1.8	1.7
OVERALL MEANS	1.3	1.3	1.5	1.5
± s.d.	± 0.2	± 0.2	± 0.2	± 0.2

See text for key to table (Chapter IV Section 4-2).

Table 15. Rates for the First Ten Consecutive Chews in Unprepared Gum [UG] and Prepared Gum [PG] Chewing Tests: Normal Facial Type Subjects.

SUBJECTS/SESSION	CHEWING RATES (Chomps per second)			
	RUG	LUG	rPG	lPG
AM1 AM2	0.9 1.3	1.0 1.4	1.2 1.3	1.3 1.7
KN1 KN2	1.2 1.6	1.1 1.6	1.7 1.6	1.7 1.8
NH1 NH2	0.9 0.9	1.1 0.6	1.3 1.1	1.3 1.2
SK1 SK1	1.0 1.3	1.0 1.3	1.3 1.6	1.2 1.5
TAI1 TAI2	1.4 1.3	1.2 1.3	1.4 1.4	1.2 1.5
TM1 TM2	0.8 1.2	0.9 1.2	1.2 1.4	1.2 1.4
OVERALL MEANS ± s.d.	1.2 ± 0.2	1.1* ± 0.2	1.4 ± 0.2	1.4 ± 0.2

See text for key to table (Chapter IV Section 4-2).

* Significantly different from LF group, LUG.

5 Single Chomp Results

5-1 Muscle Activity

The ISE results from the four jaw elevating muscles, for the initial chomp in each turnip chewtest and gum chewing task, were normalized and calibrated, and summed in the manner described in Chapter III Section 3. The results were expressed in Newton-equivalents of bite force [N-eq BF]. These were then summed to obtain a value that represented the total EMG activity for the four main jaw elevator muscles during an initial chomp. The results from the turnip chomps represent a mean of 3 trials per session. Tables 16 to 18 contain the total EMG activities associated with single chomps on boluses of turnip and gum, for the LF, SF, and NF groups, respectively.

The means and standard deviations for the group results are also presented in Tables 16 to 18. Where data from more than one recording session were available for an individual, an average value was used in the calculation of the group mean. The mean EMG activity associated with an initial chomp tended to be higher in the SF group in general. Significant differences associated with the total EMG activity for an initial chomp [bolus-side] were found between:

- LF and SF groups for unprepared gum-right, prepared gum-right and -left, and turnip-left
- SF and NF groups for turnip-right.

The key to Tables 16 to 18 is as follows:

T = standard turnip bolus
UG = unprepared gum bolus
PG = prepared gum bolus
Dashed line separates females [above], from males [below].

Table 16. Normalized and Calibrated Total EMG Activity for *in vivo* Initial Chomps on the Test Boluses: Long Facial Type Subjects.

SUBJECTS/ SESSION	MEAN TOTAL EMG ACTIVITY FOR INITIAL CHOMPS [N-eq BF x 10^2]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
FH1 FH2	8.5 3.0	17 3.5	31 4.7	3.4 5.0	7.4 5.2	7.3 5.5
FK1 FK2	3.9 8.3	6.4 14	2.3 5.8	9.9 11	19 21	6.4 10
GAM1 GAM2	3.1 5.6	3.1 9.5	1.3 2.5	6.0 5.0	15 13	2.8 5.0
GJ1 GJ2	16 21	9.2 30	3.3 8.4	37 34	31 37	8.9 9.9
JA1 JA2	76 25	75 53	15 13	27 28	46 29	8.8 7.2
MD1 MD2	37 55	33 120	20 11	51 52	84 100	69 13
MI1	19	14	33	7.1	9.8	9.0
SD1 SD2	22 21	28 25	17 3.7	21 13	26 25	5.2 7.1
DB1 DB2	6.4 7.1	20 23	7.4 15	2.5 5.3	9.5 19	2.9 13
DT1 DT2	0.2 1.7	0.6 3.9	0.2 3.0	1.6 1.1	3.6 2.6	1.0 1.0
JM1	7.0	12	9.7	3.2	5.0	2.2
JW1 JW2	53 56	19 20	60 20	34 90	71 88	12 48
MM1 MM2	35 62	77 120	42 79	28 4.6	73 15	23 7.7
RM1 RM2	14 11	22 15	9.6 4.1	8.9 6.4	9.8 9.3	4.8 3.4
OVERALL MEAN ± s.d.	22 ±20	28* ±29	16** ±17	18† ±19	28 ±28	11 ‡ ±11

See text for key to table (Chapter IV Section 5-1).
Significantly different from SF group:
* UG-Right side, ** PG-Right side, † T-Left side,
‡ PG-Left side.

Table 17. Normalized and Calibrated Total EMG Activity for *in vivo* Initial Chomps on the Test Boluses: Short Facial Type Subjects.

SUBJECTS/ SESSION	MEAN TOTAL EMG ACTIVITY FOR INITIAL CHOMPS [N-eq BF x 10^2]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
CG1	11	18	3.6	5.3	21	8.5
CG2	8.7	13	9.6	10	18	13
JH1	70	71	90	51	20	48
JH2	77	99	130	67	64	71
MG1	7.4	13	3.9	3.5	6.0	4.3
MG2	4.7	17	4.3	-	-	-
RW1	8.7	30	1.7	13	28	3.3
RW2	18	49	5.7	27	30	11
ST1	56	51	43	74	61	40
ST2	55	69	31	120	120	53
CH1	34	99	36	73	140	190
CH2	29	78	53	13	26	34
CH3	72	140	140	5.4	16	16
DO1	26	130	32	60	270	130
DO2	61	160	66	27	61	35
KL1	42	110	86	3.3	7.6	4.1
KL2	38	18	17	11	4.8	2.2
ML1	26	19	14	33	38	4.6
ML2	32	34	5.9	16	17	5.6
MP1	64	73	120	21	22	15
MP2	32	72	55	52	69	97
RC1	23	33	21	51	59	22
RC2	-	44	7.1	-	13	10
TG1	8.9	21	4.3	-	-	-
TG2	19	30	12	32	48	41
TS1	89	80	72	-	-	-
TS2	48	54	69	50	130	37
OVERALL MEAN ± s.d.	36# ±22	58* ±38	41** ±36	36† ±26	54 ±48	34‡ ±29

See text for key to table (Chapter IV Section 5-1).
Significantly different from NF group: # T-Right side.
Significantly different from LF group: * UG-Right side,
** PG-Right side, † T-Left side, ‡ PG-Left side.

Table 18. Normalized and Calibrated Total EMG Activity for *in vivo* Initial Chomps on the Test Boluses: Normal Facial Type Subjects.

SUBJECTS/ SESSION	MEAN TOTAL EMG ACTIVITY FOR INITIAL CHOMPS [N-eq BF x 10^2]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
AM1	1.8	2.8	1.4	13	28	2.9
AM2	1.9	3.5	0.5	6.1	18	0.9
KN1	29	22	30	7.0	6.1	2.2
KN2	25	26	15	14	19	7.9
NH1	30	61	53	100	110	85
NH2	16	26	12	140	250	250
SK1	6.4	9.8	1.6	10	11	4.4
SK2	13	19	3.7	14	11	4.0
TAI1	20	32	9.5	26	38	13
TAI2	14	18	7.3	20	35	15
TM1	10	36	25	11	27	37
TM2	20	57	9.2	9.2	26	13
OVERALL MEAN ± s.d.	16# ± 9	26 ±17	14 ±12	31 ±44	48 ±65	36 ±65

See text for key to table (Chapter IV Section 5-1).
Significantly different from SF group: # T-Right side.

5-2 Work Done

Tables 19 to 21 summarize the results of the *in vitro* test chomps described in Chapter III Section 2-2, for the three facial type groups. Standard sized boluses of turnip, unprepared gum, and prepared gum were used. The work done in a single chomp between the first molars was expressed in Newton-meter [N-m] units. The turnip bolus tests were repeated a number of times with a fresh, intact bolus each time, to get a mean value for a given side of biting, subject, and session.

The overall mean work done and standard deviations for the groups in terms of type of bolus and side of biting are also presented in Tables 19 to 21. These means were calculated using averaged values for each subject for a given bolus and side of biting. No significant differences were found between the mean work done for right side biting as compared to left side biting for the same bolus within a group. Between the groups, the only statistically significant difference found was for the mean work done in an initial chomp on the unprepared gum bolus, which was less in the LF group than in the NF group for both sides of biting.

The key to Tables 19 to 21 is as follows:

T = *in vitro* chomp on a standard turnip bolus
[mean $\geq$ 5 trials]
UP = *in vitro* chomp on an unprepared gum bolus
PG = *in vitro* chomp on a prepared gum bolus
Dashed line separates females [above], from males [below].

Table 19. Mechanical Work Done Measurements for Single, *in vitro* Chomps on the Test Boluses: Long Facial Type Subjects.

SUBJECTS/ SESSION	WORK DONE IN A SINGLE CHOMP [N-m x 10^{-2}]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
FH1	63	38	5	64	44	8
FH2	68	38	2	59	40	3
FK1	79	62	8	68	57	5
FK2	68	62	4	55	61	7
GAM1	61	35	1	58	49	2
GAM2	50	49	2	52	51	3
GJ1	68	59	10	88	53	7
GJ2	69	54	6	80	52	5
JA1	71	52	5	80	52	5
JA2	58	54	3	58	48	5
MD1	72	46	14	64	34	7
MD2	65	44	6	58	39	3
MI1	47	48	5	70	27	6
SD1	65	38	4	42	59	3
SD2	69	42	3	43	42	4
DB1	58	52	3	60	48	4
DB2	61	40	3	79	50	4
DT1	39	34	6	46	39	7
DT2	47	24	4	31	23	4
JM1	54	28	4	47	22	4
JW1	36	36	4	35	40	6
JW2	51	35	5	34	36	5
MM1	42	60	3	45	56	6
MM2	48	44	3	50	46	6
RM1	58	34	4	51	19	5
RM2	63	36	5	51	23	3
OVERALL MEAN ± s.d.	58 ± 10	44* ± 10	5 ± 2	57 ± 14	41** ± 12	5 ± 1

See text for key to table (Chapter IV Section 5-2)

* Significantly different from NF group, UG-Right side

** Significantly different from NF group, UG-Left side.

Table 20. Mechanical Work Done Measurements for Single, *in vitro* Chomps on the Test Boluses: Short Facial Type Subjects.

SUBJECTS/ SESSION	WORK DONE IN A SINGLE CHOMP [N-m x 10^{-2}]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
CG1	48	41	5	46	42	5
CG2	43	35	7	44	34	6
JH1	53	50	4	61	48	4
JH2	52	45	4	58	42	3
MG1	69	34	5	69	37	8
MG2	59	49	4	65	54	6
RW1	43	41	4	45	42	4
RW2	35	43	4	43	35	2
ST1	66	48	5	68	51	8
ST2	65	55	5	64	47	10
CH1	60	36	8	58	40	10
CH2	45	-	-	61	34	6
CH3	55	65	9	53	67	6
DO1	48	64	6	48	67	6
DO2	45	52	3	43	49	6
KL1	49	50	6	55	32	8
KL2	42	43	3	48	43	3
ML1	63	40	4	68	35	1
ML2	84	49	3	93	50	3
MP1	76	70	6	55	60	8
MP2	61	50	6	53	47	4
RC1	58	46	3	67	56	4
RC2	63	58	1	46	54	10
TG1	60	48	8	60	44	12
TG2	80	52	2	95	71	8
TS1	59	34	3	72	50	4
TS2	60	45	5	56	53	5
OVERALL MEAN ± s.d.	57 ± 11	48 ± 7	5 ± 1	59 ± 12	48 ± 7	6 ± 2

See text for key to table (Chapter IV Section 5-2)

Table 21. Mechanical Work Done Measurements for Single, *in vitro* Chomps on the Test Boluses: Normal Facial Type Subjects.

SUBJECTS/ SESSION	WORK DONE IN A SINGLE CHOMP [N-m x 10^{-2}] Right side T	UG	PG	Left side T	UG	PG
AM1 AM2	50 51	44 60	5 3	45 54	40 42	5 4
KN1 KN2	46 37	41 25	5 3	54 44	72 30	6 3
NH1 NH2	50 78	43 71	6 5	70 81	65 51	5 5
SK1 SK2	82 56	54 65	4 5	79 64	60 62	4 5
TAI1 TAI2	73 80	48 63	5 7	70 78	42 57	2 4
TM1 TM2	76 70	42 76	5 5	62 62	51 51	4 6
OVERALL MEAN ± s.d.	62 ± 14	53* ± 10	5 ± 1	65 ± 12	54** ± 8	4 ± 1

See text for key to table (Chapter IV Section 5-2)

* Significantly different from LF group, UG-Right side

** Significantly different from LF group, UG-Left side.

5-3 Efficiency

The efficiency calculations for the initial chomps on the three test boluses are presented in Tables 22 to 24 according to facial type groups. These data were calculated from the averaged results of two sessions for each subject (where possible). For these calculations, the work done [N-m] is divided by the product of the EMG activity [N-eq BF] and the distance travelled through the bolus in the first chomp [10 mm], and the results are expressed as a percentage.

