MASTICATORY FUNCTION OF THE DENTULOUS VERSUS

PROSTHODONTICALLY TREATED EDENTULOUS MANDIBLE

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ABSTRACT

Sorin Uram-Tuculescu: Masticatory function of the dentulous versus prosthodontically treated edentulous mandible

(Under the direction of Dr. Greg Essick, DDS, PhD)

Background: There is general agreement that implant supported prostheses offer better masticatory function than traditional prostheses that are not supported by teeth or implants. However, solid evidence is lacking to fully support this, and contrary findings are mentioned in the literature.

Aim: To characterize differences in chewing and neuromuscular control characteristics of patients with upper and lower natural teeth, upper full dentures and lower natural teeth, upper and lower full dentures, upper full dentures and lower implant-supported overdentures, upper full dentures and lower implant supported fixed prostheses.

Materials and methods: Chewing function is evaluated subjectively (questionnaires) and objectively (electromyographic measurements), while subjects are chewing agar based model foods with 4 different consistencies.

Conclusions: Electromyographic methods using i) engineered test foods with controlled physical properties and ii) rigorous analytical techniques can detect and characterize meaningful differences among human subjects who differ in dental status and prosthodontic treatments.
To my wife Cora, who sacrificed a lot for me to continue my graduate education.
To my son Dorin, who is the joy of my life.
To my parents, to my sister, for all their support and understanding.
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LIST OF ABBREVIATIONS AND SYMBOLS

ACP – American College of Prosthodontists
AUC – area under the electromyography curve
BDA – balancing digastric anterior muscle
BMM – balancing superficial masseter muscle
BTA – balancing temporalis anterior muscle
BS – balancing side
c – multiplicative constant
CD/CD – conventional full denture group
CD/FD – upper conventional full denture, lower implant-supported prosthesis group
CD/ND – upper conventional full denture, lower natural dentition group
CD/OD – upper conventional full denture, lower implant supported overdenture group
CD/XX – prosthodontically treated subjects
cv – coefficient of variation
D – total duration of chewing
DA-L – left anterior digastric muscle
DA-R – right anterior digastric muscle
EMG – electromyography
IRB - Institutional Review Board
MM-L – left superficial masseter muscle
MM-R – right superficial masseter muscle
N – sample size
n - power function exponent
ND/ND – natural dentition group
$R^2$ – R-square goodness of fit of the data to a power function model
rms – root mean square
SAS – Statistical Analysis Software
sd – standard deviation
TA-L – left anterior temporalis muscle
TA-R – right anterior temporalis muscle
UNC – University of North Carolina
USP – United States Pharmacopeia
W – relative muscle work
WDA – working digastric anterior muscle
WMM – working superficial masseter muscle
WS – working side
WTA – working temporalis anterior muscle
w/w – weight percentage
∆ % - change in agar concentration
▲ – fracture point
1. INTRODUCTION

Mastication is a highly coordinated neuromuscular function involving purposeful movements of the jaw and continuous modulation of force (Karkazis and Kossioni 1998), representing a function that matures with growth as the teeth erupt. It is characterized by complex movements of the stomatognathic system structures, most importantly the mandible, which vary depending on the foods ingested, resulting in manipulation of a food bolus, salivation, and associated oscillatory movements of the head.

The commands underlying the basic rhythmical movements of mastication are generated centrally, but those responsible for their adaptive control are regulated by afferent (sensory) information, particularly related to oro-facial kinesthetic inputs. Sensory receptors, such as periodontal mechanoreceptors and muscle spindle afferents, strongly influence the activity of motor neurons and thus, control of the masticatory muscles. Much of the integration of sensory feedback with the centrally generated drive occurs at the level of the protoneurons in the nucleus reticularis parvocellularis and in the mesencephalic trigeminal nucleus and adjacent nuclei, neural substrates associated with the central pattern generator for mastication (Lund 1991).

Mandibular kinematics and the masticatory muscle activity during chewing have been described in numerous studies using various methods. Characteristic chewing patterns in children and adults (Gibbs et al 1982; Neill and Howell 1988) seem to be established early in childhood with some restricted adaptation to new conditions such as the locations of permanent teeth (Gibbs et al 1982) or tooth loss. However, individual chewing patterns vary widely within (Plesh Bishop and McCall 1987) and between (Gibbs et al 1982) subjects.
The loss of teeth, and consequently, prosthodontic rehabilitation pose new challenges to the stomatognathic system, which alter masticatory function. Relatively little is known about the extent to which chewing differs between dentate subjects and completely or partially edentulous patients treated in various ways. Moreover, the methods of assessment are relatively few and have often provide conflicting data.

### 1.1. METHODS USED FOR ASSESSMENT OF MASTICATORY FUNCTION

Masticatory function can be evaluated subjectively (subject reported assessments) and objectively (laboratory tests of function).

**A. Subjective methods.**

In subject reported assessments, subjects judge their masticatory function via questionnaires or interviews (Agerberg and Carlsson 1981; Osterberg and Steen 1982; Uchida 1991). A patient’s general satisfaction is determined by a number of factors directly related to treatment: comfort, perceived chewing ability, oral health-related quality of life, dietary difficulties and overall nutritional status enabled by the oral status. The subjective method is sensitive to differences in dental and prosthetic state, while data gathering and analysis is easy. The method is inexpensive and the data is easy to interpret.

**B. Objective methods.**

The most frequently used objective methods target the determination of the following outcomes:

a) Total duration of mastication in subjects eating standard-sized pieces of food (Lindquist and Carlsson 1985; Lucas et al 1986a, Jemt and Stalblad 1986, Peyron et al 2004). In addition, several other associated measures can be extracted from observation of the masticatory sequence, including the frequency and number of chews. The total duration of mastication is


c) Masticatory forces (Haraldson et al 1988). Masticatory forces can be evaluated directly between the upper and lower teeth using bite bars instrumented with strain gauges (Carlsson and Lindquist 1994; Fontijn-Tekamp 2000; Hatch et al 2001), force transducers placed in prostheses, or indirectly by sound transmitted between the teeth (Gibbs et al 1981) or EMG activity (Youssef et al 1997) calibrated to known to force levels.

d) Electrical activity of jaw muscle. EMG analysis enables specific physiologically relevant measures to be extracted, such as the peak amplitude, its time of occurrence, area under the EMG curve (also referred to as ‘muscle work’ in some literature), and duty cycle of the jaw closing muscles (Feine et al 1994a; Garrett et al 1996; Karkazis 2002; Kohyama Mioche and Bourdiol 2003; Miralles et al 1989; Peyron et al 2004; Mishellany-Doutour et al 2008).

e) Jaw movement patterns during mastication (Jemt 1984; Jemt and Stalblad 1986; Feine and Lund 2006), recorded using a jaw tracking system.

Probably the most commonly used objective methods in the assessment of masticatory function are: i) determination of food particle reduction, ii) evaluation of masticatory muscle forces, iii) evaluation of masticatory muscle EMG activity, and iv) analysis of jaw movements.
i) Food particle size reduction determination.

Particle size measurement is meant to assess the ability to pulverize food. Fractional sieving as a technique of separating the food after chewing for a given time period has been used for a long time (Gunne et al 1982; Gunne 1985), and is still considered to be a viable method (Fontijn-Tekamp et al 2000; Mishellany-Dutour et al 2008). Some disadvantages of this method relate to the following: data analysis is messy and time consuming, particularly if one tries to measure the distribution of particle sizes. Additionally, the method is applicable only to brittle substances (Feine and Lund 2006).

Computer-assisted image processing can also be used to analyze the size of masticated test particles (Mahmood et al 1992; Nakano et al 1989). Compared with sieving, image analysis of test particles offers considerable advantages such as simplicity, speed, accuracy, reproducibility, and hygiene. This method is also practical for measuring a large number of samples (Boretti Bickel and Geering 1995).

ii) Masticatory muscle force evaluation.

Force measurements have been purported to measure masticatory efficiency. Since maximal biting forces are not generated during normal chewing, it seems more relevant to measure the forces generated during mastication (Feine and Lund 2006). This can be performed by placing force transducers into prostheses, or using a sound transmission method to measure the mechanical coupling between the upper and lower teeth when occluding (Gibbs et al 1981). Masticatory muscle force can also be evaluated by calculations using EMG outputs (Youssef et al 1997).

The measurement of bite force is an indirect method for assessing masticatory efficiency, is based on the assumption that function is correlated with bite force, and has been advocated by a number of investigators (Helkimo Carlsson and Helkimo 1978). However, Jemt et al (Jemt Lindquist and Hedegard 1985), and some other investigators, have found only a weak correlation between bite force measurements and chewing efficiency.
iii) Masticatory muscle EMG.

EMG method provides a variety of measures, offering valuable information about the amplitude of muscle activity during a chew and timing of masticatory muscle recruitment, with the possibility to calculate multiple secondary behavioral outcomes, including total duration of the chewing sequence and chewing frequency, number of chewing cycles, masticatory muscle activity (e.g. area under the EMG curve), and duty cycle of the jaw closing muscles (e.g. the chewing cycle when the jaw-closing muscles are active). EMG is considered a repeatable technique if done under standardized conditions (Komi and Buskirk 1970; Nouri Rothwell and Duxbury 1976).

iv) Jaw movements tracking.

Jaw movement tracking represents a useful method to characterize masticatory function. Mandibular movements while chewing can be quantified by a variety of measures, such as vertical and mediolateral amplitude during a chewing cycle, opening and closing velocity (i.e. jaw speed), closing acceleration (i.e. mean change in velocity during the closing portion of the chewing cycle), and angle of approach (relative to the horizontal plane) to maximal intercuspation (Wilding and Lewin 1994).

Jaw movements have demonstrated variability between individuals (related for example, to dentofacial deformity, or gender) and also within the same individual, as it can be influenced by dental state and/or various dental treatments as well as the mechanical properties of foods.

The usefulness of jaw movement tracking is well illustrated in the orthodontic literature, which has demonstrated a correlation between jaw function and altered chewing of individuals with dentofacial deformities. As an example, the envelope of jaw motion and the chewing movements of Class III (prognathic) individuals present characteristics, which when observed in Class I individuals signify challenged jaw mobility and decreased chewing performance. The Class III phenotype exhibits a restricted envelope of motion, i.e. protrusive and lateral jaw movements are limited in extent compared to Class I or Class II (retrognathic) individuals (Zimmer et al 1991 1992; Ehmer and
Broll 1992). Class III subjects tend to chew more slowly and require additional chewing cycles to masticate a standard food item (Ingervall et al 1979; Miyawaki et al 2001). Irregularity in jaw movement (e.g. abrupt changes in velocity) is observed more frequently in Class III individuals than in Class I individuals (Miyawaki et al 2001; Yashiro and Takada 2004). Finally, jaw closing movement during chewing tends to occur vertically, rather than laterally, resulting in food substances being chopped rather than ground and milled (Ehmer and Broll 1992). In contrast, smooth, flowing movement and wide lateral closures are typical for Class I subjects, which are the two major predictors of good chewing performance (Wilding and Lewin 1994) and are often lacking in Class III individuals. One might hypothesize that many of the alterations in chewing movements observed for Class III individuals also apply to individuals who wear conventional full dentures, although this has never been tested.

C. Test foods used in studies.

The test foods used in objective studies of mastication can be either natural foods (e.g. bread, cheese, carrots, nuts, apples) or artificial model foods (e.g. elastomers, gelatine, agar gels). The natural foods present the undisputed advantage of relating to ecologically valid mastication, but their size, texture, hardness, and rheological characteristics are difficult to standardize, and fabrication of samples with reproducible properties is practically impossible. Use of model foods provides a means to standardize (without seasonal variation) the dimensions, color, and taste/smell of test substances with consistent, well characterized textural properties. Model foods can be repeatedly given to the same subject from appointment to appointment, and to different subjects (Barrangou Daubert and Foegeding 2006a; Barrangou Daubert and Foegeding 2006b; Brown et al 2003; Foegeding et al 2003).