The mean efficiencies and standard deviations for the groups are also presented in Tables 22 to 24. No significant differences were found within the groups for right side biting compared to left side biting for the same bolus. The mean results from the groups were compared. No significant differences were found except for the case of right side biting on the unprepared gum bolus, where, for the LF group the mean was lower than for the SF group.

Table 22. Efficiency Calculations for Initial Chomps on the Test Boluses: Long Facial Type Subjects.

SUBJECTS/ SESSION	EFFICIENCY OF INITIAL CHOMP [percent]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
FH	11.4	4.0	0.2	14.6	6.7	0.8
FK	12.0	6.1	1.5	5.9	3.0	0.4
GAM	6.4	6.7	0.8	10.0	3.6	0.6
GJ	3.7	2.9	1.4	2.4	1.5	0.6
JA	1.3	0.8	0.3	2.5	1.3	0.6
MD	1.5	0.6	0.6	1.2	0.4	0.1
MI	2.5	3.4	0.2	9.8	2.8	0.7
SD	3.1	1.5	0.3	2.5	2.0	0.6
DB	8.8	2.1	0.3	17.8	3.4	0.5
DT	45.3	13.0	3.1	14.2	10.0	5.5
JM	7.7	2.3	0.4	14.7	4.4	1.8
JW	0.8	1.8	0.1	0.6	0.5	0.2
MM	0.9	0.5	0.05	2.9	1.2	0.4
RM	4.8	1.9	0.6	6.7	2.2	1.0
OVERALL MEAN ± s.d.	7.9 ± 11.0	3.4* ± 3.3	0.7 ± 0.8	7.6 ± 5.9	3.1 ± 2.6	1.0 ± 1.4

Key: T = standard turnip bolus
UP = unprepared gum bolus
PG = prepared gum bolus
Dashed line separates females [above], from males [below].

* Significantly different from SF group, UG-Right side.

Table 23. Efficiency Calculations for Initial Chomps on the Test Boluses: Short Facial Type Subjects.

SUBJECTS/ SESSION	EFFICIENCY OF INITIAL CHOMP [percent] Right side T	UG	PG	Left side T	UG	PG
CG	4.6	2.4	0.9	5.9	1.9	0.5
JH	0.7	0.6	0.04	1.0	1.1	0.06
MG	10.6	2.8	1.1	19.1	7.6	1.6
RW	2.9	1.1	1.1	2.2	1.3	0.4
ST	1.2	0.8	0.1	0.7	0.5	0.2
CH	1.2	0.5	0.1	1.9	0.8	0.1
DO	1.1	0.4	0.1	1.0	0.4	0.1
KL	1.1	0.8	0.1	7.2	6.0	1.7
ML	2.5	1.7	0.4	3.3	1.5	0.4
MP	1.4	0.8	0.1	1.5	1.2	0.1
RC	2.6	1.4	0.1	1.1	1.5	0.4
TG	5.0	2.0	0.6	2.4	1.2	0.2
TS	0.9	0.6	0.1	1.3	0.4	0.1
OVERALL MEAN ± s.d.	2.8 ± 2.7	1.2* ± 0.8	0.4 ± 0.4	3.7 ± 5.0	2.0 ± 2.2	0.4 ± 0.6

Key: T = standard turnip bolus
UP = unprepared gum bolus
PG = prepared gum bolus
Dashed line separates females [above], from males [below].

* Significantly different from LF group, UG-Right side.

Table 24. Efficiency Calculations for Initial Chomps on the Test Boluses: Normal Facial Type Subjects.

SUBJECTS/ SESSION	EFFICIENCY OF INITIAL CHOMP [percent]					
	Right side			Left side		
	T	UG	PG	T	UG	PG
AM	27.3	16.5	4.2	5.2	1.8	3.2
KN	1.5	1.4	0.2	4.7	2.0	0.9
NH	2.8	1.3	0.2	0.6	0.3	0.03
SK	7.1	4.1	1.7	6.0	5.5	1.1
TAI	4.5	2.2	0.7	3.2	1.4	0.2
TM	4.9	1.3	0.3	6.8	2.2	0.2
OVERALL MEAN ± s.d.	8.0 ± 9.6	4.5 ± 6.0	1.2 ± 1.6	4.4 ± 2.2	2.2 ± 1.8	0.9 ± 1.2

Key: T = standard turnip bolus
UP = unprepared gum bolus
PG = prepared gum bolus
Dashed line separates females [above], from males [below].

6 Gum Chewing Task Results

6-1 Muscle Activity for Prepared Gum Chewing

The ISE results from the right and left masseter and anterior temporalis muscles, for the first 10 consecutive chews in a given prepared gum chewing test, were normalized and calibrated in the manner described in Chapter III Section 3, and expressed in N-eq BF. These were then summed to obtain a value that represented the total EMG activity for the four main jaw elevating muscles during the 10 specified chews on a prepared gum bolus. There were two trials of natural chewing for each session, one beginning on the right, and one beginning on the left. The results are presented in Tables 25 to 27, which follow. The percentage of right chomps in each trial are indicated in parentheses.

The overall mean muscle activities and standard deviations were calculated for the three facial type groups from averaged individual results for a given task. These means and standard deviations are also presented in Tables 25 to 27. A statistical comparison of the means did not demonstrate any significant differences between the results from the three groups.

The key to Tables 25 to 27 is as follows:

rPG = natural chewing, prepared gum, beginning on the right
lPG = natural chewing, prepared gum, beginning on the left
(%r) = percentage of chomps on the right side
Dashed line separates females [above], from males [below].

Table 25. Normalized and Calibrated Total EMG Activity for the First Ten Consecutive Chews in Prepared Gum Chewing Tasks: Long Facial Type Subjects.

SUBJECTS/SESSION	TOTAL EMG ACTIVITY FOR THE FIRST 10 CHEWS [N-eq BF x 10^2] rPG	(%r)	lPG	(%r)
FH1	6.1	(30)	4.2	(70)
FH2	2.0	(100)	2.4	(60)
FK1	2.3	(90)	4.9	(0)
FK2	2.6	(100)	3.5	(0)
GAM1	1.8	(100)	1.9	(0)
GAM2	3.8	(40)	3.6	(40)
GJ1	2.6	(100)	7.5	(0)
GJ2	6.3	(100)	7.4	(0)
JA1	14	(40)	4.3	(0)
JA2	9.7	(100)	8.2	(0)
MD1	22	(30)	25	(30)
MD2	14	(100)	22	(40)
MI1	-		1.4	(100)
SD1	6.6	(40)	6.2	(0)
SD2	4.7	(100)	5.2	(0)
DB1	3.5	(50)	2.5	(0)
DB2	12	(100)	7.1	(0)
DT1	0.7	(70)	0.7	(50)
DT2	1.2	(100)	0.9	(0)
JM1	3.5	(100)	2.4	(70)
JW1	34	(100)	29	(0)
JW2	44	(80)	45	(0)
MM1	29	(90)	33	(70)
MM2	75	(100)	4.0	(0)
RM1	4.3	(100)	3.0	(0)
RM2	3.0	(100)	1.9	(0)
OVERALL MEAN ± s.d.	12 ± 16		9 ± 10	

See text for key to table (Chapter IV Section 6-1)

Table 26. Normalized and Calibrated Total EMG Activity for the First Ten Consecutive Chews in Prepared Gum Chewing Tasks: Short Facial Type Subjects.

SUBJECTS/SESSION	TOTAL EMG ACTIVITY FOR THE FIRST 10 CHEWS [N-eq BF x 10^2]			
	rPG	(%r)	lPG	(%r)
CG1	3.6	(70)	4.3	(0)
CG2	6.4	(70)	9.7	(0)
JH1	64	(100)	33	(0)
JH2	72	(100)	51	(0)
MG1	4.3	(90)	3.0	(0)
MG2	6.4	(100)	-	
RW1	2.6	(100)	2.1	(80)
RW2	5.0	(100)	9.7	(0)
ST1	3.9	(40)	10	(90)
ST2	5.7	(30)	9.3	(0)
CH1	31	(100)	61	(0)
CH2	29	(100)	20	(0)
CH3	61	(100)	7.4	(0)
DO1	17	(100)	35	(0)
DO2	17	(100)	10	(0)
KL1	32	(70)	2.0	(0)
KL2	8.0	(100)	2.9	(0)
ML1	18	(80)	8.8	(60)
ML2	21	(100)	16	(20)
MP1	77	(100)	17	(0)
MP2	12	(80)	41	(0)
RC1	10	(100)	13	(0)
RC2	14	(100)	7.9	(0)
TG1	1.7	(100)	-	
TG2	2.6	(100)	12	(0)
TS1	23	(100)	-	
TS2	26	(100)	23	(50)
OVERALL MEAN ± s.d.	20 ± 20		16 ± 12	

See text for key to table (Chapter IV Section 6-1)

Table 27. Normalized and Calibrated Total EMG Activity for the First Ten Consecutive Chews in Prepared Gum Chewing Tasks: Normal Facial Type Subjects.

SUBJECTS/SESSION	TOTAL EMG ACTIVITY FOR THE FIRST 10 CHEWS [N-eq BF x 10^2]			
	rPG	(%r)	lPG	(%r)
AM1	1.0	(100)	8.0	(0)
AM2	4.4	(50)	6.5	(0)
KN1	16	(100)	4.4	(0)
KN2	14	(60)	8.1	(0)
NH1	30	(100)	70	(20)
NH2	11	(100)	140	(0)
SK1	1.6	(100)	2.9	(50)
SK2	3.8	(100)	3.7	(0)
TAI1	17	(100)	17	(0)
TAI2	9.7	(100)	24	(0)
TM1	9.7	(100)	14	(0)
TM2	9.6	(100)	8.2	(50)
OVERALL MEAN ± s.d.	11 ± 7		26 ± 39	

See text for key to table (Chapter IV Section 6-1)

6-2 Estimated Efficiency of Prepared Gum Chewing

The efficiency of the first ten consecutive chews on prepared gum has been estimated for the sample groups. The estimated efficiency is derived from the comparison of the estimated work done in ten chews (work done *in vitro* in the initial chomp x 10) versus the product of the normalized and calibrated EMG data from the *in vivo* chews on prepared gum and the estimated distance travelled through the bolus in ten chews (approximately 8 mm x 10). Such an estimate is valid, since the bolus is of a consistent nature, and the work done relative to the distance travelled through the bolus should be a constant for a given subject and session. The sidedness of the chomps for each ten chew sequence has been taken into account in each calculation. The average of four trials (where possible) of natural chewing, starting on the right and starting on the left, from two sessions, are presented in Table 28. These results are expressed as percentages.

The means and standard deviations for the efficiencies measured for the three facial type groups are also presented in Table 28. No significant differences were found between the group means.

Table 28. Estimated Efficiencies for the First Ten Consecutive Chews in Prepared Gum Chewing Tasks.

ESTIMATED EFFICIENCIES FOR THE FIRST TEN CHEWS ON THE PREPARED GUM BOLUS [%] FOR:					
LF Subjects:		SF Subjects:		NF Subjects:	
FH	1.7	CG	1.3	AM	2.2
FK	2.5	JH	0.1	KN	0.7
GAM	0.9	MG	1.9	NH	0.2
GJ	2.0	RW	1.4	SK	2.0
JA	0.8	ST	1.5	TAI	0.4
MD	0.4	CH	0.4	TM	0.6
MI	5.4	DO	0.4		
SD	0.7	KL	1.7		
DB	1.1	ML	0.2		
DT	8.2	MP	0.4		
JM	1.8	RC	0.6		
JW	0.1	TG	2.6		
MM	0.5	TS	0.2		
RM	1.8				

OVERALL MEANS ± s.d. FOR:		
LF Subjects:	SF Subjects:	NF Subjects:
2.0 ± 2.2	1.0 ± 0.8	1.0 ± 0.9

6-3 Muscle Activity Associated with Preparing a Gum Bolus

Work is required to change an unprepared gum bolus to the prepared state. The work done in an initial chomp on unprepared gum and on prepared gum has been presented in Section 5-2 of this chapter. Presumably, the resistance of the unprepared gum decreases with consecutive chomps, until it reaches a relatively consistent stage, termed "prepared," in this investigation.

The total ISE activity from the right and left masseter and anterior temporalis muscles, associated with each chomp in a consecutive series of chomps, starting with an unprepared gum bolus, are plotted for unilateral gum chewing tasks in two subjects in Figures 9 and 10. The total ISE per chomp for the first 15 chomps are plotted, as well as for 10 consecutive chomps more than 30 seconds after the start of the sequence. These later chomps are presented to exemplify the ISE associated with a relatively well-prepared gum bolus.

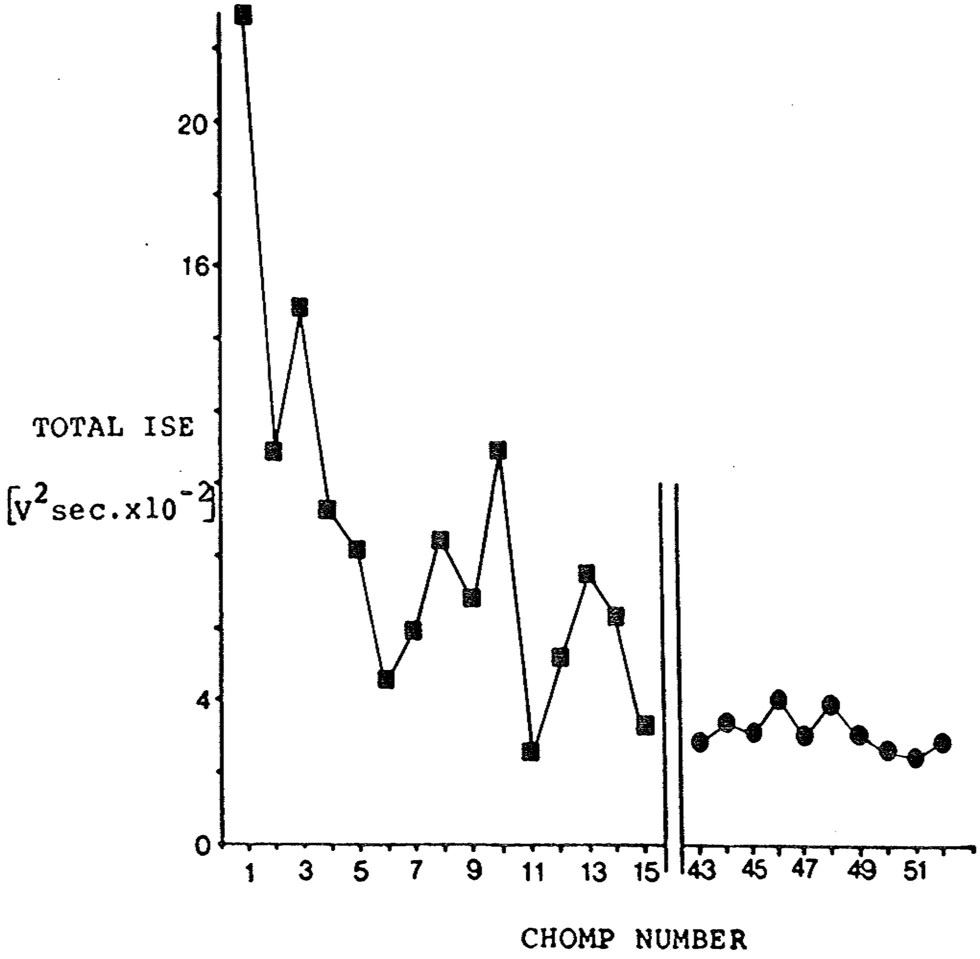

Figure 9. Unilateral Gum Chewing Task - Right, beginning with an unprepared gum bolus. The sequence is split: Chomps 1-15, starting at time = 0; and Chomps 43-52, after 30 seconds of chewing for Subject SD, Session 1).

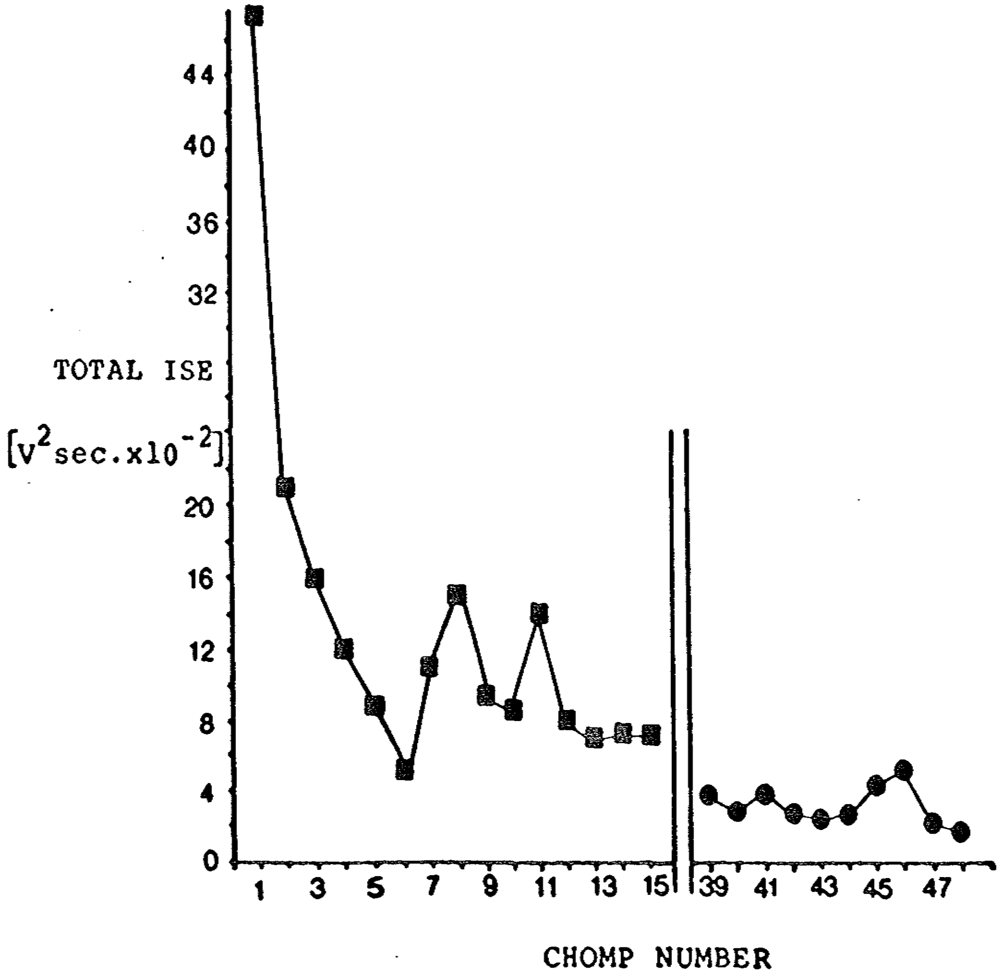

Figure 10. Unilateral Gum Chewing Task - Left, beginning with an unprepared gum bolus. The sequence is split: Chomps 1-15, starting at time = 0; and Chomps 39-48, after 30 seconds of chewing for Subject DO, Session 1).

7 Muscle Activity for the Turnip Chewtests

The ISE results for a given chewtest, from the right and left masseter and anterior temporalis muscles were normalized and calibrated in the manner described in Chapter III Section 3, and expressed in N-eq BF. These were then summed to obtain a value that represented the total EMG activity for the four main jaw elevating muscles during a chewing task. The results from repeated trials of the same nature, carried out at the same session, were meaned, and are presented in Tables 29 to 31.

Included in Tables 29 to 31 are the mean activities and standard deviations for the three facial type groups in terms of natural, unilateral right, and unilateral left turnip chewing. These means were calculated from averaged results for an individual. A comparison of natural, unilateral right, and unilateral left chewing results from within a group showed no significant differences. A comparison of the group means also showed no significant differences between the groups for these parameters.

Table 29. Normalized and Calibrated Total EMG Activity for the Turnip Chewtests: Long Facial Type Subjects.

SUBJECTS/SESSION	MEAN TOTAL EMG ACTIVITY FOR CHEWTESTS [N-eq BF x 10^2]			
	N	(%r)	RT	LT
FH1	12	(74)	9.3	3.9
FH2	5.9	(49)	2.4	4.3
FK1	7.2	(62)	2.6	6.9
FK2	13	(74)	6.6	9.6
GAM1	4.0	(22)	1.4	3.5
GAM2	5.8	(30)	2.8	4.3
GJ1	13	(54)	5.2	24
GJ2	17	(24)	12	21
JA1	33	(57)	47	18
JA2	19	(64)	17	17
MD1	27	(72)	28	31
MD2	55	(79)	44	36
MI1	6.6	(67)	10	4.4
SD1	12	(43)	13	11
SD2	18	(19)	14	10
DB1	3.4	(24)	9.3	2.4
DB2	6.0	(17)	9.8	4.7
DT1	1.8	(59)	0.2	1.9
DT2	0.9	(44)	0.7	0.8
JM1	3.4	(24)	5.4	2.4
JW1	44	(0)	58	36
JW2	78	(64)	46	88
MM1	22	(52)	31	23
MM2	40	(49)	69	8.8
RM1	8.3	(68)	8.0	4.1
RM2	3.2	(70)	4.2	4.1
OVERALL MEAN ± s.d.	17 ± 17		17 ± 18	14 ± 17

Key: N = Natural chewing [mean of ≥ 4 chewtests]
(%r) = percentage of chomps on the right side during N
RT = unilateral chewing, right*
LT = unilateral chewing, left*

Dashed line separates females [above], from males [below].

* [mean of ≥ 4 chewtests, except JA1: mean of 2 chewtests, and MI1: mean of 3 chewtests].

Table 30. Normalized and Calibrated Total EMG Activity for the Turnip Chewtests: Short Facial Type Subjects.

SUBJECTS/SESSION	MEAN TOTAL EMG ACTIVITY FOR CHEWTESTS [N-eq BF x 10^2]			
	N	(%r)	RT	LT
CG1	5.2	(55)	5.2	4.7
CG2	6.7	(45)	4.5	7.5
JH1	51	(54)	59	36
JH2	78	(75)	64	46
MG1	7.7	(75)	6.4	4.4
MG2	-		5.0	-
RW1	13	(89)	10	15
RW2	32	(82)	22	25
ST1	22	(50)	15	22
ST2	50	(36)	12	26
CH1	34	(71)	31	71
CH2	22	(42)	32	17
CH3	30	(34)	54	6.0
DO1	39	(26)	23	46
DO1	22	(36)	27	14
KL1	33	(100)	48	3.3
KL2	14	(93)	15	4.7
ML1	25	(94)	20	25
ML2	30	(70)	38	28
MP1	22	(0)	52	20
MP2	54	(22)	26	43
RC1	30	(65)	21	36
RC2	22	(20)	-	-
TG1	6.0	(100)	4.7	-
TG2	5.9	(81)	5.1	17
TS1	52	(71)	49	-
TS2	46	(41)	35	32
OVERALL MEAN ± s.d.	28 ± 17		26 ± 17	23 ± 12

Key: N = Natural chewing [mean of ≥ 4 chewtests]
(%r) = percentage of chomps on the right side during N
RT = unilateral chewing, right*
LT = unilateral chewing, left*
Dashed line separates females [above], from males [below].
* [mean of ≥ 3 chewtests, except RC2: not done].

Table 31. Normalized and Calibrated Total EMG Activity for the Turnip Chewtests: Normal Facial Type Subjects.

SUBJECTS/SESSION	MEAN TOTAL EMG ACTIVITY FOR CHEWTESTS [N-eq BF x 10^2]			
	N	(%r)	RT	LT
AM1	8.0	(49)	1.4	12
AM2	8.8	(42)	2.4	8.7
KN1	10	(12)	23	6.2
KN2	13	(0)	19	12
NH1	100	(16)	33	76
NH2	110	(54)	16	200
SK1	8.4	(72)	5.2	8.3
SK2	11	(66)	7.2	9.2
TAI1	18	(54)	20	23
TA12	16	(39)	12	19
TM1	21	(75)	21	15
TM2	24	(65)	28	12
OVERALL MEAN ± s.d.	29 ± 38		16 ± 9	32 ± 52

Key: N = Natural chewing [mean of $\geq$ 4 chewtests]
(%r) = percentage of chomps on the right side during N
RT = unilateral chewing, right*
LT = unilateral chewing, left*
Dashed line separates females [above], from males [below].
* [mean of $\geq$ 5 chewtests, except NH1: mean of 4 chewtests].

Chapter V Discussion

1 The Sample

1-1 Age

The age range of the sample overall and in the facial type groups was similar. Age-related changes to the pattern of mastication have been reported by others (Beyron, 1964; Karlsson and Carlsson, 1990), but in populations considerably more elderly than this sample.

1-2 Facial Type

The two extreme groups demonstrated a significant difference from one another and also from the group labelled "normal," for the facial type parameters.

According to the Manitoba Analysis, the normal mean and standard deviation for MPA measurements should have been 25.3 ± 4.7 degrees. The mean and standard deviation for the NF group in this investigation was 22.8 ± 2.3 degrees, which fell within the Manitoba norms. The mean MPA and standard deviation for the LF group and SF group were 35.0 ± 6.1 and 15.2 ± 4.4, respectively.