Viscoelastic model products with progressively increasing hardness constitute a very useful tool, as found by many studies (Peyron Lassauzay and Woda 2002; Lassauzay et al 2000; Peyron et al 2004). The properties of these substances can be carefully adjusted to match the necessities of
specific study designs. Moreover, it has been shown that artificial test food substances, although not swallowed, are chewed similarly as are natural foods with respect to the number of strokes and particle size reduction (Fontijn-Tekamp et al 2004).

**D. Objective compared to subjective methods.**

A number of studies (Lindquist and Carlsson 1985; Slagter et al 1992a; Carlsson and Lindquist 1994; Feine et al 1994a; Feine and Lund 2006; Gunne et al 1982; Gunne 1985; Slagter et al 1992b; Stellingsma et al 2005; Geertman et al 1999) report that subjects’ ratings of chewing ability and the results of laboratory-based tests of chewing efficiency or performance are not significantly related. For example, Garrett et al (1996) found that subjects reported improved chewing ability when conventional full dentures were adjusted or replaced, but found no corresponding improvement in laboratory measures of mastication. Other investigators have argued that patient-reported measures are more sensitive than objective measures for detecting differences between prosthetic treatments (de Grandmont et al 1994; Feine et al 1994a; Feine et al 1994b; Garrett Kapur and Perez 1996). The discrepancy between patient’s perceptions and the outcomes of functional tests suggests that study subjects’ and scientists’ concepts of masticatory function differ, or that subjective and objective data assess very different aspects of masticatory behavior. Chewing duration or particle size measures are used by scientists as indications of mechanical efficiency, but patient’s ratings of ease of chewing reflect the experience of eating, which may more closely reflect stability and comfort (Garrett Kapur and Perez 1996). This is supported by the observation that self-assessments of the ease of chewing are consistent with those of general satisfaction, comfort, and stability (Tang et al 1997). Because prosthodontic therapy is an art as well as a science, laboratory-based chewing tests cannot predict the impact of treatment on patient’s quality of life, and questionnaires remain as valuable tools in the assessment of chewing (Boretti Bickel and Geering 1995).
1.2. MASTICATORY FUNCTION IN DENTATE INDIVIDUALS

Masticatory function and physiology in dentate subjects have been extensively studied (Gibbs et al 1982; Neill and Howell 1988; Plesh Bishop and McCall 1987; Lassauzay et al 2000) by various means and methods, and the influence of different factors on the variation of chewing patterns has been researched (Table 1.1). The origin of some variations is not clearly established and likely depends in some extent on morphological features (Lassauzay et al 2000), related for example, to cusp inclination (Jemt and Hedegard 1982), or malocclusion (Karlsson 1979).

A. Subjective evaluation.

Patient’s assessments of masticatory function, even though poorly correlated with objective measurements, have proven able to detect differences related to the dental state, like quality of dental treatments, number of remaining teeth (van der Bilt et al 1994), and dentofacial phenotype.

B. Food particle size reduction.

A prominent observation from these studies is the large variability between individuals in terms of the particle size reduction of comminuted foods.

i) “Good” chewers and “bad” chewers.

Subjects who exhibit greater particle size reduction are regarded as “good” chewers, while individuals who produce coarser boluses, are considered “bad” chewers. “Good” chewers and “bad” chewers tend to preserve their chewing habits in terms of particle size reduction regardless of the dental state, prosthetic treatment, or food characteristics (Fontijn-Tekamp et al 2004).

“Bad” chewers will not necessarily chew longer before swallowing than good chewers; as a consequence, the former will, on average, swallow larger food particles (Fontijn-Tekamp et al 2004).
ii) Influence of age on particle size reduction.

If confounding factors such as missing teeth are controlled for, then ageing alone has little impact on the ability of subjects to reduce food into small particles (Mishellany-Dutour et al 2008; Wayler and Chauncey 1983; Feldman et al 1980; Fontijn-Tekamp et al 2000; Hatch et al 2001; Carlsson 1984; Helkimo Carlsson and Helkimo 1978; Lucas and Luke 1986; Ship et al 1996). It was demonstrated that aged dentate subject can exhibit increased particle size reduction, as compared to their younger counterparts (Mishellany-Dutour et al 2008).

C. Masticatory muscle force.

Analysis of masticatory muscle force has identified differences with respect to gender and age, which could be explained in part by variations in masticatory muscle mass (Newton et al 1987). Masseter muscle cross-sectional area and thickness is related to craniofacial morphology (Weijs and Hillen 1986; Bakke et al 1992; Raadsheer et al 1996, 1999), and body size (Raadsheer et al 1996; Shiau et al 1999).

The masticatory muscle force appears to be decreased in women, as compared to men, and in aged individuals, as compared to younger ones (Hatch et al 2001). Most studies suggest that masticatory muscle force does not represent a strong predictor of masticatory function in dentate individuals (Hatch et al 2001), since its influence on chewing function is relatively minor compared to other factors, such as craniofacial phenotype, dental state, or prosthetic treatment.

D. Masticatory muscle EMG.

Electromyographic records in dentate individuals have demonstrated differences in masticatory function related to food texture, as well as to subject factors. Lassauzay et al (2000) detected large variation in EMG recordings between dentate individuals, despite the use of controlled model foods and rigorous selection of the subjects by oral criteria. See also (Brown et al 1994).
Lassauzay et al (2000) also found differences between cycles during a masticatory sequence with the largest difference observed between the first and second cycles), in accord with other studies (Lucas et al 1986b; Schindler Stengel and Spiess 1998).

i) Response to different textures.
Analysis of EMG records have shown that with increased food toughness, dentate subjects chew for a longer time with relatively unchanged masticatory force (Shiau Peng and Hsu 1999).

Plesh et al (Plesh Bishop and McCall 1986) found a slower chewing frequency (calculated by dividing the number of chewing cycles by the chewing duration) when dentate subjects changed from chewing a non-comminutable soft to a hard chewing gum. However, Horio and Kawamura (Horio and Kawamura 1989) observed no differences in chewing frequency in dentate individuals chewing various foods.

ii) Influence of gender.
Analyzing EMG records, no significant difference between males and females has been established for the number of cycles in a masticatory sequence. However, a higher EMG activity per cycle and per sequence was demonstrated in males versus females (Peyron et al 2004; Neill and Howell 1988; Youssef et al 1997).

It was shown also that men have shorter chewing cycles (higher chewing frequency) than women (Youssef et al 1997). The increased frequency observed in men as compared to women was attributed to the greater muscle strength found in males. It may be explained by a larger cross-sectional area of muscle and/or larger muscle fiber diameter. Moreover, for a given level of EMG activity, it was suggested that the jaw muscles of men produce more masticatory force than do the jaw muscles of women (Tate et al 1994).
iii) Influence of age.

Age is another factor which influences masticatory performance. It is documented that there is a progressive decline in total body muscular mass (Porter Vandervoort and Lexell 1995) and mechanical performance of muscles as age advances (Peyron et al 2004).

The adaptation of the masticatory function to ageing is seen as an increase of total EMG activity, number of cycles, and sequence duration. Specifically, aged dentate subjects use significantly more chewing strokes to reach swallowing threshold than younger dentate subjects, with increased particle size reduction, longer chewing sequence duration, and greater total EMG activity (Mishellany-Dutour et al 2008). As such, the formation of a food bolus ready to be swallowed uses more energy in aged subjects (Mishellany-Dutour et al 2008; Peyron et al 2004). However, the EMG per cycle was not significantly different between the young and old dentate groups (Mishellany-Dutour et al 2008; Feldman et al 1980; Peyron et al 2004).

E. Jaw movements.

Mandibular kinematics recordings demonstrated significant differences between individuals, (for example gender related, or specific to different dentofacial types) and also within the same individual, depending on dental state, dental treatments. Variation between subjects eating the same food was documented by Jemt (Jemt 1984). His data suggests that the chewing movements are more related to individual behavior and type of test bolus, than to differences in oral status.

i) Influence of food texture.

Changes in food texture may affect the chewing frequency, as found by Plesh et al (Plesh Bishop and McCall 1986). They found a slower chewing frequency when dentate subjects switched from chewing a non-comminutable soft to a hard chewing gum. Other data (Horio and Kawamura 1989) revealed no differences in chewing frequency in dentate individuals chewing various foods.
ii) Influence of craniofacial type.

Class III individuals exhibit a low efficiency pattern, as compared to Class I and Class II subjects, as documented by a number of studies (Zimmer et al 1991 1992; Ehmer and Broll 1992; Ingervall et al 1979; Miyawaki et al 2001; Yashiro and Takada 2004; Wilding and Lewin 1994).

iii) Influence of gender.

It was shown that men have shorter chewing cycles than women, determining a higher chewing frequency (Youssef et al 1997). However, another study found no significant gender related difference in chewing frequency (Kiliaridis Karlsson and Kjellberg 1991).

A higher velocity of the chewing cycle was found in men, as compared to women (Youssef et al 1997; Peyron et al 2004; Neill and Howell 1988). The vertical amplitude of the jaw movement during chewing is also greater in men than in women (Peyron et al 2004; Neill and Howell 1988; Youssef et al 1997).

1.3. MASTICATORY FUNCTION IN CONVENTIONAL FULL DENTURE WEARERS

Fully edentulous patients, even those with well-fitting dentures, can be regarded as individuals having oral disabilities, with reduced capacity in various functions of the stomatognathic system such as chewing force, chewing efficiency and oral perception of specific food characteristics (Helkimo Carlsson and Helkimo 1978; Lucas and Luke 1986; Fontijn-Tekamp et al 2000; Akeel Nilner and Nilner 1992; Jiffry 1983; Haraldson Karlsson and Carlsson 1979; Kelly 1975; Miralles et al 1989; Slagter et al 1992a,b; Slagter et al 1993; Veyrune and Mioche 2000; Slagter Bosman and Van der Bilt 1993; Kapur and Soman 1964). Table 1.2 presents findings of a number of studies evaluating the masticatory function of conventional full denture wearers, as compared to dentate individuals.
In conventional full denture wearers, masticatory efficiency is considered to be decreased by 50 to 85% compared with subjects with intact dentition (Carlsson 1984; Kapur Soman and Yurkstas 1964; Feldman 1983; Garcia Perlmuter and Chauncey 1989; Wayler et al 1984).

**A. Subjective evaluation.**

The altered masticatory function in conventional full denture wearers has been documented by studies using questionnaires to rate chewing ability, food preference, and patient satisfaction (Geertman et al 1996; Wayler and Chauncey 1983; Wayler et al 1984; Slagter et al 1992a).

**B. Food particle size reduction.**

It was established that denture wearers make a much coarser bolus than dentate subjects (Mishellany-Dutour et al 2008; Wayler and Chauncey 1983; Slagter et al 1993; Fontijn-Tekamp et al 2000). The increased chewing activity in conventional full denture patients does not lead to a better comminution of food. Therefore, the increased number of cycles does not compensate the impaired masticatory performance in conventional full denture wearers (Wayler and Chauncey 1983; Hirai et al 1994; Mishellany-Dutour et al 2008).

**C. Masticatory muscle EMG.**

Mishellany-Dutour et al (2008) studied masticatory function by EMG methods in conventional full denture wearers versus dentate individuals, while chewing groundnuts and carrots. They showed that mastication in conventional full denture wearers reflects an effort to compensate for their stomatognathic system deficiency by an increase in the number of chewing cycles, duration of mastication sequence and EMG activity per sequence.
i) Chewing duration, number of chews and chewing frequency.