The ideal facial height proportions suggested by Proffit and co-workers (1980) and Legan and Burstone (1980), are associated with a G-Sn/Sn-Me' ratio of 1.0. An acceptable range of variation for this value was not given by these authors. Scheideman and associates (1980) have provided a range of variation valid for a group of "dentofacial normals," who were chosen for normal characteristics, including an anterior facial height ratio [G-Sn/Sn-Me'] within 15 percent of the ideal ratio. According to these authors, the mean and standard deviation within a group of 24 females (average age 24 years) who met the criteria for normal, was 1.02 ± 0.08, while for a group of 32 normal males (average age 25 years), it was 0.96 ± 0.07.

In general, standards for facial height proportions are expressed as a ratio, and tend to have a very narrow range of normal variation. For example, according to the Manitoba Analysis, anterior facial height proportions are assessed using the radiographic landmarks of Nasion [Na], anterior nasal spine [ANS], and bony Menton [Me], to indicate the superior, middle, and lower facial height landmarks, respectively. These are expressed as the percentage of the lower anterior facial height relative to the total anterior facial height [ANS-Me/Na-Me]. The mean and standard deviation for this measurement should be 56.57 ± 0.31 percent, according to Manitoba standards for normal.

The NF group in this study had a mean Sn-Me'/G-Sn ratio of 1.00 (the standard deviation for the group was almost negligible, ± 0.005), while the mean and standard deviation for the LF group and the SF group were 1.13 ± 0.04 and 0.82 ± 0.05, respectively.

The facial type parameters measured in the group called "normal" in this study, therefore, concurred with standards appropriate to the sample population. The LF and SF groups showed a significant difference from the norms, with respect to both facial type parameters to the 99 percent confidence level.

1-3 Occlusion

The entire sample showed some degree of occlusal malrelations although in a few cases (JA, JW), discrepancies from "ideal" as conventionally defined (Roth, 1981) were relatively minor. The majority of LF and SF subjects showed rather marked malocclusions. These extremely different facial type groups, on the whole, also demonstrated extremely different anterior tooth relationships, as would be predicted by classical descriptions of LF and SF. That is, seven of the 14 LF subjects displayed anterior open bites, while eight of the 13 SF subjects showed complete overbites that impinged on the palatal soft tissues.

A functional posterior occlusal assessment scheme was devised and applied to the sample. The cuspal inclines and the interdigitation of the posterior teeth were assessed by two independent examiners. Good agreement was demonstrated between and within these examiners, with respect to the conventional classification of the malocclusions, and the posterior occlusal rating scores.

On a scale of zero (flat cusps, poor interdigitation) to eight (sharp cusps, good interdigitation), a range of zero to seven was demonstrated by the sample. Although there was a wide variability within the groups, there was a general trend towards higher posterior functional occlusal ratings for the groups in the order LF, SF, and NF. The mean scores and standard deviations for these groups were: 2.8 ± 1.5, 3.8 ± 2.1, and 4.7 ± 1.0, respectively. The LF and NF ratings were shown to be significantly different at the 95 percent confidence level.

2 The Normalization and Calibration Technique

The plots of isometric bite force versus EMG data showed strong linear characteristics, demonstrated by high correlation coefficient values for the individual plots ($r^2 \geq 0.72$). Overall, there was good agreement between the slopes of the isometric force versus EMG plots obtained from session 1 and session 2 for a given subject.

There are a number of variables which affect the surface EMG recording, including electrode type and position, skin and soft tissue impedance, and the psychological state of the subject. These variables are well-described in the literature. Based on this, arguments advocating and criticizing surface EMG recording may be found. It is recognized that reliability and consistency are particularly important to the employment of surface EMG data as a quantitative measure. Through the application of careful, standardized techniques however, in terms of electrode type, position, and placement; the skin preparation; and the handling of the subject during the recording session, a reasonable degree of reliability and repeatability from the surface EMG recorded can be achieved. According to Garrett and co-workers (1964), the expected variation between subjects due to recording techniques and/or other unknown factors, is about 20 percent.

Any relative discrepancies between the slopes from session 1 and session 2, for a given muscle, due to variable electrode-contact characteristics, electrode placement, and/or muscle activation, are addressed by the normalization and calibration of the chewing test results relative to the standardized isometric biting results. As long as the EMG-isometric bite calibrations are accurate, and have a consistent relationship with the forces and muscle activities involved in chewing, this method should provide a means of making direct comparisons of EMG results from different recording sessions, and from different people. One would expect to find, therefore, consistencies in the expressed N-eq BF between sessions for most subjects compared with the range demonstrated by the sample overall.

Lindauer and associates (1991) recently reinforced the expectations for high intersubject variability in masticatory muscle function, and supported the use of EMG quantitatively as a reliable and sensitive method of assessing this. In particular, they emphasized the value of the EMG-isometric force parameter as a statically-determined representation of a dynamic event. Because this relationship is statically determined, the requirements for good control of the experimental conditions can be met by the use of careful methods of EMG and bite force recording.

In order to test the accuracy of the methods, the biting test described in Chapter III Section 3-3.2.3 was conducted. This was carried out in 20 sessions involving 12 different subjects from the sample. This served as a check for possible errors in measuring bite force magnitude via the BFT, and also for discrepancies in the relative muscle activations required to stabilize the bite on the BFT compared with that on the test boluses. If, for example, the biting tasks on the BFT required increased muscle tension for stabilization, or if the particular biting situation was unfamiliar to the subject, it might be expected that the muscle activities during the normalization and calibration bites would be higher than those used in a more natural chewing and biting situation. This would result in a relatively low expression of N-eq BF for the EMG results from that individual. For the subsample of individuals and experimental sessions checked, the tests confirmed the BFT methods as valid for measuring force and for representing the patterns of muscle activities during natural biting.

As mentioned, interindividual variability in masticatory muscle function has been acknowledged and emphasized by many authors (for a review, see Lindauer *et al.*, 1991). When EMG recording is used quantitatively, the additional variables inherent to EMG recording techniques must be addressed. By expressing the quantitative results relative to standard, predictable EMG-isometric force relationships, these problems are alleviated, and more valid comparisons can be made.

3 The Characteristics of Chewing

Approximately half of the sample expressed no preference with respect to chewing side. Of those that did express a preference, this sidedness was not consistently reflected in the results from natural chewing, where no chewing-side was stipulated. Most of the subjective reasons given for a side preference related to a specific awareness (past or present) associated with a particular tooth or teeth (for example, past sensitivity to temperature or sweets, large restorations, area of frequent food impaction).

For the turnip chewtests, the mean number of chomps per individual varied between 9 and 57 for natural chewing, with no particular facial type-specific trends. The intrasubject results were generally consistent, however there was a tendency in some subjects to use more chomps in the second session than the first, and in many subjects, to use more chomps in the unilateral chewing tasks than in the natural chewing tasks. This may have been due to an enhanced consciousness to the experimental situation.

The rate of chewing in the sample population also did not show strong facial type specificities, although a difference in unprepared gum chewing rates for the first ten chomps was noted between LF and NF groups for chewing on the left side only. The rates were generally consistent for an individual from session to session, but variable between people. A decrease in rate for the unprepared gum chewing task (first ten consecutive chews) compared with turnip and prepared gum, was the only other finding of note.

The large intersubject variability in the chewing characteristics demonstrated, is consistent with past reports described in the literature (Carlsson, 1974; Bates *et al.*, 1975a, 1975b, 1976).

4 The Single Chomp

4-1 Muscle Activity Input

The sum of normalized and calibrated EMG activities from the right and left masseter and temporalis muscles in carrying out a single chomp on a standard bolus, represented the muscle effort put into doing work on the bolus. In general, the results in Tables 16, 17, and 18 show a large range of variability within the sample. A tendency for higher EMG activity associated with the initial chomps in the SF group was also demonstrated. For some but not all of the biting situations measured (5 of the 18 comparisons made) the SF group showed significantly greater mean EMG activity for the same task than the LF group or the NF group. Relatively high masticatory muscle EMG activity is a SF characteristic that has been commonly reported in the literature (Ahlgren, 1966; Møller, 1966; Ringqvist, 1973; Ingervall and Thilander, 1974; Ingervall, 1976; Lowe and Takada, 1984).

The results from some subjects show inconsistencies between session 1 and session 2 for the same side and test bolus. There may be a number of reasons for these discrepancies. For instance, the results for the initial chomps on the turnip bolus represent a mean value from a number of trials (3 to 7), whereas those for initial chomps on both unprepared and prepared gum boluses represent single trials. A larger variation in the results between sessions, within a subject, would therefore be expected for the data from single chomps on gum.

Although single chomps on the turnip and unprepared gum appeared to be associated with more muscle activity than the prepared gum, this was not always so. Certainly, from the results of Chapter IV Section 5-2, the prepared gum bolus provided the least resistance to mechanical deformation. The nature of the turnip material itself made test chomps on it more variable. The turnip was a rather brittle bolus, and hence, it failed readily in shear. Sharp cusps, therefore, were more likely to have sliced through the turnip bolus, as opposed to flat cusps, which were more likely to have compressed the bolus. In either case, once the turnip cube was ruptured, it tended to split. How much further work was carried out on the turnip depended upon its position relative to the teeth. If the degree of interdigitation of the teeth was high, there would be an increased chance of the turnip being held to realize the full crushing effect of the chomp as the teeth came together.

Two very different outcomes for the turnip were therefore possible during a single chomp. In one case, the turnip would have simply been split into two or more parts, with the pieces sliding away from the occlusal table. This situation would have required relatively little muscle effort, since the teeth and the nature of the turnip would have accounted for most of the work done in splitting. On the other hand, if the turnip bolus or parts of it remained between the teeth to be more fully crushed, more muscle effort would have been required, particularly if the morphology of the teeth was very flat. Such potential differences in the handling of the turnip bolus may have been demonstrated in the EMG activities, but they were not reflected in a correlation between the muscle activity data and the posterior functional occlusal scores.

The gum boluses in contrast to the turnip, were very plastic, and in one form, relatively resistant to deformation (unprepared state), while in the other, easily deformable (prepared state). In the case of the gum boluses, the details of the dental morphology and occlusion were not expected to have large effects on the nature and amount of work done in the single chomps or in chewing.

One factor that appeared to influence the EMG activity measured from the muscles was the "attitude" of the bite. That is, single chomps executed in a very deliberate (and usually faster) manner showed higher general EMG activity than those executed in a more relaxed fashion. This effect was especially notable in the prepared gum chomps, and contributed to the variability shown in the intrasubject results in some cases. Although only a small amount of muscle effort was required to carry out a chomp on the prepared gum, it appeared that increased consciousness to the act and/or the psychological state of the subject had an influence on the level of muscle tension recorded. Instructions to the subject were therefore a factor, particularly in the case of the unprepared gum chomps.

Further to this, the psychological state of the subject and the physical state of the muscles are known to have an effect on the EMG activity. (Consider the use of EMG in biofeedback techniques; see Lund and Widmer (1989).) Other circumstances may have also influenced the results. Subject FH, for example, reported a period of nocturnal clenching and bruxing in the time prior to session 2. There was no frank pain upon presentation for the recording session, but the subject reported an increased awareness of the masticatory muscles on the right side. This may have increased the slope of the muscle activity versus isometric bite force relationship, especially on the right. If this higher muscle tension was not reflected during ordinary chewing tasks, this may account for the much lower N-eq BF results from the right sided tests for FH in session 2.

Similarly, the intersession differences shown by subject MM may be related to increased awareness, subconscious or otherwise, to the fracture of part of the upper right second bicuspid, which occurred in the period between session 1 and session 2. The tooth had been endodontically restored some time prior to the first recording session, so the tooth was not painful, and the subject did not report any "problems" associated with chewing on the right side.

Finally, subject DT demonstrated remarkably low normalized and calibrated EMG activities. One possible explanation to account for this may be related to the unusual dental and skeletal relations in this case. Subject DT showed a Class III dentoskeletal malocclusion with a complete cross-bite, in the sense that the maxillary dental arch fit lingually in relation to the mandibular dental arch, anteriorly and bilaterally. For this subject, relatively more muscle tension may have been associated with the isometric biting situation used for normalizing and calibrating, than for ordinary chewing. Difficulty with stabilizing the BFT in this case may have resulted in relatively high EMG activities for the isometric biting tasks. This in turn would have adversely affected the normalized and calibrated results. (DT was not one of the subjects randomly selected to be tested by the methods described in Chapter III Section 3-3.2.3., so this could not be verified.)

4-2 Work Done

The work done results from the *in vitro* single chomp experiments have been shown in Tables 19, 20, and 21. The turnip results were a mean of a number of repeated trials (≥ 5), whereas the gum boluses, which were expected to be more consistently "chomped," were the results of single trials for a given experimental session. On the whole, for the initial chomps, the work done on the turnip and the work done on the unprepared gum were similar, consistent, and higher than the work done on the prepared gum by a factor of approximately 5 to 15 times. This large range of differences was attributed to the variability in how the bolus was handled with respect to the tooth morphology in each individual chomping situation. In particular, whether and how the bolus was gripped between the teeth made a significant difference in terms of how much work could be done on the bolus in a single chomp. For this reason, the observed placement of the bolus in the *in vivo* situation was critical to the *in vitro* simulation.

The significant difference found between the mean work done in an initial chomp on the unprepared gum bolus in the LF group versus the NF group was consistent with the significant difference found for the posterior occlusal ratings between the two groups. The mean occlusal rating was lower in the LF groups than the NF group as was the amount of work done in a single chomp, but only for the case of the unprepared gum. There were no other significant differences in the results regarding the work done on the test boluses that related to facial type groupings. Although the results of the work done on the different boluses may have reflected differences in occlusal relations in some cases, these did not otherwise show strong links to the results of the functional posterior occlusal assessment.

4-3 Efficiencies

Despite the potential variability in the state of the muscles and the nature of the work done in the execution of a single chomp, each *in vivo* task resulted in some amount of mechanical work done on the bolus at the cost of some amount of muscle energy. Attempts were made to gauge the event in different individuals by recording the EMG activity from the muscles and expressing this relative to the isometric biting ability of the individual, and comparing this with the mechanical work done in an *in vitro* simulation of the chomp (in accordance with the observed *in vivo* situation).

The results presented in Tables 22, 23, and 24 for the subject groups show generally that the efficiencies measured for single chomps on the test boluses were very low.

No strong facial type or occlusal correlations could be demonstrated, although for one single chomp situation (right side, unprepared gum bolus) the mean efficiency was significantly lower in the LF group than in the SF group. The efficiency measures for single chomps on prepared gum were almost all less than 2.0 percent. The efficiency measured for the single chomps on unprepared gum were somewhat higher, but were generally below 8.0 percent. The turnip chomp efficiencies were low also, but in many cases, were higher than the gum boluses. The most outstanding efficiency measures were above 10.0 percent and up to 27.3 percent. These higher efficiencies for some of the turnip chomps may be explained by the brittle nature of the bolus, and its tendency to split under pressure, especially if influenced by sharp cuspal inclines. Those subjects with higher turnip chomp efficiency scores may have been able to split the bolus with relatively little muscle effort and engage the bolus through completion of the chomp, so that a large amount of mechanical work was done for very little muscle involvement. The relatively high efficiency scores for subject DT may be a consequence of the very low N-eq BF measure calculated for this subject. The sample in general, nevertheless, still demonstrated low efficiencies for single chomps on the test boluses.

5 Gum Chewing

The masticatory efficiency of the sample has been further investigated by analysis of the gum chewing tasks.

Gum in the prepared state was expected to require a force magnitude for deformation that was approximately the same for each chew in a chewing sequence, and that was similar for all people, independent of tooth morphology and occlusion. The work done in a series of chews would therefore be dependent on the distance travelled through the bolus as determined by the shape and size of the bolus. This may have varied to a limited extent, from individual to individual, depending on the specific handling of the bolus, in a manner that was characteristic to the individual. This, however, should not have had a large influence on the efficiency estimates made for a series of 10 consecutive chews.

The total EMG activity measures presented in Tables 25, 26, and 27 were used to estimate the efficiencies associated with prepared gum chewing in the sample population, in the manner described in Chapter IV Section 6-2. The condition of the subject was likely to be less variable in a repeated-chew situation than for the initial chomp situation. This likely accounted for the greater agreement between sessions and sides for a given individual, for the EMG results from the 10-chew sequences on prepared gum.

The results presented in Table 28 show that the chewing efficiency for prepared gum chewing was very low for the entire group, with no significant differences in efficiencies demonstrated between facial type groups.

It seems that efficiencies for single chomps and for prepared gum chewing in the sample population, were generally very low, and did not demonstrate large differences between people who were expected to function very differently. This raised the question: Was the technique used to measure masticatory efficiency in fact sensitive enough to detect differences, if they existed?

The Figures 9. and 10. show typical patterns of the total ISE per chomp associated with the "preparation" of gum, beginning with a standard bolus. The gum in its unprepared form was quite stiff, and a considerable amount of force was required to plastically deform it, compared with that required to deform gum in its fully-prepared state. As the gum was softened and condensed through a series of chews, the work done per chomp was expected to decrease in a progressive fashion from the initial chomp to a point where the consistency of the bolus was no longer changed. The examples shown in Figures 9. and 10. demonstrated that the ISE reflected the change in the work done on the bolus as it was progressively softened by chewing. That is, the results confirmed that the EMG activity decreased as the force requirements and the work done in chewing decreased.

6 Turnip Chewtests

The EMG activity results presented in Tables 29, 30, and 31 represent the input from the muscles in macerating a turnip cube to a degree adequate for swallowing. This required-work standard could be denoted as "one unit" and was set by the threshold for swallowing of the individual. This amount of work done was therefore meaningful for that particular individual.

Compared on this basis, the results from the turnip chewtests showed a wide variability, but no distinct correlations to facial type or occlusion. It was thought that the nature of the turnip bolus (failure in shear) might be more discriminating for differences in these characteristics, particularly tooth morphology. The mechanical efficiency of chewing turnip was not measured more precisely in this investigation. In light of what has already been presented, however, it seems reasonable to predict that turnip chewing was also not very efficient, in a mechanical sense.

The EMG activities expressed as N-eq BF for the turnip chewtests were comparable to those associated with the initial chomps on turnip. According to Sheine and Kay (1982), the first chew is by far the most effective in terms of pulverizing the bolus (work done). More mechanical work may be done on the turnip bolus over the course of a chewtest before it is swallowed; this would increase the efficiencies measured compared to the initial chomp situation. Other factors involved with chewing turnip might also tend to decrease the efficiency, however. For example, since turnip is not a very cohesive bolus (compared to gum), the effectiveness of each chew is more likely to be more random, with some chews doing little or no work on the bolus.

Possible reasons for the variability in the results between sessions for one individual have been discussed in the previous sections of this chapter. Any difference in the normalized and calibrated muscle activity on one side compared to the other may also help to explain some of the differences observed in the mean total EMG activities for session 1 and session 2, where natural chewing sequences were concerned. For MP1 (Table 30), for example, the mean total activity for the chewtests in natural chewing was very similar to that for left unilateral chewing, since all of the natural chews were done on the left during this session.

VI Significance of the Findings

The mechanical efficiency of the human chewing apparatus does not appear to be markedly affected by the form and relationships of the dentofacial complex. The thesis hypothesis therefore has been refuted. It seems that the human chewing apparatus is generally not very efficient in mechanical terms. It is expected that this low efficiency is a characteristic common amongst human masticatory systems. Even subjects demonstrating extremely different dentofacial forms did not demonstrate consistent, remarkable differences in mechanical function.

The most important outcome of this work is the proviso explaining how the adaptive potential and the versatility of the chewing apparatus remain high. A low mechanical efficiency reflects redundancy, ie. spare capacity, in the system. This characteristic maintains the "flexibility" of the system and permits it to be so versatile. The preservation of this flexibility is important both to species evolution and to the development of the individual with respect to long-term survival and the quality of life. It is thus suggested that the adaptation of the system and high functional efficiency are entropically related.

The so-called "energetic paradox" of human evolution has been studied in terms of locomotion (Carriere, 1984). Man is considered a relatively inefficient runner compared with other mammals. Humans characteristically lack an optimal running speed, which makes every means of locomotion within their aerobic scope approximately as costly as any other. However, the human system is particularly well-adapted for endurance and stamina, having the physiology to cope with high levels of energy consumption and metabolic heat production. The relatively high constant cost of transport is hence seen as providing humans with the option of moving in a number of different ways, at a wide variety of speeds.

It is said that evolution tends to optimize fitness (Alexander, 1989). "Fitness" in this sense, is the modification of structures and behaviour to ensure survival, and thereby increase the probability of gene transmission to future generations. This is compatible with the concept that essential functions such as locomotion and feeding must remain non-specialized to ensure flexibility, versatility, and adaptability.

Consider the importance of homeostasis to living systems, and the measures taken to ensure homeostatic balance whenever possible. The biochemical and metabolic processes in the body show a high degree of redundancy to maintain energy stores. Energy costs in terms of adenosine triphosphate hydrolysis, are very difficult to measure *in vivo* since any healthy system is so effective at replenishing high energy phosphate compounds. These insurance measures are energetically expensive in themselves, but they permit the organism to cope with a much wider variety of environmental and circumstantial challenges.

The results described herein support the idea that the masticatory system functions in a manner that is mechanically effective but quite inefficient, and that in an important way this ensures that the flexibility of the system is preserved. In an evolutionary sense, the need for a high degree of masticatory effectiveness and efficiency may have diminished with the increased cognitive ability demonstrated in mammals, and especially in man. It seems that mastication is still important, but man, in particular, has developed many ways to ensure that the nutritional requirements for survival are met. Along with the development of more and better ways to procure and prepare food, man is able to appreciate a highly omnivorous diet.

Although increasing the exposed surface area of the food through mastication does not appear to be essential to digestion and good nutrition, the preparation of food for the act of swallowing is still important. Mastication serves to protect the body by preparing the food to ensure that it is not only easy, but also safe, to swallow. That is, chewing is an important part of food assessment, a very basic act that involves visual, olfactory, gustatory, and tactile sensations, in conjunction with awareness from past experiences.

In general, mastication is a rhythmic, basic-pattern activity that is usually carried out at a habitual rate. It also appears to be designed to easily handle the forces involved in chewing, which in the case of ordinary foodstuffs, are much less than the maximal forces that the system is capable of exerting. In addition, the low fatigability of the masticatory muscles in relation to other systems has been demonstrated (Van Steenberge *et al.*, 1978; Naeije and Zorn, 1981; Lindstrom and Hellsing, 1983; Clark and Carter, 1985; Clark and Adler, 1987). Low force requirements, in a controlled range of muscle shortening, and muscle shortening velocities suggest that only low threshold muscle fibres need be recruited within the jaw elevating muscles during ordinary chewing at habitual rates. These muscle fibres are characteristically less powerful; that is, they can do less work in a given time than other muscle fibre types. Perhaps, then, in normal mastication low forces are involved and small amounts of mechanical work are accomplished at relatively high energetic costs to the muscles. This scenario may describe mastication in a wide range of individuals quite independent of: their facial form (as conventionally classified), of the specific details of their muscle architecture and histology, or the testable extremes of their muscular capabilities (such as maximal bite strength or the limits of endurance).

Through this investigation, the theory behind the relationships between EMG and muscle energy for muscles in motion has been further explored. The theoretical grounds for applying EMG methods to quantitatively assess the input of muscle energy associated with the production of mechanical work, have been experimentally tested. This aspect of the work contributes to the general knowledge regarding surface EMG and the validity of its use in the study of the human chewing apparatus.

The major findings of this work have important applicability to clinical concepts, and in this sense have direct pertinence to the primary goal of dental health care delivery. These results help to explain why such quantifiably large changes in dentofacial form can be realized through treatment without apparent functional penalties to the system. These findings, therefore, contribute to the goal of providing a more sound, scientific rationale for addressing the maintenance and improvement of the functional chewing apparatus through treatment.

Chewing efficiency has been supported as a clinically measurable and meaningful parameter. Its clinical applicability and its specific sensitivity as a measure of individual function remain to be more fully verified. This is a consideration for further work. Interindividual differences have been measured, and it is suspected that these may be due to the detailed mechanics of force-delivery and bolus handling associated with tooth morphology and occlusion. These were not borne out directly, however, by a simple static assessment of the functional occlusion. In addition, the assessment of efficiency changes with respect to treatment may deserve quantitative follow-up.

It is the philosophical impact of this work that is most significant, however, since it has important scientific and clinical ramifications. The finding that the human chewing apparatus exhibits low mechanical efficiency, and the realization that this may in fact be critical to the high adaptive potential and versatility demonstrated by the human masticatory system, raises serious questions about the many theories and ideas based on the assumed relationship between ideal form and function. In clinical terms, it demands the modification of the intent of treatment regimens that are based on such long-standing assumptions. Certainly, it indicates a need to reassess the treatment imperatives and the implications of treatment for many people seeking or being referred for dental procedures.

In summary, the knowledge gained through this work contributes to the basic understanding of masticatory function. This on its own, has scientific merit, but should also provide a stronger rationale to support indications for or against the clinical treatment of the human chewing apparatus.

VII Conclusions

The concept of chewing efficiency was investigated as a means to better understand and quantify masticatory function. Individuals considered to be extremely different morphologically, were compared as to their ability to efficiently macerate food and non-food boluses.

The mechanical efficiency measurements were derived from a comparison of the mechanical work done on a standard bolus, and the muscle energy required to carry out this work. The amount of work done was measured through *in vitro* simulations of *in vivo* tasks. The muscle energy input was measured using quantitative surface EMG data, recorded from the main jaw elevating muscles. These EMG data were normalized and calibrated to permit the direct comparison of results from different individuals and different recording sessions.