Veyrune et al (Veyrune et al 2007) compared the EMG recordings in dentate individuals versus conventional full denture wearers, using gummy model foods. They found that preparing the same food bolus for swallowing required a greater number of masticatory cycles and a longer duration of mastication for conventional full denture wearers than for dentate subjects. The number of masticatory cycles increased more with hardness in denture wearers than in dentate subjects (Veyrune et al 2007). Another study (Veyrune and Mioche 2000), using meat as test food, found no differences in chewing duration and individual chewing cycle duration between conventional full denture and dentate groups, as previously mentioned by Slagter et al (Slagter et al 1993, 1992a), who used artificial foods in their determinations.

The frequency of chews was found unaffected by food texture or dental state (Slagter et al 1993), and seems to be improved by stable dentures (Garrett et al 1996; Garrett Kapur and Perez 1996).

ii) Peak amplitude.

Differences between denture wearers and dentate subjects were also encountered for the amplitude of muscular activity, particularly associated with the masseter muscles rather than the temporalis muscles. Denture wearers present lower peak amplitudes, as compared to their dentate counterparts. During a normal chewing cycle, the maximal crushing force is expected to occur during the period of tooth contact. Denture wearers may limit this load due to pain from the oral mucosa if this is pinched by the denture (Veyrune and Mioche 2000).

Slagter et al (1993) found that peak amplitudes of activity during mastication and maximal voluntary clenching were more than twice as large in the dentate subjects as in the denture wearers. In both groups, chewing softer food was associated with lower peaks of activity than with firmer food. However, the peak amplitudes were weakly related to masticatory efficiency measurements, such as
reduction in particle size (Slagter et al 1993), so the impact of chewing with low amplitude, and thus low force, on chewing efficiency is not clear (Ingervall and Hedegard 1980).

**iii) Area under EMG curve.**

In general, conventional full denture wearers show lower EMG muscle activity during chewing compared to dentate individuals (Karkazis and Kossioni 1998). Veyrune and Mioche (Veyrune and Mioche 2000) performed EMG recordings from individuals chewing different samples of beef, and also found that muscle work during chewing was reduced and poorly adapted to food texture, in denture wearers, as compared to dentate subjects. It was also found that conventional full denture wearers failed to increase EMG activity per cycle in response to hardness of food (Veyrune et al 2007).

Another study found no significant difference in the EMG per cycle between dentate subjects and denture wearers (Mishellany-Dutour et al 2008). Other studies have found an increase (Veyrune et al 2007) or a decrease in EMG activity per cycle in denture wearers (Kapur and Garrett 1984; Slagter et al 1993; Veyrune and Mioche 2000). When difficult to chew food is offered, such as meat, full denture wearers may not accomplish mastication. They reject the food or display a markedly decreased EMG activity (Veyrune and Mioche 2000), indicating that non-prepared pieces of food are being swallowed. It was also been shown that, for a given food, only minimal variations occur as the hardness of the same food is increased, regardless of whether natural or model foods were used (Peyron Lassauzay and Woda 2002; Peyron et al 2004; Slagter et al 1993; Jemt and Hedegard 1982).

Garrett et al (1996) studied the effects of improvements of poorly fitting dentures and new dentures on masseter EMG activity during chewing. The results revealed that new dentures or the stabilization of poorly fitting dentures through occlusal correction and restoration of occlusal vertical dimension permits patients to use less muscle while chewing; also the chewing rate is considerably improved. In contrast, the loss of vertical dimension has little effect on temporalis activity; these muscles are particularly responsible for guiding mandibular motion (Blanksma Van Eijden and Weijs
1992), and their contraction was found to be basically similar for both dentate and edentulous subjects.

D. Jaw movements.

Jaw tracking methods found, in accord with EMG measurements, that conventional full denture wearers exhibit a longer duration of mastication, and an increased number of chewing cycles (Jemt 1981; Slagter et al 1993, 1992b; Veyrune et al 2007; Mishellany-Dutour et al 2008).


The shortened vertical displacement and the slowed velocity of the opening and closing phases probably correspond to denture stabilization needs (Veyrune et al 2007). Moreover, the effect of dental state on the movement and the velocity of the mandible appears to weaken with advancing age. These differences between chewing performed with natural or artificial dentitions were less accentuated with the elderly individuals (mean age 80 years), as found by Karlsson et al (1991).

E. Significance of the loss of periodontal receptors.

The extent in which the loss of teeth and elimination of periodontal afferent inputs affects the neurophysiological mechanisms regulating mastication is not fully established. Karkazis and Kossioni (Karkazis and Kossioni 1998) found that, despite the great individuality in the particular characteristics of EMG patterns, there are similar general tendencies when chewing soft or hard foods in dentate persons and denture wearers. This indicates that functional adjustments to food consistency are mainly due to a powerful peripheral input modifying the basic cyclic pattern of activity (Karkazis
and Kossioni 1998). It can be speculated then that while in healthy dentate subjects periodontal ligament mechanoreceptors have a considerable influence on mechanism regulating mastication, in experienced denture wearers their role is successfully taken over by other receptors (Karkazis and Kossioni 1998).

1.4. MASTICATORY FUNCTION IN SUBJECTS WITH UPPER CONVENTIONAL FULL DENTURES AND LOWER IMPLANT-SUPPORTED OVERDENTURES


Mandibular implant-supported overdenture represents one of the successful treatment alternatives in edentulous patients. It seems that most of the deficiencies encountered with lower conventional full dentures can be efficiently alleviated.

Some data on masticatory function in subjects with upper conventional dentures and lower implant-supported overdentures are presented in Table 1.3., as compared to individuals with upper and lower conventional dentures.

A systematic review performed by Fueki et al (2007) concluded that the combination of a mandibular implant-supported overdenture and maxillary conventional conventional full denture provides significant improvement in masticatory performance compared to conventional full dentures both in the mandible and maxilla for a limited population having persistent functional problems with an existing mandibular conventional full denture due to severely resorbed mandible.
A. Subjective evaluation.

After implant treatment, patients report high levels of satisfaction regarding various aspects of their denture function and they are more satisfied than patients with similar problems who receive a conventional denture without implant support (Stellingsma et al 2005; Cune et al 2005; Cune de Putter and Hoogstraten 1994; Naert et al 1999; Naert Alsaadi and Quirynen 2004; Thomason et al 2003; Geertman et al 1996; de Grandmont et al 1994; Gunne and Wall 1985). However, the data on patient satisfaction reported by Garrett et al (1998) found no significant advantage of the implant-supported overdentures, as compared to conventional dentures.

Tang et al (1999) compared two treatments for edentulous patients: the “hybrid” overdenture (supported by 2 implants and mucosa/bone) and the long bar overdenture, which acts more like an implant bridge, having more implant support (4), and very little mucosal support. All patients preferred the long bar overdentures, despite the fact that objective functional assessments by EMG showed no significant differences between the two alternatives (Tang et al 1999).

B. Food particle size reduction.

Objectively, subjects with mandibular implant-supported overdentures need 1.5 to 3.6 times fewer chewing strokes than conventional full denture wearers to obtain a similar reduction in food particle size (Geertman et al 1994). Van Kampen et al (van Kampen et al 2004) also reported that the number of chewing cycles until swallowing slightly decreased after implant treatment, and a significantly better masticatory performance was obtained. However, in another study, no significant advantage in masticatory performance evaluated by the size of chewed particles was found for implant-supported overdentures compared with conventional dentures (Garrett et al 1998).

The degree of mandibular overdenture support, 2 vs. 4 implants (Geertman et al 1994) did not influence the masticatory performance.
C. Masticatory muscle EMG.

Karkazis (Karkazis 2002) showed that implant-supported overdenture wearers presented significantly higher EMG activity during chewing compared to denture wearers and in some instances the recorded values were even higher than those of the young dentate persons.

In general when a conventional full denture is exchanged for a more stable and well supported prosthesis, various chewing parameters are expected to improve. On the other hand, individual analysis of the EMG tracings revealed an individual basic EMG pattern stable in repeated registrations. This finding suggests the existence of a stable background mechanism obviously capable of modifying itself with changes in the oral situation: teeth – dentures – implants (Karkazis 2002).

Van der Bilt et al (2006) evaluated the muscle activity in edentulous subjects who received 2 lower implants. They performed separate EMG recordings with the lower dentures unattached and unsupported by the implants, and with the prostheses attached to the implants, while chewing natural and artificial foods, as well (van der Bilt van Kampen and Cune 2006). Their findings show that when subjects chewed with an unsupported denture, the masseter and temporalis muscle activities did not differ significantly, whereas while chewing with an implant-supported denture the muscle activities of the temporalis muscles were significantly larger than those of the masseter muscles.

D. Significance of the loss of periodontal receptors and addition of implants.

From a neurophysiological perspective, implant-supported overdentures present fundamental differences. The lack of periodontal ligament mechanoreceptors with their specific functions results in important alterations of the oral sensory perception skills (Karkazis 2002), with loss of inhibitory reflexes. The reduced tactile function could lead to an impaired control of the maximum biting force which is well reflected in the high EMG activity during chewing (Karkazis 2002).

However, activation of periosteal mechanoreceptors, or other intra-osseous neural endings through bone deformation, might be an explanation for the capacity of most implant patients to
discriminate interocclusal thickness and perceive loads, a situation similar to the “osseoperception” seen in patients with osseo-integrated amputation prostheses (Jacobs and van Steenberghe 1993).

1.5. MASTICATORY FUNCTION IN SUBJECTS WITH UPPER CONVENTIONAL FULL DENTURES AND LOWER IMPLANT-SUPPORTED FIXED PROSTHESES

The fully implant-supported fixed prosthesis represents a further upgrade from the implant-supported overdenture, with little to no tissue contact, and the feature of not being removable is greatly appreciated by patients.

A. Subjective evaluation.

Lindquist & Carlsson (Carlsson and Lindquist 1994; Lindquist and Carlsson 1985) found that treatment with implant-supported fixed prostheses, produced a marked improvement of the patients assessment of their chewing ability, and of the results of chewing tests (particle size reduction and masticatory force).

Feine et al (1994a) compared two different treatments for the lower jaw (long bar implant-supported overdentures and implant-supported fixed prostheses) for edentulous patients treated with upper conventional dentures. They found that, despite the fact that the long bar implant-supported overdenture treatment proved no less efficient in functional tests (e.g. EMG activity, chewing duration), scoring even better than the implant-supported fixed prosthesis in some instances, patients generally preferred the fixed prosthesis. It seems that patient’s perception plays an important role in the acceptance of prosthesis and the overall treatment outcome. This is also supported by the findings of Fueki et al (Fueki et al 2007), who established that mandibular fixed implant-supported prostheses provide significant improvement in masticatory function compared to mandibular conventional full dentures in subjects dissatisfied with their previous dentures.
1.6 RATIONALE OF OUR STUDY

Clinically, it is accepted that implant supported/retained prostheses offer better masticatory function than traditional prostheses that are not supported or retained by teeth or implants (Geertman et al 1996; de Grandmont et al 1994; Lindquist and Carlsson 1985). However, solid evidence is lacking to fully support this, and contrary findings are found in the literature (van Waas Kalk and Engels 1992; Kalk van Waas and Engels 1992; Haraldson et al 1988; Garrett et al 1998). For example, Haraldson et al (1988) reported no significant improvement in chewing ability after treatment with an implant-supported mandibular overdenture compared to a conventional full denture. As a second example, Garrett et al (1998) performed a randomized clinical trial comparing the efficacy of mandibular implant-supported overdentures and conventional dentures in diabetic patients, in regard of masticatory performance. The mandibular implant-supported overdentures and conventional dentures were considered functionally equivalent in terms of their ability to comminute test foods.

There is insufficient data to explain how the loss of natural dental units and the replacement with artificial dental units often results in poorer masticatory function. A possibility is that the replacements, at least for traditional removable dentures, are not as retentive or stable as their natural predecessors (Slagter Bosman and Van der Bilt 1993). Alternatively, the loss of periodontal feedback might lead to impaired masticatory function from loss in the fine motor control of the jaw (Trulsson and Johansson 1996; Trulsson and Gunne 1998).

Our pilot project aimed to develop and evaluate a novel method using model foods, engineered to have specified physical properties, to study the masticatory sequence in human subjects. Moreover, patients without and with periodontal sensory feedback were studied, and the stability and retentiveness of the lower dentitions varied according to the patients’ dental status and method of rehabilitation. Five groups of subjects were identified, albeit limited by small sample sizes (N=5 for each subject group).
A group of subjects having natural dentition was used to evaluate the masticatory function while chewing the model foods of different consistencies. The individuals in the four other study groups were edentulous in the maxillary arch and accustomed to wearing conventional upper dentures. One of the study groups consisted of patients with lower natural dentition, the other three groups designated individuals treated in the lower arch with either a conventional full denture, an implant-supported overdenture, or an implant-supported fixed prosthesis --- enabling a comparison of different treatment modalities for the edentulous mandible, accepting the limitations of the small sample size.

The objective evaluation of chewing function relied on a novel method to standardize the dimensions, color, and taste/smell of test food substances, with consistent, well characterized properties, for administration to different patients at different times (Barrangou Daubert and Foegeding 2006a; Barrangou Daubert and Foegeding 2006b; Brown et al 2003; Foegeding et al 2003). The timing and symmetry measures in muscle activation during chewing and the level of EMG activity were anticipated to bear directly on differences in the manner mastication is controlled by the central nervous system to accommodate differences in the textures of the model foods as well as putative differences related to the prosthodontic treatments. A long term goal of this study is to better understand the functional impact of implant placement in the treatment of the edentulous deficient mandible.
2. MATERIAL AND METHODS

2.1 HUMAN SUBJECTS

Subjects were recruited for each of the five treatment groups from the University of North Carolina School of Dentistry. The initial 20 subjects that were recruited and tested were all edentulous in the maxilla, wearing an upper conventional full denture, and in the mandible had some combination of natural teeth, crowns, and fixed partial dentures (5 subjects, group CD/ND), or wore a conventional full denture (5 subjects, group CD/CD), an implant-supported overdenture (5 subjects, group CD/OD), or an implant-supported fixed prosthesis (5 subjects, group CD/FP). An additional group of 5 subjects with natural teeth in both arches was identified after the initial 20 subjects had been tested. From the total pool of potential study subjects contacted (n = 35), seven declined to participate, and three failed to qualify due to the inability to comply with the study protocol or to comminute the model foods.

All study subjects were required to be 45 to 85 years old, to be able and willing to follow study procedures and instructions, and to give written informed consent. Subjects in the dentate group (ND/ND) were required to have at least 10 dental units (natural teeth, and/or tooth supported crowns or fixed partial dentures) in each jaw. Subjects in all the other groups were required to have an upper conventional full denture of satisfactory adaptation and function. Subjects in the CD/ND were required to have at least 10 dental units (as defined above) in the mandible. Subjects in the other three groups were required to have in the mandible one of the following: a conventional denture, with satisfactory adaptation and function (group CD/CD); an implant-supported overdenture, retained/partially supported by at least 2 implants (group CD/OD); or an implant-supported fixed prosthesis, entirely supported by at least 3 implants (group CD/FP). All edentulous individuals were
required to fall within the description of class II or III of the American College of Prosthodontists (ACP) classification for complete edentulism.

Patients with uncontrolled diabetes, bruxism, class III ridge relationship, or prostheses older than 5 years were excluded from the study.

2.2. APPROVALS AND LEGAL DOCUMENTATION

Biomedical IRB approval was obtained in the fall of 2006, then renewed in the fall of 2007 to study the five additional subjects.

Potential subjects were selected from the UNC School of Dentistry patient’s pool via referrals from colleagues and faculty members. Volunteers who responded to an e-mail notice addressed to the UNC School of Dentistry faculty and staff were also considered. For those selected, a health history questionnaire, comprehensive oral evaluation, and radiographic examination, which already were available in patients charts, were consulted to confirm that potential study subjects met the inclusion criteria. Subject contact was made by telephone, at which time the subject was appointed for testing. The phone conversation did not deal with any sensitive information that could affect subject's privacy. A letter was also sent to potential study subjects, explaining in lay language the purpose of the project, inclusion criteria, testing procedures, potential benefits and risks. Legal aspects, including means of privacy protection were also dealt with in the letter.

At the initial appointment, the subject was briefly examined to confirm compliance with the inclusion criteria, then was handed a hardcopy of the informed consent to read. Questions were addressed by the principal investigator before being signed by the subject. Interviews and testing procedures took place in a special designated office with the participation of the principal investigator only.

Personal data collected from subjects included: names, telephone numbers, birth dates, street address, medical record numbers as extracted from the School of Dentistry Electronic Patient Record database, in compliance with the IRB approval terms and School of Dentistry regulations.
Subjects were identified with a unique number in all study documents that is linked to dental/medical records via code known only by the principal investigator. The study records are secured in locked areas to which only the study investigators have access. Access to electronic files is protected by password, which was known only by the study investigators.

2.3. TESTING PROCEDURES

Any questions raised by the subjects were answered before testing, details about the model foods, and study procedures were given.

Each subject was offered a calm atmosphere, so good relaxation and optimal cooperation was obtained. The individual was seated in a dental chair, in comfortable position, as determined by subject.

Chewing function was evaluated subjectively and objectively.

A. Subjective evaluation.

Chewing function was evaluated subjectively from the subject’s reported assessments. A questionnaire, designed to rate chewing ability, chewing side preference, difficulty in mouth opening and pain while chewing, as described by Ow et al (1998) – Table 2.1, was used. This questionnaire has been used in the past to assess the masticatory performance in dentate, and edentulous subjects (Ow et al 1998). The presence of parafunction was investigated also using the questionnaire of Miyake et al (2004) – Table 2.2. This questionnaire has been used in the past to assess whether oral parafunction is associated with symptoms of temporomandibular disorders (Miyake et al 2004).

B. Objective evaluation.

Chewing function was evaluated objectively using physiological measures extracted from electromyographic activity (EMG) from the masticatory muscles. The EMG was recorded while the subject chewed each of four foods on both the right and left sides of the mouth until the bolus was
ready to swallow – providing a total of eight masticatory sequences per subject for analysis. The four foods were prepared in a highly standardized manner to differ systematically in compressive load to fracture (i.e., ‘firmness’).

i) Model foods preparation and storage.

The model foods were cylindrical samples of agar gels. They were prepared from food-grade agar powder (TIC Gums, Belcamp, MD) and food-grade glycerol (Star Glycerine, USP, Procter & Gamble Chemicals, New Milford, CT) in the Food Science Department at the North Carolina State University under the supervision of Dr. Allen Foegeding. The requisite quality of the samples was established by Dr. Foegeding and the model foods were prepared following a strict protocol.

Gels contained 1.75 to 7 % w/w agar, 60% w/w glycerol and deionized water as the remaining mass. Also 0.02 grams of strawberry flavor (Mother Murphy’s, Greensboro, NC) was added to each sample to make the model food more palatable. Dispersions were made by slowly sprinkling agar powder into the water/glycerol liquid while stirring to prevent clumping. Dispersions were rapidly heated in a microwave to 90 to 95°C, then held in a water bath at 85°C for 30 min to assure complete molecule unfolding. Hot solutions were poured into cylindrical glass tubes (19 mm inner diameter and 150 mm long) having rubber stoppers at one end, held at room temperature (25 ± 2°C) for at least 2 hrs, and refrigerated (4°C) 16-24 hrs for gel formation.

Initially, several gel samples were prepared with the different agar concentrations and were tested to fracture using an Instron 5565 Universal Testing Machine (Instron Corporation, MA). The aim was to confirm the consistency in the value of fracture stress and strain for a given % agar (Figure 2.1). Briefly summarized, the test samples were removed from the preparation tubes, cut in to 19-mm height pieces, and placed between the 50-mm diameter upper plate and the 150-mm lower plate of the testing machine. The samples were compressed to 80% of their original height at a rate of 15 mm/min using a load cell of 500 N. The data were processed using Bluehill2® software (Instron Corporation, MA).
Based on data available in Dr. Foegeding’s lab, fracture stress is linearly related to % agar, as shown in Figure 2.2:

\[
\text{Fracture stress} = -5.54 + 51.9 \times \text{Agar Concentration} \quad [1]
\]

The four different concentrations of agar (1.75, 3.5, 5.25, and 7%) used in the present study resulted in gels with fracture stress values ranging roughly from 85 to 357 KPa.

Gels containing 60% glycerol have a water activity of <0.8 and are therefore considered shelf-stable. Nonetheless, gels can be held or shipped such that the temperature remains below 10°C. However, gels were made in advance only after an appointment with a certain study subject was made, in order to assure a fairly consistent period of refrigeration between gel formation and subject testing.

Samples used to evaluate mastication were cut into 1.9 cm long cylinders before subject testing, and placed into sealed bags, in order to avoid dehydration during the short storage period between cutting and testing. After refrigeration (4°C), the samples need to be equilibrated at room temperature (25±2°C) for 1 hr before testing.

ii) Masticatory muscle electromyography.

Surface muscle activity was recorded from the right (R) and left (L) side superficial masseter (MM), anterior temporalis (TA), and anterior digastric (DA) muscles using a BioEMG II electromyograph (Bioresearch Inc., 9275 North 69th Street Suite 150, Milwaukee, WI 53223, tel: 800-251-2315).

The study subject was comfortably seated. After cleaning the skin with an alcohol pad, the subject was asked to clench the teeth together to identify the borders of each muscle. Particular attention was paid to female subjects, make-up (if present) was carefully removed in order to assure a proper contact between the electrode and the skin. Also, prescription glasses were removed for the
period of the experiment, so proper exposure of the skin overlying the anterior temporalis skin was attained. Surface electrodes were placed over each muscle belly, parallel to the muscle fiber orientation (Figure 2.3). A total of 6 bipolar surface electrodes (BioFLEX, BioResearch, Milwaukee, WI) were placed on each subject’s facial skin.

The lead wires for the 6 surface electrodes were connected to the BioEMG II Amplifier. The amplified EMG signals passed through the BioEMG II computer interface box to a PCMCIA card (connected to a designated laptop computer). The PCMCIA card provided an analog to digital conversion (12 bit conversion) and data collection. The BioPAK software package was used to select the recording parameters; number of channels, sampling rate, and the duration of sampling sequence. A sampling rate of 5020 Hz for each electrode was used for this investigation.

After the electrodes were secured into position, a resting EMG was sampled, in order to visually assess the electrical activity of the involved masticatory muscles and their relaxation status. The actual experiment began only after sufficient relaxation was obtained, with nearly isoelectric EMG readings (i.e., very low amplitude electric activity recorded on all six investigated muscles, when the jaw was at rest in a postural position).

During testing, the following procedure was observed. Tap water and three cylindrical samples of each of four model foods were given to the subject, who was instructed to ingest each and chew to the point of swallowing, then to expectorate, and rinse. The subject chewed the first set of samples freely; for the second and third sets the subject was instructed to chew only on the right or left sides.

Inspection of the free chewing data obtained from the first few subjects studied revealed that the chewing side could not be reliably determined from the EMG recordings alone. Additional instrumentation was needed (e.g. Jaw Tracker, BioResearch Technologies) in conjunction with the EMG device, to consistently determine the working side/ balancing side, during free chewing. Because such instrumentation was not available, the recording of the free chewing was abandoned, and subjects were required only to furnish two masticatory sequences (right and left side) for each gel
sample, for a total of 8 masticatory sequence recordings. The two sequences (right and left side chewing) were taken to best assess the individual subject’s chewing of each gel sample, in contrast to only right or left side chewing of the sample.

During data collection, the digitized EMG signals (raw data – Figure 2.4.) were monitored for quality and reviewed on the computer screen. The digitized EMG was then saved to the computer hard drive. Thereafter, the raw data were retrieved and visualized, as needed, using Igor Pro software (Wave Metrics Inc, Lake Oswego, OR) – Figure 2.5.

iii) Processing of the EMG data.