From the results of this investigation, based on data collected from a total sample of 33 individuals (14 long facial types, 13 short facial types, and 6 normal facial types), the following conclusions have been made:

1. The human chewing apparatus exhibits a low degree of mechanical efficiency. This lack of efficiency appears to be an important feature, however, that is compatible with the high degree of versatility and adaptability demanded of the human masticatory system. This finding may help to explain how the masticatory system is able to cope with changes associated with aging and with treatment, particularly the more radical changes that can be introduced through surgery.

2. Chewing efficiency is a measurable functional parameter of the masticatory system.

3. Individuals who exhibited dentofacial form that was deviant from accepted norms were not shown to be functionally handicapped in terms of ordinary biting and chewing.

4. Consistent and remarkable correlations were not found between conventional facial types, statically-assessed functional occlusion, chewing patterns, and/or chewing efficiency measures.

5. The use of surface EMG recording to obtain quantitative information regarding the muscle energy involved in ordinary masticatory functions has been theoretically analyzed and experimentally verified. The method used to normalize and calibrate the EMG data permitted a direct comparison of EMG results.

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Appendix A

The Use of EMG in the Quantitative Analysis of Chewing Efficiency in Human Subjects

(Based on a presentation to the Neuroscience Research Group, Department of Physiology, University of Manitoba - June 23, 1989.)

Electromyographic recording [EMG] is used for neuromuscular investigations on a number of levels: membrane, cellular, and gross. For the work proposed, EMG will be employed at the gross anatomical movement level, as an epiphenomenal estimate of the mechanical contributions of muscles to the "gross anatomical" act of chewing.

It is known that when muscles are activated, action currents are generated that flow through the resistive media of the tissues. Voltage gradients are produced that are recordable as myoelectric signals [EMG]. At best, these represent only major aggregate changes in the currents and voltages that result whenever muscle fibres are activated by their motoneurons.

The drawbacks and precautions regarding the gathering and interpreting of EMG data are well-described in the literature.

Relatively simple physical principles have been applied to the clinically relevant problem of how to measure better and to understand better the function of the chewing apparatus. The rationale behind this application, will now be discussed.

The efficiency of an engine system is usually expressed as a ratio of energy output to energy input, or the amount of work done compared to the energy required in performing that work. It seems reasonable to look at the efficiency of the chewing apparatus in a similar way - that is, to measure the amount of work done by an individual in the "chew-until-swallow" of a standardized food bolus. This would require a quantitative comparison of the amount of work done and the energy required by different individuals in chewing the same kind of bolus in their own way. The current experiments are designed to investigate this method.

The mechanical work done on a given food bolus, in a single chomp, can be measured by *in vitro* simulation in a materials testing device. In addition, the limit of the work done on a consistent bolus will be set by the individual. That is, the person will chew until they are ready to swallow.

It is expected that an indication of the muscle energy required for this task can be devised from the true integration of the square of the EMG recordings of the four main adductor muscles involved in the closing of the jaws. (The four muscles involved are the right and left anterior temporalis and right and left masseter muscles. They are easily accessible for whole-muscle recording with surface electrodes.) This is distinctly different from the "rectified, averaged" EMG data that is commonly referred to by the term "integrated." For one thing, it very importantly is not waveform-dependent, as rectified, averaged data definitionally, must be. An example of integrated, squared

EMG activity [ISE] for the right masseter muscle during comminution of a standardized bolus can be found in the accompanying figure.

As already mentioned, the integration of the square of the raw EMG signal represents waveform independent data. Also, Ohm's Law and related electrical principles provide a convenient theoretical analogy that can be applied to the use of ISE. Ohm's Law describes the electrical "pressure" [V] caused by a potential difference, needed for a flow of current [I] through an electrical conductor - eg. muscle soft tissues - with a resistance [R]:

$$V = I \times R.$$

By definition:

$$P = \frac{E}{\Delta t} = \frac{WORK\ DONE}{\Delta t} = I \times V$$

Where: P = Power
E = Energy
Δt = Time interval

and therefore, since:

$$P = \frac{E}{\Delta t} = \frac{V^2}{R}$$

it can be said that:

$$V^2 \times \Delta t = E \times R.$$

Consider now, the significance of the integration over time, of the square of the EMG signal; that is, the running summation of the electrical activity of the musculature during a given chewing or biting task, which is:

ISE = Sum of the EMG^2 x Time taken to carry out the task.

As long as the connection between EMG and voltage is valid for chewing, then:

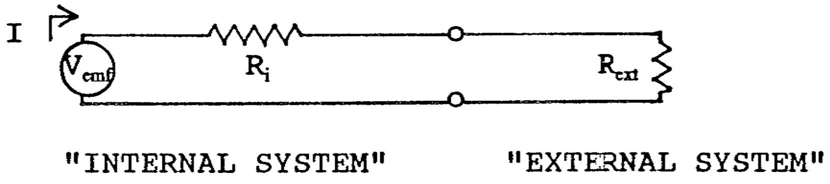
$$\text{ISE} = \text{Sum of } V^2 \times \Delta t = \text{Sum of } E \times R$$

where ISE, represents the total energy output for a system with a certain resistance, R, for a given chewing or biting task. This gives us a waveform-independent measure of energy, and in addition, the squaring of the EMG signal:

1) is in accordance with the units of the above relationship between recorded activity (V^2) and energy

2) de-emphasizes the contributions of any unavoidable background noise to the integrated results.

The resistance, R, must also be considered. A very simplified circuit diagram can be represented approximately as:



Here, there is some source of electromotive force [V_{emf}]; some internal resistance [R_i], given by the "internal system," which cannot be directly measured; and some external resistance

[R_{ext}], given by the food bolus, which is measurable.

If EMG activity is proportional to the total power in the system, which is true for isometric situations, then:

$$\text{TOTAL POWER} = V \times I = \frac{V^2}{R} \quad \text{where } R = R_i + R_{ext}.$$

R_{ext} can be measured; and although R_i cannot be directly measured, some information about it can be gained by looking at situations where R_{ext} is known to be zero. For example, it is known that in a single chomp, work is done on the bolus and the ISE during that activity is quite representative of the energy used in performing this work on the bolus. However, the system can be using energy without any real work being done - for example, during an isometric clench. This is analogous to the situation of a stopped car where the engine is running and the brakes provide the resistance to prevent the car from moving. More must also be known about the relationship between EMG and energy use in a moving situation, for example, ISE during so-called "phantom-chewing."

Although the internal system is "unknown" and cannot be directly measured, some information about it can be obtained by looking at such energy-consuming, but no real-work-producing activities, when the energy consumed is largely dissipated as heat.

The application of the ideas described involve a combination of *in vivo* and *in vitro* investigations. In brief, these involve a number of standardized biting and chewing tasks that are carried out *in vivo*: the raw EMG signals from surface electrodes are recorded, and the ISE obtained. The mechanical aspects of these tasks are simulated in a testing machine in order to measure the bite forces involved and the work done in Newtons [N], and Newton-meters [Nm], respectively. These results are used to normalize and calibrate the ISE for a given individual, at a particular recording session in terms of "real" measures of force, work done, and to account for the ISE that is attributable to chewing movements that are not actually involved in doing work on the bolus ("phantom-chewing," or chewing without a bolus). This will allow the analysis of a chewing sequence, and the assessment of the chewing efficiency of an individual, at a given recording session. It will furthermore allow a comparison between individuals, and between results from session to session for one individual.

The quality and reliability of the experimental evidence is currently being tested. If this method is viable - that is, if the use of ISE as a measure of the energy expenditure of a system of muscles can be substantiated - its application to the much larger problems of measuring functional parameters and understanding function in the human masticatory apparatus, is very exciting. Having a measure of chewing efficiency, will thus not only be very relevant clinically, but also provide better insight into the design of the chewing apparatus and how it actually works.

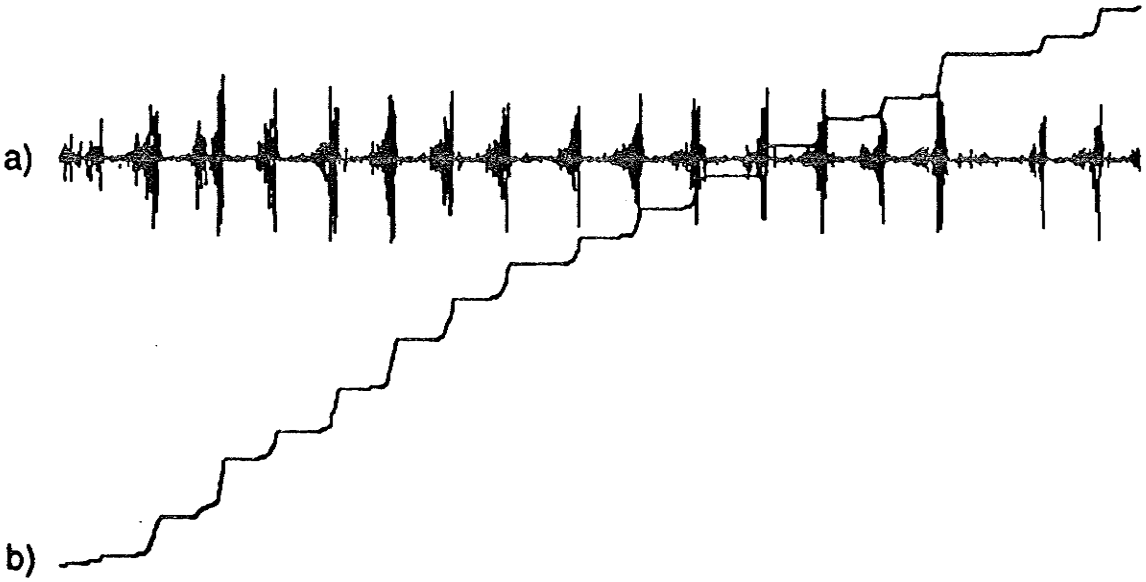


Figure A. Turnip Chewtest Result for Right Masseter Muscle (Subject: PT2, FEB/89):

a) Raw EMG Recording (17 chomps)

b) Integrated, Squared EMG Activity

Appendix B Information, History, and Consent Forms

1 Information for Prospective Subjects

A Study of the Efficiency of Chewing in Humans

The purpose of this study is to gain an improved understanding of the design and function of the human chewing apparatus by knowing more about its efficiency in chewing. The principle investigator has qualifications as a general dentist and orthodontic specialist, and is conducting the research in fulfilment of her Ph.D. degree.

The basic research techniques involved in this study are used commonly as part of dental examinations, and/or in clinical research involving human subjects. These techniques are non-invasive, and are not associated with any known harm or irreversible changes to human tissues or organ systems.

Subjects may be required to have impressions of their teeth and photographs of the head and neck made. In addition, the electrical activity (EMG) from two pairs of jaw muscles will be recorded while the subject performs a number of simple biting and chewing tasks using specially-constructed bite-measuring devices, chewing gum, and normal foods. This will require the scrubbing and cleaning of the skin of the cheeks and the sides of the forehead with rubbing alcohol, in preparation for the taping of small metal electrodes to these areas.

The general health and well-being of subjects participating should not be affected by any of the techniques applied in this study. Furthermore, immediate and obvious physical benefits to the participants as a result of involvement in this study are not expected. On the other had, significant, foreseeable risks to the subjects are highly unlikely. Among the remote, but possible risks are: allergic reactions to the materials or foods used; gagging on, choking on, and/or accidental inhaling of the experimental materials or foods; tenderness and/or redness in the areas of the skin prepared for the recording electrodes; minor discomfort during adhesive tape removal from the skin; slight jaw muscle tiredness for a short time following the experiments. Risks of damage to the teeth and jaws should be no greater than the risks involved in the mastication of ordinary foods.

The required total time commitment is approximately two to three hours, divided over two separate session. The first session will include time to explain the details of the procedures, review the general medical/dental history form, obtain consent, and to have the dental records required made. Both sessions will involve recording from the jaw muscles (as outlined above). Prior to each session, the subject will be asked to: shave or wash the face and avoid applying any facial ointments or make-up.

Subjects should contact Dr. Iwasaki at the telephone numbers supplied, should any questions, or problems arise, regarding this study.