For processing of the objective data, the digitized EMG values first were exported from the BioPAK software as text files. They were digitally filtered and quantified by calculating the root-mean-square (rms) using the LabView graphical programming system (National Instruments, Austin, TX), so positive, single summation wave forms were obtained (Figure 2.6). Values for each rms EMG were output at 2 ms intervals using a 42 ms time constant (Hylander and Johnson, 1993). The quantified rms EMG was analyzed using both Igor Pro, and analysis applications written by Dr. Chris Vinyard at the Department of Anatomy of the Northeastern Ohio Universities Colleges of Medicine and Pharmacy, in Labview software.

The rms EMG versus time relationship for each masticatory sequence was expanded along the time (bottom) axis, in order to facilitate identification of each individual chewing cycle (Figure 2.6 a, b, c). From the EMG activity profile for each muscle during each individual chewing cycle, the following three measures were extracted:

 a) Peak activity (although originally scaled in millivolts, rms EMG values were amplified, i.e., scaled, see below, by a constant to provide a reasonable range of variation; see Hylander and Johnson 1993); this is the largest value reached by a given muscle during a chewing cycle.

 b) Peak time (milliseconds, ms), the time at which the peak activity occurred during a
chewing cycle. Peak time is measured in absolute time since the start of recording.

c) Area under the curve (AUC). The total integrated area under the root-mean-squared EMG curve describing the activity over time relationship for a muscle during a chewing cycle. The area under the curve was calculated using the Simpson’s rule, which is a method for numerical integration. The AUC summed for the entire masticatory sequence is often used as a measure of the total muscle work associated with chewing a food substance (Mioche et al 1999).

Scaled values were calculated for the peak activity and AUC, in order to minimize the confounding effect of the differences in electrodes, electrode position and electrode location relative to a muscle. To measure scaled values, the largest peak activity or AUC for a given muscle during an experiment was identified. This event was given the value of 1.0 and all other values were linearly rescaled to be between 0 and 1 (Hylander et al 2000).

From the basic three measures extracted for each muscle during a chewing cycle (described above), a number of derived measures were calculated:

a) Duration of a single chew (seconds, s). The duration of chew i was arbitrarily defined as the period of time from the peak activity in the working side masseter during chew i to the peak activity in the same muscle during chew i+1, i=1 to n-1 where n is the total number of apparent chews in the masticatory sequence. If the chew cycle duration was less than 0.3 s, the chew was considered incomplete, and eliminated from all subsequent analyses. The remaining chews in the sequence re-numbered accordingly (Bhatka et al 2004; Throckmorton et al 2001).

b) Timing (milliseconds, ms) of the peak activity of the anterior temporalis muscles, digastric muscles, and balancing masseter muscle with reference to the timing of the working side superficial masseter muscle, which was arbitrarily assigned a value of zero (Hylander et al., 2000). Positive values indicated that the respective muscle’s peak firing
occurred after that of the working side masseter, while negative ones indicated that peak firing occurred before that of the working side masseter. The timing values represent the temporal asymmetry in the recruitment of the four jaw-closing muscles and the two jaw-opening muscles.

c) Duty cycle of the jaw-closing muscles (% of total cycle). For each chewing cycle, the duration of time between the first and last peak of activity in the elevator muscles was determined and represented as a percentage of the duration of the associated cycle during which the jaw muscles were active and the jaw potentially loaded.

d) Ratios of peak activity (working side anterior temporalis/masseter, balancing side anterior temporalis/masseter, temporalis working/balancing side, masseter working/balancing side, digastric anterior working/balancing) with corresponding logarithmic values, as well (Hylander et al. 2000).

In addition, three behavioral measures were extracted from each masticatory sequence:

a) Total duration of chewing (seconds, s), before expectoration (i.e., before swallowing would have occurred). This provides a measure of masticatory efficiency (Kapur et al, 1998; Lindquist and Carlsson, 1985, Jemt and Stalblad 1986; Peyron et al 2004).


c) Chewing frequency (#/s), the total number (#) of chewing cycles divided by the total duration of chewing (s). Along with bolus particle size distribution, chewing frequency is regarded as an important factor to detect impaired mastication (Woda et al 2006). Frequency is the chewing parameter with the most repeatable values between trials in a single individual (Peyron Lassauzay and Woda 2002; Lassauzay et al 2000; Youssef et al 1997).
A single file was generated, containing all the processed EMG data for the entire experiment. The obtained file was then copied into an Excel document template, having designated columns for the outcome measures. Each row contained the descriptive labels and outcome values for one chew of one sequence for one subject. The entire data set consisted of 9606 such records. The data was checked for errors and analyzed via applications written in SAS software by Dr. Greg Essick, from the Department of Prosthodontics of the School of Dentistry at the University of North Carolina at Chapel Hill.

### 2.4. DATA ANALYSIS

**A. Characteristics of subject population.**

Descriptive statistics were calculated to characterize the age and gender composition of the five groups of subjects.

**B. Subjective evaluation of chewing.**

Descriptive statistics (proportions of questionnaires answer choices) were calculated to characterize the subjects’ responses to the questionnaires.

**C. Objective evaluation of chewing.**

The **total duration of chewing** and the **chewing frequency** were analyzed using mixed model analysis of variance (Proc Mixed, SAS Institute Inc, Cary, NC). Explanatory variables included subject group (ND/ND, CD/ND, CD/OD, CD/FD, and CD/CD), percentage agar in the model foods (1.75, 3.5, 5.25, and 7 %), and subject age. Given the exploratory nature of this study, a step-wise approach was used for analysis of the objective data:

a) First, the data from only the dentate subjects (ND/ND, i.e., those without a removable prosthesis) was analyzed in order to best characterize chewing in dentate subjects.
b) A second analysis considered the dentate subjects as one group and all prosthodontically treated subjects as a single, second group of subjects. The rationale was to determine if there were differences, in general, between prosthodontically treated subjects who wear an upper full denture, and dentate subjects.

c) A third analysis then considered only the prosthodontically treated subjects to determine if these subjects could be considered equivalent in terms of their masticatory function. If not, any observed differences in chewing function could be attributed to the manner in which the mandibular arch had been treated (i.e., dentate, no treatment; edentulous, conventional full denture; edentulous, implant-supported overdenture; and edentulous, implant-supported fixed prosthesis) or to undefined differences between the four groups of subjects.

Because the total number of chewing cycles varied from 11 to 132 among the 200 masticatory sequences in the data set, other analyses used only the first 10 chews of each sequence. The following outcome measures were selected from the many possibilities for analysis: the duration of individual chews, the duty cycle of the jaw-closing muscles, the jaw-closing muscle activity (i.e., scaled values of EMG AUC), and the timing of peak muscle activity relative to the superficial masseter muscle on the working side. Explanatory variables for analysis of the duration of individual chews and for analysis of the duty cycle included the chew cycle number (1 to 10), as well as group, % agar, and age. Explanatory variables for analysis of jaw-closing muscle activity included ‘side’ (working versus balancing), ‘muscle’ (superficial masseter vs. anterior temporalis), and chew cycle number (1 to 10), as well as group, % agar, and age. Explanatory variables for analysis of the timing of peak muscle activity included ‘muscle’ (working side anterior temporalis WTA, working side anterior digastric WDA, balancing side masseter BMM, balancing side anterior temporalis BTA, balancing side anterior digastric BDA) and chew cycle number (1 to 10), as well as group, % agar, and age.
For some analyses logarithms (base 10) of the outcome measures were used to obtain normality of residuals and to equalize the variance of subsets of values associated with different levels of the explanatory variables. P-values for pair-wise comparison of multiples means were Bonferroni corrected.
3. RESULTS

3.1. CHARACTERISTICS OF SUBJECT POPULATION

The age and gender composition of the study population is presented in Table 3.1 and Figure 3.1. The mean age of the participants was 62.48 years (range = 45 to 83). Sixty percent of the participants were female. The age and gender compositions within groups roughly paralleled that of the entire study population, with the exception of the CD/CD group (20% females), and the CD/OD group (100% females).

3.2. SUBJECTIVE EVALUATION OF CHEWING

A. Evaluation of chewing ability.

The subjects’ responses to the chewing ability questionnaire can be viewed in Table 3.2 and are summarized below.

All five dentate subjects reported that they chewed well, and gave the maximum rating for the first question: how well can you chew? In contrast, none of the subjects in the CD/CD group gave the maximum rating: All individuals in this group reported that they chewed fairly well. A summary rating was calculated for each group by multiplying the number of subjects reporting each rating option by the assigned number of points (see Table 3.2), adding the results over the response options, and then dividing by 5. The summary rating for the dentate group was ‘3’ and for the CD/CD group ‘2’. The other three groups reported chewing fairly well to well, with the summary score for the CD/FD group (2.6) slightly greater than that for the CD/OD and CD/ND groups (2.4).
All but two subjects reported the ability to chew hard and soft foods. One subject in each of the CD/CD group and the CD/FD group reported being able to chew soft foods only.

All but three subjects reported a preference for hard and soft foods. Two subjects in the CD/CD group and one subject in the CD/OD group preferred only soft foods.

Half of the subjects reported no side preference for chewing; whereas, half recognized a preferred chewing side (either the right or left side). This was true for all five groups.

None of the dentate subjects reported difficulty in opening the mouth. Individuals in the CD/FD reported similarly. In the CD/ND group, two subjects reported difficulty in mouth opening, as did four subjects in the CD/OD group. In the CD/CD group two subjects encountered the problem sometimes, and one subject often.

The subjects in the dentate group and the CD/FD group did not report pain in the jaws or face when chewing. Pain was reported by only four subjects in the study and the pain occurred only sometimes. Two of the subjects were in the CD/CD group, and one subject each was in the CD/ND and CD/OD groups.

B. Evaluation of reported parafunction.

The proportions of “Yes” answers to the reported parafunction questionnaire are presented in Table 3.3 and summarized below.

No bruxism, nail biting, and biting foreign objects were reported by the subjects in this study (Figure 3.2.).

One of the dentate subjects reported sleeping on one side. Sleeping on one side was reported to the greatest extent by the CD/OD group (4 subjects), followed by the CD/ND and CD/FD groups (3 subjects each), then the CD/CD group (one subject).

Leaning on the palm was reported by the CD/OD group (2 subjects), followed by the CD/ND and CD/FD groups (one subject each).
Gum chewing represented a habit of two of the dentate subjects. It was also reported by one individual in each of the CD/ND, CD/OD and CD/FD groups.

Chewing on one side only was reported by three of the CD/CD group members, and to a lesser extent by the subjects in the CD/FD group (2 subjects) and the CD/OD group (one subject).

One subject in each the dentate and CD/OD groups reported tongue, cheek or lip biting; whereas, three subjects in the CD/ND group (60%) and two subjects in the CD/FD group reported this problem.

Overall, the most parafunction-related items were reported by subjects with dental implants, and the least by subjects with conventional upper and lower dentures.

3.3. OBJECTIVE EVALUATION OF CHEWING

The test procedures averaged about one hour in duration for each subject, including time for completion of paperwork, instructions regarding the testing session, filling out the questionnaires, and actual EMG testing. The majority of individuals felt indifferent about the properties of the gels, a few really liked the taste and texture, and a few disliked them. Even though the subjects were instructed to chew on the gels as if they were real food, there is a possibility that some subjects regarded the model food samples as chewing gum. On the other hand, it is understandable for those who really liked the gels, to chew more than required, and for those who did not, to chew less than necessary. Because the sizes of bolus particles were not measured, it is impossible to assess the quality of the chewed material. Some of the subjects complained about the gels being “slippery”, almost escaping the triturating action of the jaws (this was most often encountered with the “soft” ones – 1.75 % and 3.5 %), while other subjects complained that the chewed material was caught between their dentures and oral tissue.
**A. Total duration of chewing**

For each group of subjects, the total duration of chewing increased with the % agar in the food samples. The relationship was well described by a power function:

\[ D = c \cdot (\%\text{Agar})^n \]  

where \( D \) is the total duration of chewing, \( c \) is a multiplicative constant expressing the predicted duration of chewing samples with 1% agar, and \( n \) is the power function exponent, expressing the rate at which the duration increased with increases in % agar. The logarithmic form of the power function in equation [2] enabled estimates of \( c \) and \( n \) to be obtained by simple linear regression:

\[ \log_{10}(D) = \log_{10}(c) + n \cdot \log_{10}(\%\text{Agar}). \]  

where \( \log_{10}(c) \) is the estimated y-intercept and \( n \) is the estimated slope of the linear relationship.

**i) Dentate subjects only.**

On average, dentate subjects chewed the least firm (1.75% agar) samples 17.3s and the most firm (7% agar) samples 31.5s. The total duration of chewing increased as a power function of % agar with exponent \( n=0.414 \) (\( p<0.0001 \); see Figure 3.3 and Table 3.4). This indicates, e.g., that increasing the agar concentration 2.66 times is predicted to increase the total duration of chewing by 50% in this subject group.

**ii) Prosthodontically treated versus dentate subjects.**

The mean, total duration of chewing versus percentage of agar is plotted in Figure 3.4 for the 20 prosthodontically treated subjects and compared to the mean data obtained from the five dentate subjects. The prosthodontically treated subjects chewed 36% longer than the dentate subjects, on average. However, the duration of chewing did not differ significantly for the two groups of subjects (\( p > 0.11 \)), nor was the subject group x \( \log_{10}(\% \text{Agar}) \) interaction statistically significant (\( p > 0.37 \).
Thus, neither the parameter $c$ nor $n$ differed significantly as a result of prosthodontic treatment when all treatments were considered to have the same effect on chewing (Table 3.4).

iii) Prosthodontically treated subjects only.

However, when considered separately, the duration of chewing varied significantly among the four prosthodontically treated subject groups ($p<0.0017$; see Figure 3.5). An almost two-fold difference was observed between subjects with implant-supported fixed prostheses in the lower arch compared to subjects with lower natural teeth. The two groups differed statistically. In addition to a main effect of group, the subject group x $\log_{10}$(% Agar) interaction was statistically significant ($p<0.02$), suggesting that the exponent $n$ differed among groups of subjects. The exponent $n$ was highest for the subjects with upper and lower conventional full dentures (0.6), suggesting that they responded most strongly to differences in food firmness by chewing different lengths of time. However, a separate analysis of variance of the exponent $n$, calculated for each individual subject, failed to identify statistically significant differences among the four groups ($p>0.26$; see Table 3.4 for values).

iv) Effect of age.

There was no evidence to suggest that the subjects’ age affected their total duration of chewing ($p>0.70$).

B. Chewing Frequency

i) Dentate subjects only.

In contrast to the total duration of chewing, the chewing frequency of the dentate subjects was not affected by the % agar in the model foods ($p>0.81$; Figure 3.6). On average, the subjects took 1.55 chews/s while chewing the least firm (1.75% agar) samples and 1.60 chews/s while chewing the
most firm (7% agar) samples (see also Table 3.5). The subjects were also remarkably similar in their chewing frequencies, varying from 1.36 chews/s to 1.82 chews/s.

**ii) Prosthodontically treated versus dentate subjects.**

The mean chewing frequency versus percentage of agar is plotted in Figure 3.7 for the 20 prosthodontically treated subjects and compared to the mean data from the dentate subjects. The prosthodontically treated subjects chewed 0.20 chews/s slower than the dentate subjects, on average. However, the chewing frequency did not differ significantly between the two groups (p > 0.20), nor was the subject group x log_{10}(%Agar) interaction statistically significant (p > 0.29). Thus, the chewing frequency was affected by neither food firmness nor prosthodontic treatment when all treatments are considered to have the same effect on chewing.

**iii) Prosthodontically treated subjects only.**

The mean chewing frequency versus percentage of agar is plotted in Figure 3.8 for the four groups of prosthodontically treated subjects. The subjects with upper and lower conventional dentures (group CD/CD) took 1.58 chews/s on average (similar to dentate subjects), compared to only 1.11 chews/s taken by subjects with implant-supported overdentures (group CD/OD; see Table 3.5). Although the chewing frequency did not vary statistically among the four prosthodontically treated subject groups on average (p>0.12), the subject group x log_{10}(%Agar) interaction was statistically significant (p<0.05). Comparison of the group means at each level of food firmness revealed that the chewing frequency was significantly higher for the CD/CD than for the CD/OD group for foods with 1.75% agar (p<0.05). The differences between these two groups were not statistically significant at higher concentrations because the subjects who wore conventional upper and lower dentures chewed progressively slower as the firmness of the model food samples increased.
iv) Effect of age.

There was no evidence to suggest that the subjects’ age affected their frequency of chewing (p>0.42).

C. Duration of single chews

The following analyses were performed only for the first 10 chews in each masticatory sequence.

i) Dentate subjects only.

The average duration of a single chew was 0.621 s, but varied significantly, albeit modestly, with the firmness of the food samples, as assessed by the % agar in the samples (p<0.03; Figure 3.9). Comparison of the means at the different % agar levels revealed that the chews were longest in duration for the 1.75% agar samples (0.667 s) and shortest for the 3.5% agar samples (0.613 s). No other means differed statistically.

The duration of the chewing cycle also varied with chew number (p<0.0001; Figure 3.10). Specifically, the duration of the 1st chew (0.742 s) was longer than the following nine chews, significantly so for all except the second, fifth, and ninth chew.

ii) Prosthodontically treated versus dentate subjects.

Inspection of the data plots shown in Figure 3.11 suggests that the chews were longer for the prosthodontically treated subjects than for the dentate subjects, and that the difference between the two groups increased with firmness of the model foods, as assessed by the % agar in the samples. Consistent with this observation, the subject group x log$_{10}$(%Agar) was significant (p<0.009), although the main effect of group was not (p>0.17). Comparison of the means for the two groups at each concentration of agar failed to identify a statistically significant difference (p>0.05).
As for the dentate subjects, the duration of the chewing cycle varied with chew number for
the prosthodontically treated subjects (p<0.0001; Figure 3.12). Although the plots for the two groups
deviate notably for the initial chews, the two groups did not differ statistically in the pattern of
variation (p>0.52 for subject group x chew number interaction), and the pattern of variation was not
affected by the firmness of the model foods (p>0.99 for log_{10}(\% Agar) x chew number interaction).

iii) Prosthodontically treated subjects only.

The mean duration of the chewing cycle is plotted in Figure 3.13 for the four groups of
prosthodontically treated subjects. Differences between groups are suggested upon visual inspection;
however, the duration did not vary statistically among the four prosthodontically treated subject
groups on average (p>0.26). The group x log_{10}(\% Agar) interaction was statistically significant
(p<0.003); however, comparison of the group means at each level of food firmness failed to identify a
statistically significant difference (p>0.05).

A significant effect of \% agar was also detected (p<0.0001). On average, the duration of a
single chew was longer for the higher two concentrations of agar (mean = 0.795 s) than for the lower
two concentrations of agar (mean = 0.730 s). No other difference between concentrations was
statistically significant.

The duration of the chewing cycle also varied with chew number (p<0.0001). The four
groups did not differ in the pattern of variation (p>0.22 for subject group x chew number interaction),
and the pattern of variation was not affected by the firmness of the model foods (p>0.24 for log_{10}(\% 
Agar) x chew number interaction). Thus, the mean data for all prosthodontically treated subjects
shown in Figure 3.11 sufficiently describes the pattern of variation for each group.

iv) Effect of age.

There was no evidence to suggests that the subjects’ age affected the duration of individual
chews (p>0.52).
v) Chew to chew variation in cycle duration.

The coefficient of variation (cv) of the chew duration was calculated and analyzed to determine if the variance in duration varied significantly among the five groups of subjects or among the model food samples that varied in firmness (Figure 3.14). Only chews 6-10 were considered in this analysis to avoid any systematic variation associated with the first five chews. The estimates of cv were found to vary among groups (p<0.006) and concentrations of agar (p<0.02).

The subjects who wore conventional upper and lower dentures were most variable (mean cv=26%) and statistically more variable than the dentate subjects or the subjects with implant-supported fixed prosthesis (mean cv = 11 and 14%, respectively), who were the least variable. No other differences between groups were statistically significant.

Variability from chew-to-chew increased with the firmness of the model foods, differing statistically between the 1.75% agar samples (mean cv = 16%) and 7% agar samples (mean cv = 23%). No other differences between concentrations were statistically significant.

D. Duty cycle of the jaw-closing muscles.

The following analyses were performed accounting for the first 10 chews only in each masticatory sequence.

i) Dentate subjects only.

For the dentate subjects, the duty cycle of the jaw-closing (‘elevator’) muscles, expressed as a percentage of total cycle duration, averaged 10.2% and did not vary with the firmness of the model foods (p>0.09; Figure 3.15). In contrast, the duty varied significantly with the chew number (p<0.05; Figure 3.16), being lowest for the first chew (6%) and highest for, and statistically different from, the 3\textsuperscript{rd} and 6\textsuperscript{th} chews (~12.7%).
ii) Dentate subjects versus prosthodontically treated individuals.

Inspection of the data plots shown in Figure 3.17 shows that the duty cycle was longer for the prosthodontically treated subjects (mean = 13.6%) than for the dentate subjects (mean = 10.2%). Consistent with this observation, the subject group x log\(_{10}(\%\text{Agar})\) was significant (p<0.05), although the main effect of group was not (p>0.18). Comparison of the means for the two groups at each concentration of agar failed to identify a statistically significant difference (p>0.05).

As for the dentate subjects, the duty cycle varied with chew number for the prosthodontically treated subjects (p<0.01; Figure 3.18). Although the plots for the two groups deviate notably for the initial chews, the two groups did not differ statistically in the pattern of variation (p>0.12 for subject group x chew number interaction), and the pattern of variation was not affected by the firmness of the model foods (p>0.29 for log\(_{10}(\%\text{Agar})\) x chew number interaction).

iii) Prosthodontically treated subjects only.

The elevator duty for individuals treated with different types of prostheses is shown in Figure 3.19. The duty cycle averaged a high 19.8% for the subjects with implant-supported overdentures and a low 9.7% for subjects with natural lower teeth. However, neither the effect of group nor the subject group by log\(_{10}(\%\text{Agar})\) interaction attained statistical significance due to the high variability among subjects in some groups (p>0.07 and p>0.09, respectively).

The duty cycle varied with chew number (p<0.01). The four groups did not differ in the pattern of variation (p>0.24 for subject group x chew number interaction), and the pattern of variation was not affected by the firmness of the model foods (p>0.54 for log\(_{10}(\%\text{Agar})\) x chew number interaction). Thus, the mean data for all prosthodontically treated subjects shown in Figure 3.19 sufficiently describes the pattern of variation for each group.
iv) Effect of age.

Values of the duty cycle are plotted as a function of the subjects’ ages in Figure 3.20. As suggested by the figure, the duty cycle decreased with age (p<0.007). There was no evidence to suggest that age had a different effect on different groups of subjects (p>0.54 for subject group x age interaction). This suggests that the jaw-closing muscles are maximally active during a progressively shorter period of the chewing cycle as one ages.

E. EMG area-under-curve for the jaw-closing muscles

For each subject, the areas under the EMG curve of each muscle across the first ten chews were scaled to the maximum values attained for the respective muscles during the entire experiment for that subject, providing measures of the relative ‘work’ for each jaw-closing muscle. In this context, work refers to an estimate of muscle activity and is not a conventional measure of force x distance. The maximum value that could be observed on any chew was ‘4’, a value that indicated that all four jaw-closing muscles exhibited their maximum activation observed during an experiment in that chew.