2 History Forms

UNIVERSITY OF MANITOBA - FACULTY OF GRADUATE STUDIES

CHEWING STUDY: MEDICAL-DENTAL HISTORY

NAME: ______________________________ DATE: _______
(Surname) (Given name[s])

ADDRESS: ____
(No.) (Street) (City) (Postal code)

TELEPHONE NO.: _______________ _______________
(Residence) (Business)

BIRTHDATE: ______________________ PRESENT AGE: _______

MEDICAL HISTORY	YES	NO
Physician's Name _________________________________		
Currently under physician's care?	____	____
Currently taking medication?	____	____
Past severe illnesses?	____	____
Birth defects?	____	____
Past or current allergies?	____	____

Please explain all "YES" answers: ___________________________
____
____

DENTAL HISTORY

Have you ever had orthodontic treatment? (Braces) ____
If "YES," please describe: _______________________________

Dentist's name: ___________________________________
How often do you visit your dentist? _____________________

When was your last dental appointment? ___________________

Did you ever, or do you:
Clench or grind your teeth? ____ ____
Have problems with you jaws, jaw joints, or jaw muscles? ____ ____

Are you presently undergoing any dental treatment? ____ ____

If "YES," please describe: _______________________________
____

3 Consent Form

CHEWING STUDY: CONSENT FORM

I have agreed to participate in a study of chewing function, to be conducted by Laura Iwasaki, Graduate Student, Interdisciplinary Ph.D. Program, University of Manitoba. I have read the information sheet about the study, and it has also been explained to me by Dr. Iwasaki. I understand that the study may require the making of some standard dental records, and will involve surface electromyographic recordings from four jaw muscles during some biting and chewing tasks employing ordinary foodstuffs and specially-constructed bite-measuring devices. These biting and chewing tasks are not expected to demand any extraordinary effort of the chewing apparatus.

I understand that there are no specific, personal benefits to be realized as a result of my participation in this study, but that the results of the research are expected to contribute to scientific knowledge and the future of clinical treatment in dentistry. I understand that the risks of personal harm or discomfort involved in this study are very small. It has been explained to me that although the possibilities are remote, should any problems associated with my participation in this study occur and persist, I will be seen for advice and/or treatment as appropriate, in the University of Manitoba Graduate Orthodontic Clinic.

I consent to having the following records of me made; with the understanding that they will become the property of the University of Manitoba, and will be held in confidence, but may be used for research publication and presentation purposes:

1. History and examination records
2. Impressions for dental models
3. Bite registration records
4. Side- and frontal-view head and shoulder photographs
5. Surface electromyography.

I have volunteered to participate in this study on my own accord, and I realize that I am free to withdraw from participation at any time without penalty.

Signature of Subject: ______________________
Date: __________

Signature of Witness: ______________________

Appendix C

The Effects of Velocity on Human Masseter Muscle Electromyography during Anterior Biting

(Presented to the Canadian Medical and Biological Engineering Society, Winnipeg - June, 1990; see also: Iwasaki and McLachlan, 1990)

INTRODUCTION

Based on the assumption that myoelectric activity has a strong and direct relationship to the muscle energy expended, an estimate of the energy costs of masticatory function may be obtained from surface electromyography [EMG] recorded bilaterally from the major jaw elevator muscles. The EMG associated with chewing should reflect the external work as well as the internal work being done by the muscles. The external work is the work done by the muscles through the application of force via the teeth and the jaws during biting and chewing. The internal work is that done within the muscles due to internal resistances, and which results in energy loss as heat. While the external work done, for example, in chewing a food bolus, is relatively easy to quantify, the internal work done is not. Some quantitative information regarding the internal work can be gained however, through studies of the isometric muscle tension (force) situation. In this situation, where the external work being done is zero, the relationship between EMG activity and force-production is approximately linear (Inman *et al.*, 1952; Lippold, 1952; Bigland and Lippold, 1954; Close *et al.*, 1960;

Komi 1973; Pruim *et al.*, 1978). Therefore, for an increase in isometric bite force, a proportional increase in the EMG activity from the jaw elevator muscles would be expected, reflective of an increase in the internal work done.

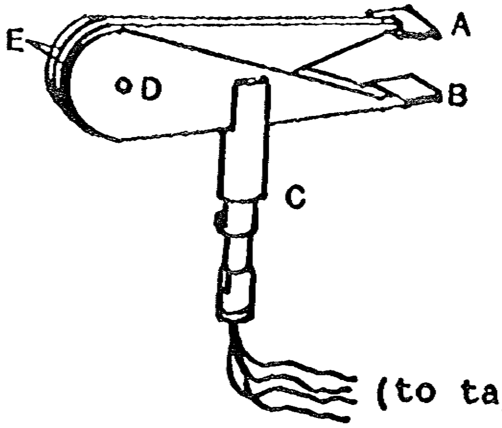
Chewing is a more complex task than isometric biting, however, since it involves not only force-production, but motion as well. How such motion might affect the EMG during chewing was of interest. A series of experiments was conducted to investigate this question. The objective was to study the velocity effects on the EMG recorded from human masseter muscles during anterior biting at known force levels.

The anterior biting position was specifically selected because theoretical and experimental evidence suggests that when biting on the front teeth, the masseter muscles act as the main jaw closing muscles and the temporalis muscles are relatively inactive. Hence, by testing the anterior biting situation, the masseter muscles could be investigated in relative isolation. In addition, normally, for a centred bite, balanced and symmetrical activity in the masticatory muscle system is expected.

MATERIALS AND METHODS

A "pseudo-bolus" device [PBD] was designed and constructed for these experiments (Figure C1). This device was hand-held by the subjects and consisted of a set of three aluminum plates each measuring about 24 centimetres long and

PSEUDO-BOLUS DEVICE



A, B - Plattens for biting
C - Linear voltage displacement transducer
D - Force magnitude adjustment screw
E - Dry friction pads

Figure C1

0.3 centimetres wide. The twin outer plates were joined by a thin stainless steel platten (marked B in Figure C1). A complimentary platten (marked A in Figure C1) was attached to the inner plate. Cork sheets were sandwiched between the aluminum plates to increase the dry friction of the system. Resistance to the movement of the two plattens together could be adjusted and set by a screw (marked D in Figure C1) which applied a normal force to the cork-aluminum plate sandwich. The bite force required to approximate the plattens could thus be quantified. This force was assumed to be consistent, at a given setting, for the range of velocities involved.

The biting surfaces of the plattens were coated with a thin film of silicone putty material (Silicone Impression Material, Great Lakes Orthodontics Limited, Tonawanda, New York) to protect the edges of the teeth. (The PBD was disinfected and the protective surfaces were changed between subjects.) When the plattens were approximated, the total separation of the teeth was about four millimetres.

The movement of one platten relative to the other platten was monitored through a linear voltage displacement transducer [LVDT] housed in the handle of the PBD. At the same time, standard bipolar surface electrode EMG recording techniques were utilized on human volunteers to record the activity from the right and left masseter muscles. Electrodes were also placed on the anterior belly of one temporalis muscle in all subjects. This served as a check that the temporalis muscle was, as expected, "inactive" for anterior biting. The EMG during biting was amplified using a two-stage system (Biosys, Winnipeg) and recorded simultaneously with the LVDT output during biting on to FM tape.

Four adults with intact natural teeth and no obvious jaw joint problems participated as subjects. Each subject carried out 20 to 30 bites of different steady velocities at required bite force levels between 4 to 36 N. For the start of each bite, the interplatten distance was 15 millimetres. The subjects were asked to "clench" lightly on the plattens when they came together.

For each biting task, analogue-to-digital conversion permitted the computation of the root mean squared EMG data [RMS] and the velocity from the LVDT. The bite force levels and velocities used were well within the range of normal human function.

Digital-to-analogue conversion capabilities permitted a four-channel display of the data from each biting task. Figure C2 shows the raw EMG output for the right masseter, left masseter, and one of the anterior temporalis muscles recorded over a period of eight seconds during one such task. In this example the required bite force was 18 Newtons [N]. The LVDT channel mapped out the displacement versus time for the biting task from the beginning of the bite to the end of the bite when the plattens came together. This display was used to select an interval of steady closing velocity near the

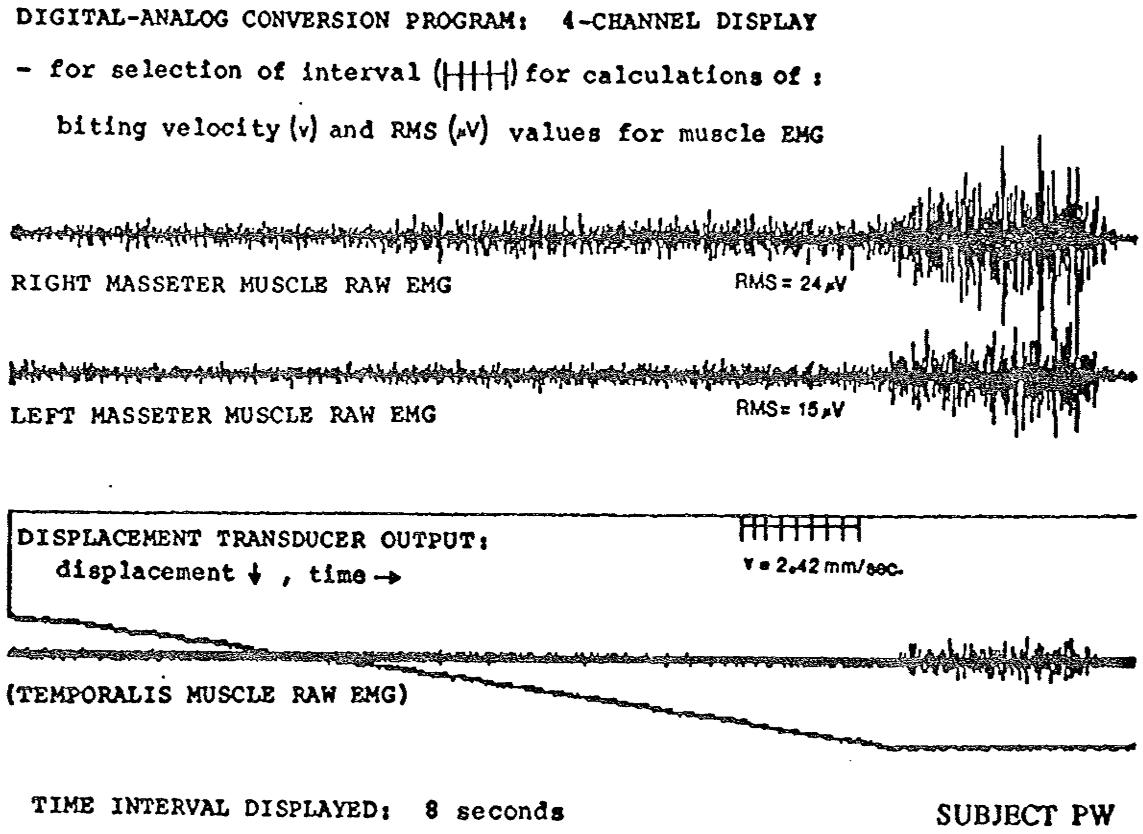

DIGITAL-ANALOG CONVERSION PROGRAM: 4-CHANNEL DISPLAY
- for selection of interval (┤┼┼├) for calculations of :
biting velocity (v) and RMS (μV) values for muscle EMG
RIGHT MASSETER MUSCLE RAW EMG
RMS = 24 μV
LEFT MASSETER MUSCLE RAW EMG
RMS = 15 μV
DISPLACEMENT TRANSDUCER OUTPUT:
displacement ↓ , time →
v = 2.42 mm/sec.
(TEMPORALIS MUSCLE RAW EMG)
TIME INTERVAL DISPLAYED: 8 seconds
SUBJECT PW

Figure C2

end of a biting task, for the calculation of RMS EMG values and the biting velocity.

RESULTS

The anterior temporalis muscle was found to be essentially inactive during the anterior biting tasks performed by all of the subjects studied. This finding was as expected for this muscle under the conditions of biting.

The results of the masseter muscle EMG versus anterior biting velocity showed a consistent pattern for all subjects tested, at all required bite force levels. The sum of the right and left masseter muscle RMS EMG from a number of different steady velocity bites by one subject for the required bite force of 9 N, are shown in Figure C3. The range of biting velocities for this subject and bite force level was from 1 to 150 millimetres/second. The relationships for all subjects at all bite force levels showed a similar, well-behaved, but nonlinear relationship. In order to study this relationship more closely at low closing velocities such as those used during chewing, the data were plotted using a log scale.

Log_{10} of the sum of the RMS EMG of the masseter muscles versus $\log_{10}$ of the anterior biting velocity for one subject showing the results for required bite force levels of 9 N, 18 N, and 36 N are shown in Figure C4. Some consistent features characterized the group of curves obtained for each

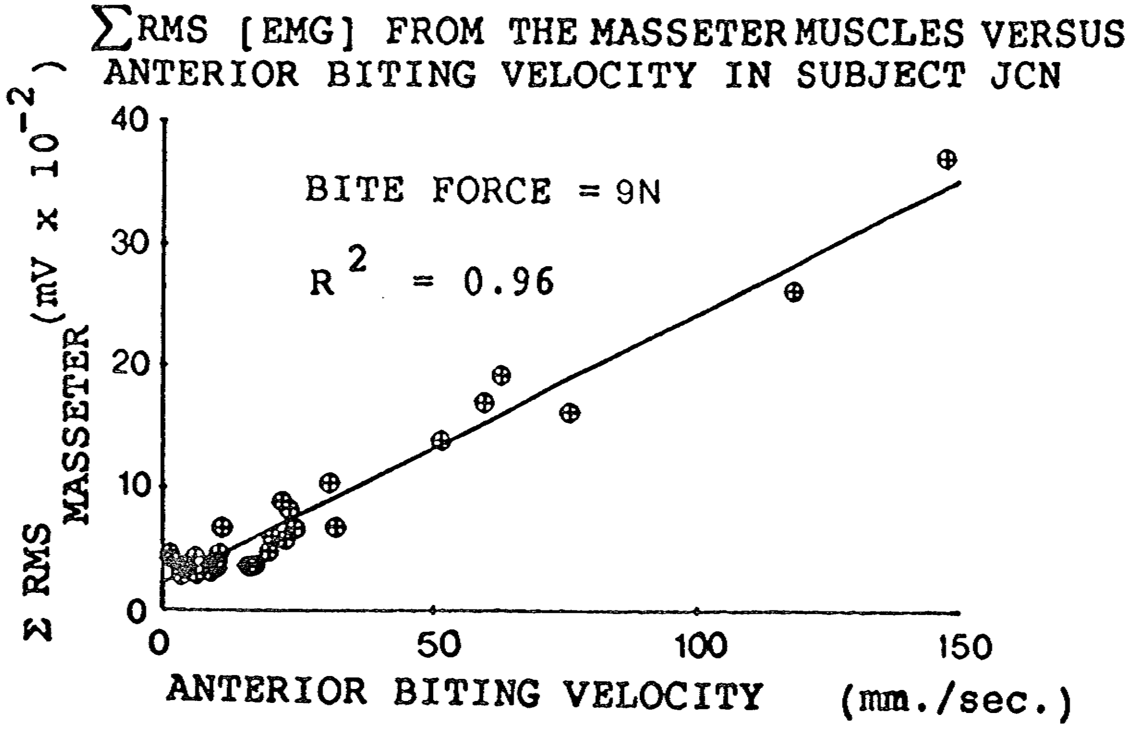

∑RMS [EMG] FROM THE MASSETER MUSCLES VERSUS ANTERIOR BITING VELOCITY IN SUBJECT JCN
BITE FORCE = 9N
$R^2 = 0.96$
Σ RMS$_{\text{MASSETER}}$ (mV x 10^{-2})
40
30
20
10
0
0
50
100
150
ANTERIOR BITING VELOCITY (mm./sec.)

Figure C3

LOG10 – LOG10 PLOT OF SUM OF RMS–EMG ACTIVITY
FOR THE MASSETER MUSCLES VERSUS
ANTERIOR BITING VELOCITY FOR SUBJECT PW

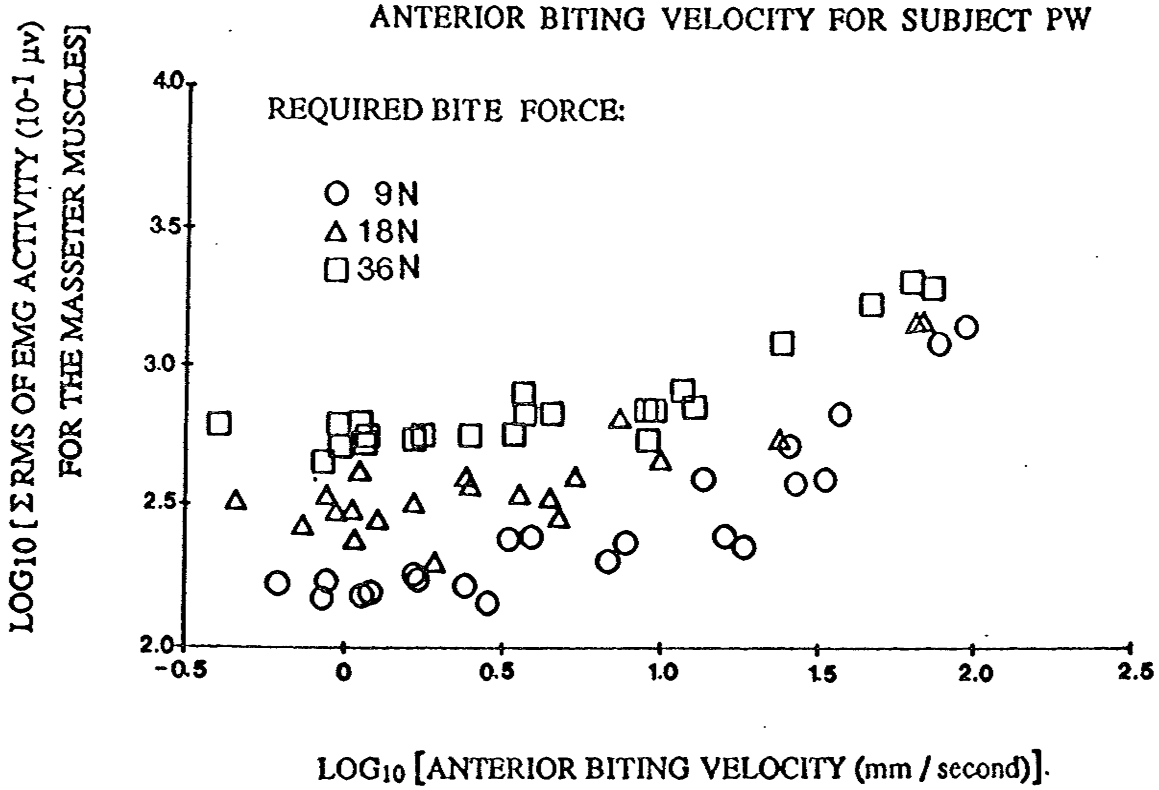


Figure C4

subject and the pattern of the results was similar for all four subjects. Firstly, the EMG was found to increase incrementally with increases in the required bite force. Secondly, a relatively flat, straight-line relationship for the points corresponding to the low velocity range were observed up to a critical velocity level, or point of inflection, whereafter the EMG was seen to rise sharply with increasing biting velocity. These features were well-illustrated by more simplified plots, obtained by representing the low velocity and high velocity results separately. The low velocity results were adequately represented by a straight-line relationship, as shown in Figure C5, where the same data as plotted in Figure C4 is otherwise presented.

The mean inflection point for all subjects and bite force levels was 10 millimetres/second (1 on the $\log_{10}$ scale). The inflection point results for the subjects and bite force levels studied are presented in Table C-I. The mean slope of the higher velocity curves for the group was 5.3 decibels/octave (6 decibels/octave equals a doubling of the EMG with doubling of velocity). The slopes for the subjects and bite force levels studied are presented in Table C-II. The trend to decreasing slopes for the higher velocity curves with increasing required bite force, may reflect a convergence of these lines to a common point, or may simply be a result of the relative difficulty in achieving higher velocities of biting at higher bite force levels.

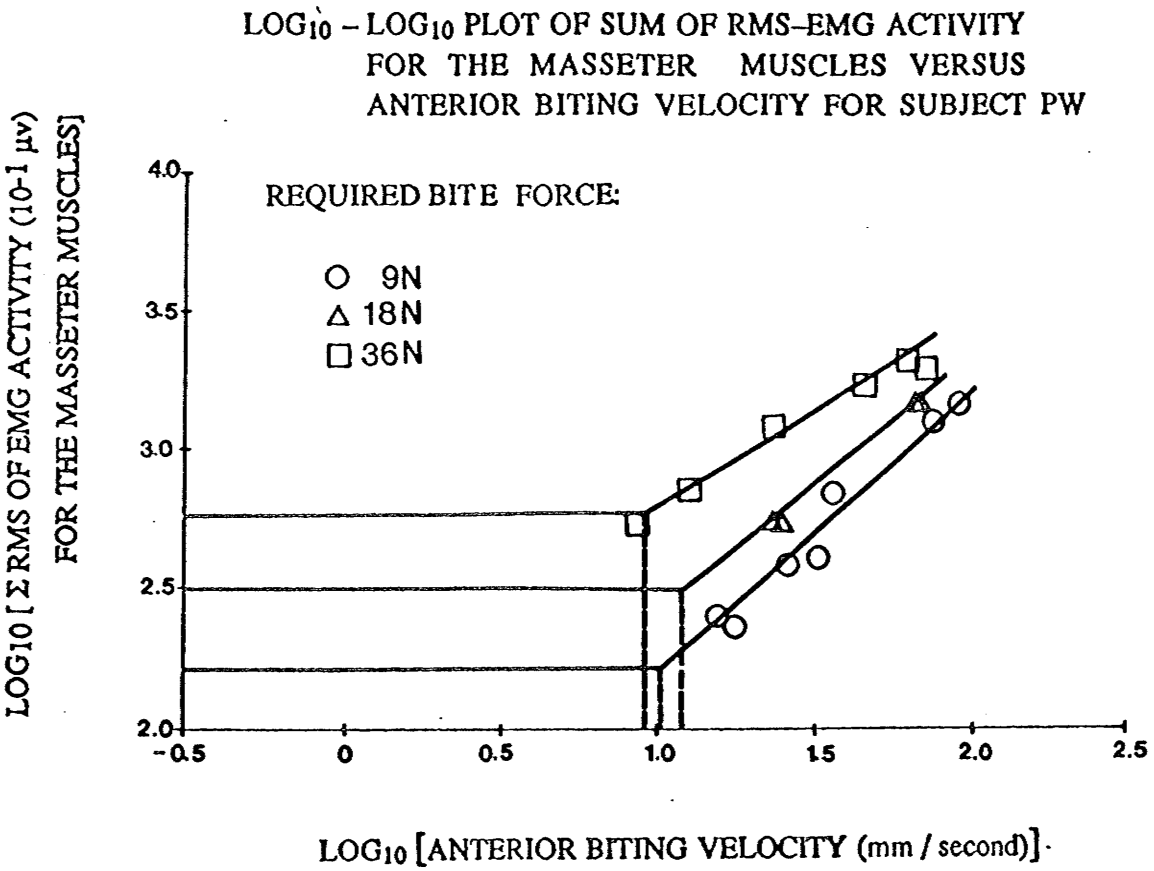

LOG$_{10}$ – LOG$_{10}$ PLOT OF SUM OF RMS–EMG ACTIVITY FOR THE MASSETER MUSCLES VERSUS ANTERIOR BITING VELOCITY FOR SUBJECT PW

Figure C5

Table C-I. INFLECTION POINTS [I] OF LOW VELOCITY AND HIGH VELOCITY CURVES* AT VARIOUS REQUIRED BITE FORCE LEVELS.

INFLECTION POINT [I] in millimetres/second for:

SUBJECT	4 N	9 N	18 N	27 N	36 N	MEAN
NG	-	8	3	-	6	6
PW	-	10	13	-	10	11
JN	20	10	20	-	6	14
PT	6	10	6	10	10	9

OVERALL MEAN [I] ± STANDARD DEVIATION 10 ± 5

* Masseter Muscle EMG Activity versus Anterior Biting Velocity.

Table C-II. SLOPES OF THE HIGH VELOCITY PORTIONS OF THE MASSETER MUSCLE EMG ACTIVITY VERSUS ANTERIOR BITING VELOCITY CURVES* FOR VARIOUS BITE FORCE LEVELS.

SLOPES in decibels/octave for:

SUBJECT	4 N	9 N	18 N	27 N	36 N	MEAN
NG	-	5.8	4.7	-	3.2	4.6
PW	-	6.4	5.5	-	4.6	5.5
JN	8.1	4.9	8.5	-	3.9	6.4
PT	6.4	5.9	4.0	3.7	4.2	4.8

OVERALL MEAN [I] ± STANDARD DEVIATION 5.3 ± 1.6

* Masseter Muscle EMG Activity versus Anterior Biting Velocity.

SUMMARY AND CONCLUSIONS

For anterior biting of known force magnitudes, in a range appropriate to normal human function, the muscular activity recorded by surface EMG varied with velocity. It appears that for normal anterior biting, at a given force magnitude, the surface EMG recorded from the masseter muscles is predictably sensitive to velocity changes. The relationships demonstrated likely reflect the speed of shortening characteristics of the masseter muscle. These results support those of others who have shown predictable linear relationships between muscle EMG and speed of contraction in other muscle systems (Bigland and Lippold, 1954; Bouisset, 1973).

The results of this study suggest that for the low ranges of velocity, a "pseudo-isometric" situation exists and the force effects on the EMG predominate. For masticatory function, therefore, in the range of muscle shortening speeds of 10 millimetres/second and less, a linear relationship can be expected between the EMG activity and masticatory force.

To reiterate, this study has lead to the following conclusions:

1. The additive effects of bite force and velocity on the masseter muscle EMG have been demonstrated, such that at:

    - low velocities of biting, the bite force effects dominate ("pseudo-isometric" situation), whereas at

    - higher velocities of biting, the velocity effects dominate.

2. An increase in the required bite force resulted in a predictable increase in the EMG output, that was consistent with a linear isometric force-EMG relationship.

3. The inflection point of the EMG-velocity curve was relatively consistent (10 millimetres/second), as was the slope of the higher velocity portion of the curve (5.3 decibels/octave).

REFERENCES TO APPENDIX C

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