A common observation was that muscle work (activity), similar to the total duration of chewing (see Section A.), increased with the % agar in the food samples. The relationship was well described by a power function:

\[ W = c \times (%\text{Agar})^n \]  

[4]

where W is the relative muscle work or activity, based on the scaled EMG area as described above, c is a multiplicative constant expressing the predicted work required to chew samples with 1% agar, and n is the power function exponent, expressing the rate at which the work increased with increases in % agar. As for the total duration of chewing, estimates of c and n were obtained by simple linear regression.
i) Dentate subjects only.

For the dentate subjects, muscle work per chew, averaged over the first 10 chews, increased as a power function of % agar with exponent n=0.372 (p<0.0001; see Figure 3.21 and Table 3.6). This indicates that, e.g., samples with 2.97 times more agar are predicted to require 50% more muscle work for chewing.

The amount of work exerted by the superficial masseter and temporalis muscles differed (p<0.0001) and the amount of work exerted by the working and balancing side muscles differed also (p<0.0001; see left side of Figure 3.22). There was no interaction between these factors (p>0.68). On average, 79% more relative work was exerted by the masseter muscle than the temporalis muscle (in relation to their respective maximum activations); and 53% more relative work was exerted by muscles on the working, as compared to the balancing, side. In addition, a significant muscle x log$_{10}$(%Agar) interaction was detected (p<0.02), indicating that the exponent n was slightly greater for the masseter (mean = 0.426) than for the temporalis (mean = 0.319) muscles (Figure 3.23 and Table 3.7). This indicates that masseter muscle recruitment was more sensitive to changes in food firmness than the temporalis muscle. This was true for both the working and balancing sides (p>0.39 for muscle side x muscle x log$_{10}$(%Agar) interaction).

The muscle work also varied with chew number, as shown by the lower curve in Figure 3.24. The work during the 1st chew was greater than all nine subsequent chews, and the work during the 2nd chew was greater than all subsequent chews except #6 and #10 (p<0.05).

ii) Prosthodontically treated versus dentate subjects.

On average, the muscle work was 2.57 times higher for the 20 prosthodontically treated subjects than for the five dentate subjects (p<0.0001; see Figure 3.25). This means that the muscles of the prosthodontically treated subjects worked relatively harder, using a greater proportion of their maximum activity during most chewing cycles. As suggested by the figure, the muscle work exerted by both groups of subjects was equally sensitive to changes in food firmness. Consistent with these
observations, the parameter $c$ was greater for the prosthodontically treated subjects than the dentate subjects (means = 0.69 versus 0.26; $p<0.0001$), but the parameter $n$ did not differ significantly for the two groups (means = 0.338 versus 0.372; $p>0.72$). The power function parameters for the two groups are reviewed in Table 3.6.

Similar to the dentate subjects, 31% more work was exerted by muscles on the working, compared to the balancing, side of the prosthodontically treated subjects. However, in contrast to the dentate subjects, the work exerted by the superficial masseter and temporalis muscles were similar ($p>0.42$; see right side of Figure 3.22): That is, the work of the masseter muscles averaged only about 1% higher than that of the temporalis muscles, instead of 79% higher as observed for the dentate subjects. The relationships between the work of the individual muscles and food firmness did not differ statistically from those observed for dentate subjects ($p$-values $>0.08$) shown in Figure 3.23.

As for the dentate subjects, muscle work varied with chew number but the pattern of variation was different ($p<0.0001$ for subject group x chew number interaction; see upper curve in Figure 3.24). Mainly, the reduction in work from the 1$^{st}$ to the 10$^{th}$ chew was proportionally less in magnitude and occurred more gradually from chew to chew. This may suggest that, although the two groups were overall equally responsive to changes in food firmness (see Figure 3.25), the pattern of response from chew-to-chew differed for the dentate and prosthodontically treated subjects.

To investigate this possibility, power functions for the relationship between work and food firmness (% agar) were fitted to the data for each group of subjects and individual chews. As shown in Figure 3.26, left panel, for each groups of subjects, the multiplicative constant $c$ remained constant from chew 1 to chew 10 ($p>0.90$ for effect of chew number). However, the exponent $n$ decreased ($p<0.0001$), significantly so from chew 1 to the other chews (see Figure 3.26, right panel). The pattern of variation did not differ for the two groups ($p>0.73$), suggesting that the prosthodontically treated subjects responded to changes in the firmness of the model foods in a similar manner to the dentate subjects, on a chew-by-chew basis as well as overall. The higher values on $n$ for the initial
Chews reflect the need for proportionally greater amounts of muscle activity to comminute the larger food piece when the sampled were whole, or had been cleaved only once or twice.

iii) Prosthodontically treated subjects only.

On average, the muscle work of the four groups of prosthodontically treated subjects did not differ (p>0.26); however, the subject group x log$_{10}$($\%$ Agar) interaction was statistically significant (p<0.001; Figure 3.27), suggesting that the groups did not respond similarly to changes in the firmness of the model foods. The exponent $n$ averaged 0.38 – 0.40 for all groups except the subjects who had natural lower teeth (Table 3.6). These partially dentate subjects were less responsive, $n$ averaged 0.19. It should be noted, however, that multiple comparison of the mean exponent values between groups failed to identify any statistically significant differences between subject groups (p>0.05).

Differences were found among groups in the relative work exerted by the masseter, compared to the temporalis, muscle (p<0.0001 for subject group x muscle interaction); and in the relative work exerted on the working, compared to the balancing, side (p<0.03 for subject group x muscle side interaction; Figure 3.28). Masseter work was greater than temporalis work for subjects who wore a lower conventional or implant-supported over-denture; was equal to temporalis work for subjects with lower natural teeth, and was less than temporalis work for subjects who wore a lower implant-supported fixed prosthesis (p<0.05). For all four groups, work was greater on the working, than on the balancing, side (p<0.05); but the difference was greater for subjects with implant-supported prostheses than for subjects with a lower conventional denture or natural teeth. These findings attest to the sensitivity of the methods to detect subtle variations among groups of subjects, but must be attributed cautiously to differences associated with the prosthodontic treatments given the small sample size of the groups.

Analysis of the prosthodontically treated subjects identified a further effect of the chewing side (Figure 3.29 and Table 3.8). Specifically, the balancing side was more responsive to the firmness
of the model foods (exponent $n$ averaged 0.37) than the working side (exponent $n$ averaged 0.31; $p<0.01$). This was true of all four groups of subjects ($p>0.29$ for subject group x side x log$_{10}$($\%$Agar) interaction).

The groups differed in a few other respects, but the differences were complex and had no obvious clinical significance to merit much discussion. For example, the variation in work from chew to chew differed among the four groups of subjects ($p<0.0001$; see Figure 3.30). Larger sample sizes are required to confidently assign importance to these findings.

iv) Effect of age.

There was no evidence to suggest that the subjects’ age affected the values of muscle work ($p>0.32$).

**F. Timing: Asynchrony in muscle recruitment**

The masticatory muscles are activated asynchronously to generate, in turn, the opening and closing phases of the chewing cycle, and to deviate the jaw laterally to produce shearing motion between the upper and lower teeth during closure. To evaluate muscle asynchrony in the present study, we calculated and analyzed the time between the peak EMG activity in each masticatory muscle relative to the time of the peak activity in the superficial masseter muscle on the working side, which proved to be the last muscle to exhibit peak activity most often. Positive values indicated that the respective muscle’s peak firing occurred after that of the working side masseter, while negative ones indicated that peak firing occurred before that of the working side masseter.

i) Dentate subjects only.

Analysis of the data from the five dentate subjects confirmed statistically significant differences in timing among the five masticatory muscles ($p<0.0001$; Figure 3.31, left side). The balancing side digastric muscle was first to peak (at -386.6 ms on average), followed by the working
side digastric muscle (at -284.6 ms), which occurred significantly later in time (p<0.05). Both of these jaw-opening muscles peaked significantly earlier than the jaw-closing muscles. Of the jaw-closing muscles, activity peaked earliest on average in the balancing side masseter (at -50.2 ms) and latest in the balancing side temporalis (at 1.4 ms), which differed significantly from the balancing side masseter. The peak time of the working side temporalis (-13.9 ms) was not significantly different than the peak times of either the balancing side masseter or temporalis muscle. No jaw-closing muscle, however, differed significantly from 0.0 in its mean estimate, given the high variability among subjects in the estimates (see standard deviations in Table 3.9).

The timing of the muscles for the dentate subjects did not differ significantly for model foods that differed in firmness, as assessed by the % agar in the samples (p>0.09; Figure 3.32, left panel). There was a subtle trend for the timing between the jaw-opening muscles and jaw-closing muscles to decrease with increasing food firmness, however.

The timing of the muscles for the dentate subjects varied on a chew-by-chew basis (p<0.0001), and the pattern of variation differed among muscles (p<0.0001 for chew number x muscle interaction). As illustrated in Figure 3.33, these effects can be attributed to the very early activity of the digastric muscles on the first two chews. This indicates that the opening phase of the first two chews was particularly long in duration, likely to accommodate the size of the samples of the model foods before notable reduction. Excepting the first 2 or 3 chews, the muscle timing was relatively stable over the remaining chews studied.

ii) Prosthodontically treated versus dentate subjects.

Analysis of the data from the 20 prosthodontically treated subjects confirmed statistically significant differences in timing among the five masticatory muscles (Figure 3.31, right side), which differed from the timing observed in the dentate subjects (p<0.0001; Table 3.9). Specifically, unlike the dentate subjects, both the balancing side masseter and temporalis muscles peaked in activity before the working side masseter (p-values <0.05), with the times for these two balancing side
muscles not being significantly different, on average (-51.3 ms and -38.9 ms, respectively). It is possible that the earlier activity of the balancing side temporalis muscle during closure in the prosthodontically treated subjects served to stabilize the position of the maxillary denture on the ridge by some mechanical action.

Unlike for the dentate subjects, the timing of the muscles for the prosthodontically treated subjects differed significantly for model foods that differed in firmness, as assessed by the % agar in the samples (p<0.004; Figure 3.32, right panel). Most notably, the timing difference between the jaw-opening and jaw-closing muscles increased with food firmness (p<0.05). For both the working and balancing side digastric muscles, the peak activity occurred significantly earlier when chewing the 7%, compared to the 1.75%, agar samples (p<0.05). This may reflect additional jaw-opening time needed by the subjects with upper conventional dentures to negotiate the firmer model foods.

As for the dentate subjects, the timing of the muscles for the prosthodontically treated subjects varied on a chew-by-chew basis (p<0.0001), and the pattern of variation differed among the muscles (p<0.0001 for chew number x muscle interaction). However, the effects did not differ significantly from those observed for the dentate subjects, as illustrated in Figure 3.33 (p>0.54 for subject group x chew number interaction; p>0.68 for subject group x chew number x muscle interaction).

iii) Prosthodontically treated subjects only.

Analysis of the data revealed significant differences in timing for the masticatory muscles among the four groups of prosthodontically treated subjects (p<0.0001 for subject group x muscle interaction; Figure 3.34). However, comparison of the mean values revealed few differences that were statistically significant due to the small samples of variable subjects (Table 3.10). Notably, peak activity in the balancing side masseter occurred significantly earlier than in the working side masseter for only subjects who wore an implant-supported lower overdenture (CD/OD group in Figure 3.34).
Moreover, activity in the digastric muscles peaked earlier for these subjects than those in the other three groups, significantly so for subjects who wore a conventional lower denture.

As noted above, the timing of the muscles for the prosthodontically treated subjects, in general, differed significantly for model foods that differed in firmness (Figure 3.32, right panel). The four groups of subjects did not differ in this regard (\( p > 0.74 \) for subject group x muscle x % agar). Moreover, there were no differences among the four groups in the manner the timing of the different muscles varied on a chew-by-chew basis (\( p > 0.94 \) for subject group x chew number x chew number interaction).

A new finding was that the timing, averaged across the five muscles, varied differently on a chew-by-chew basis for the four groups of subjects (\( p < 0.0001 \) for subject group x chew number interaction). The pattern of variation further depended on the firmness of the foods chewed (\( p < 0.0001 \) for % agar x subject group x chew number interaction), but did not differ for the different muscles (\( p > 0.94 \) for muscle x subject group x chew number interaction; \( p > 0.99 \) for muscle x % agar x subject group x chew number interaction). To investigate this complex effect, the timing values were averaged over the two lower % agar concentrations (‘less firm gels’) and the two higher % agar concentrations (‘more firm gels’) and plotted for each group for each chew. Shown in Figure 3.35 are the timing values for the jaw-opening muscles only. The figure suggests that differences in timing between groups were most likely to occur during the first few chews. Moreover, considering the vertical separation of the two curves plotted for each group of subjects, food firmness appeared to have a greater effect on the timing of the CD/CD and CD/FD groups than on the CD/ND and CD/OD groups. A comparison of mean values was not attempted: Given the high variability, small group size, and large number of tests, it is unlikely that differences in mean values would have attained statistical significance.

All considered, the data indicate that certain aspects of muscle timing differed among the four groups of prosthodontically treated subjects, and that the timing was also variably affected by the firmness of the foods chewed. Like observed values of muscle work (scaled EMG area-under-curve)
in the previous section, the muscle timing values during the first few chews were not characteristic of those observed subsequently in the masticatory sequence. However, those observed during the first few chews may serve to better discriminate between subjects who have received different prosthodontic treatments.

iv) Effect of age.

There was no evidence to suggest that the subjects’ age affected the muscle timing estimates (p>0.50).
4. DISCUSSIONS

4.1. SUBJECTIVE ASSESSMENT OF MASTICATORY FUNCTION

In the present study, the conventional full denture group reported a lower ("fairly well") chewing ability (summary rating = 2) than the other subject groups, in accord with findings of other studies that have used subjective methods (Geertman et al 1996; Wayler and Chauncey 1983; Wayler et al 1984; Slagter et al 1992a).

The subjects wearing an upper conventional full denture and a lower implant-supported overdenture or implant-supported fixed prosthesis reported better chewing ability than the conventional full denture group on almost all aspects queried. This is comparable to the better perceived masticatory function and patient satisfaction reported in other research on patients with the implant-supported prostheses (Stellingsma et al 2005; Cune et al 2005; Cune de Putter and Hoogstraten 1994; Naert et al 1999; Naert Alsaadi and Quirynen 2004; Thomason et al 2003; Geertman et al 1996; de Grandmont et al 1994; Gunne and Wall 1985). Different results were reported, however, by Garrett et al (Garrett et al 1998), who found no significant advantage of implant-supported overdentures, as compared to conventional full dentures.

Patients who had a lower implant-supported fixed prosthesis (group CD/FD) reported better chewing ability than patients who wore an implant-supported overdenture (group CD/OD), confirming patient preference for the increased support provided by a fixed prosthesis (Tang et al 1999) and/or a fixed, rather than a removable, prosthesis (Feine 1994a). These results are also consistent with the findings of Fueki et al (2007).
4.2. OBJECTIVE EVALUATION OF MASTICATORY FUNCTION

A. Total duration of chewing.

For each group of subjects in the present study, the total duration of chewing increased with the % agar in the food samples (p < 0.0001), in accord with results from other research that has found an increased duration for chewing foods that are more mechanically challenging (Shiau Peng and Hsu 1999, Peyron et al 2004; Peyron Lassauzay and Woda 2002; Jemt 1981; Wayler et al 1984; Slagter et al 1992; Horio and Kawamura 1989).

Within the prosthodontically treated group, the total duration of chewing was higher for the CD/ND group than the CD/FD group (p = 0.001). Although other differences were suggested between groups, they were not statistically significant. That prosthodontic treatments can affect the duration at which patients chew foods is well established. For example, Feine et al 1994 found that the total duration of chewing was shorter in long bar implant-supported overdenture treated subjects (the long bar overdenture acts very similarly to an implant-supported fixed prosthesis, because of extended implant support) versus implant-supported overdenture wearers. A reduction in total chewing duration with the transition from a conventional full denture to an implant-supported fixed prosthesis was also noted by Lindquist and Carlsson (Lindquist and Carlsson 1985). On the other hand, no significant difference in chewing duration was found by Garrett et al (1998), who compared a CD/CD group with a CD/OD group. Other research (Tang et al 1999) found no significant difference in total chewing duration when comparing this parameter for implant-supported overdentures and long bar implant-supported overdentures (supported by 4 implants, acting almost like implant-supported fixed prosthesis, because of little to no mucosal support).
We found no evidence to suggest that the subjects’ age affected their total duration of chewing (p>0.70). However, other data (Feldman et al 1984; Peyron et al 2004) suggest that the total duration of chewing does increase progressively with age.

**B. Chewing frequency.**

In our study, the chewing frequency did not significantly vary with the firmness of the model foods, in accord with other reports (Horio and Kawamura 1989; Peyron Lassauzay and Woda 2002; Peyron et al 2004; Slagter et al 1993; Jemt and Hedegard 1982). On the other hand, Plesh et al (Plesh Bishop and McCall 1986) found that the chewing frequency in dentate individuals becomes slower with harder foods.

Also, the chewing frequency did not vary statistically among the different subject groups. Similar findings were reported by Slagter et al (Slagter et al 1993).

There was no evidence to suggest that the subjects’ age affected their frequency of chewing (p>0.42). This finding is in accord with other data (Peyron et al 2004; Karlsson and Carlsson 1990).

**C. Duration of single chews.**

A significant (p<0.0001) intra subject variation was noted (greatest between the first and the following cycles), in accord with other research (Lucas et al 1986b; Schindler Stengel and Spiess 1998).

We found that the duration of single chews on average did not vary statistically among the four prosthodontically treated subject groups. Karkazis (Karkazis 2002) noted a higher duration of the chewing cycle in implant-supported overdenture treated individuals, as compared to conventional full denture subjects. The present study found a similar result was obtained with the less firm model foods.
D. Duty cycle of the jaw closing muscles.

The duty cycle varied little with the percent agar in the foods. Although subtle differences were suggested among the subject groups, they failed to attain statistical significance due to the high variability among subjects in some groups. Similar findings are reported by Karkazis in 2002.

E. Relative muscle work: EMG area-under-curve for the jaw-closing muscles

A common observation was that muscle activity, similar to the total duration of chewing, increased with the % agar in the food samples, following a power function (p<0.0001). Other studies (Peyron Lassauzay and Woda 2002; Horio and Kawamura 1989) documented similar variation with the firmness of food substances. However, some authors reported only minimal variations in this parameter as the hardness of the same food is increased (Peyron et al 2004; Slagter et al 1993; Jemt and Hedegard 1982).

We found no evidence to suggest that the subjects’ age affected the values of muscle work (p>0.31), in agreement with results from other studies (Mishellany-Dutour et al 2008; Feldman et al 1980; Peyron et al 2004; Mioche et al 2004).
5. CONCLUSIONS

The following conclusions can be extracted from our study:

1. EMG methods using i) engineered test foods with controlled physical properties and ii) rigorous analytical techniques can detect and characterize meaningful differences among human subjects who differ in dental status and prosthodontic treatments.

2. Observed differences in outcome measures of prosthodontically treated, compared to dentate, subjects may reflect (i) responses to stabilize the patients’ maxillary complete denture and (ii) responses to accommodate increased food firmness that are not needed in dentate subjects or some groups of prosthodontically treated subjects.

3. Larger sample sizes are needed for definitive conclusions.

4. Jaw tracking procedures are needed in concert with the EMG to appreciate the functional outcome of the patterns of EMG electrical activity.
Table 1.1 Masticatory function in dentate subjects.

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>Finding</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total duration of chewing</td>
<td>Increased with harder foods</td>
<td>Shiau, Peng &amp; Hsu, 1999</td>
</tr>
<tr>
<td></td>
<td>Increased with age</td>
<td>Mishellany-Dutour et al, 2008</td>
</tr>
<tr>
<td>Number of chews</td>
<td>Increased with age</td>
<td>Mishellany-Dutour et al, 2008</td>
</tr>
<tr>
<td>Chewing frequency</td>
<td>Slower with harder foods</td>
<td>Plesh, Bishop &amp; McCall, 1986</td>
</tr>
<tr>
<td></td>
<td>No difference with various foods</td>
<td>Horio &amp; Kawamura, 1989</td>
</tr>
<tr>
<td>Velocity of jaw movements</td>
<td>Higher in men</td>
<td>Youssef et al, 1997</td>
</tr>
<tr>
<td>Amplitude of jaw movements</td>
<td>Higher in men</td>
<td>Peyron et al, 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Youssef et al, 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kilaridis, Karlsson &amp; Kjellberg, 1991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neill &amp; Howell, 1988</td>
</tr>
<tr>
<td>Chewed particle size</td>
<td>Decreased with age</td>
<td>Mishellany-Dutour et al, 2008</td>
</tr>
<tr>
<td>EMG activity/chew</td>
<td>Not significantly modified with age</td>
<td>Mishellany-Dutour et al, 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peyron et al, 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feldman et al, 1980</td>
</tr>
</tbody>
</table>
Table 1.2 Masticatory function in conventional full denture wearers, compared to dentate individuals.

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>Finding</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not significantly changed</td>
<td>Veyrune &amp; Mioche, 2000; Slagter et al 1992, 1993</td>
</tr>
<tr>
<td></td>
<td>Not significantly changed</td>
<td>Veyrune &amp; Mioche, 2000; Slagter et al, 1992, 1993</td>
</tr>
<tr>
<td>Duration of single chews</td>
<td>Increased</td>
<td>Jemt, 1981</td>
</tr>
<tr>
<td></td>
<td>Not significantly changed</td>
<td>Veyrune &amp; Mioche, 2000; Slagter et al, 1992, 1993</td>
</tr>
<tr>
<td>Chewing frequency</td>
<td>Reduced</td>
<td>Jemt, 1981</td>
</tr>
<tr>
<td></td>
<td>Unaffected by dental state</td>
<td>Slagter et al, 1993</td>
</tr>
</tbody>
</table>
Table 1.2 (continued) Masticatory function in conventional full denture wearers, compared to dentate individuals.

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>Finding</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chewed particle size</td>
<td>Increased</td>
<td>Mishelany-Dutour et al, 2008; Slagter et al, 1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fontijn-Tekamp et al, 2000; Wayler &amp; Chauncey, 1983</td>
</tr>
<tr>
<td>Total EMG activity</td>
<td>Increased</td>
<td>Mishelany-Dutour et al, 2008; Slagter et al, 1992, 1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wayler et al, 1984; Jemt, 1981</td>
</tr>
<tr>
<td></td>
<td>Reduced</td>
<td>Veyrune &amp; Mioche, 2000; Karkazis &amp; Kossioni, 1998</td>
</tr>
<tr>
<td>EMG activity/chew</td>
<td>Increased</td>
<td>Veyrune et al, 2007</td>
</tr>
<tr>
<td></td>
<td>No difference</td>
<td>Mishelany-Dutour et al, 2008</td>
</tr>
<tr>
<td></td>
<td>Decreased</td>
<td>Veyrune and Mioche 2000; Slagter et al 1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kapur and Garrett 1984</td>
</tr>
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</table>
Table 1.3 Masticatory function in patients with upper conventional dentures and lower implant-supported overdentures, compared to individuals with upper & lower conventional dentures.

<table>
<thead>
<tr>
<th><strong>Outcome measure</strong></th>
<th><strong>Finding</strong></th>
<th><strong>Study</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not significantly improved</td>
<td>Garrett et al, 1998</td>
</tr>
<tr>
<td>Total duration of chewing</td>
<td>Not significantly different</td>
<td>Garrett et al, 1998</td>
</tr>
<tr>
<td>Number of chews</td>
<td>Reduced</td>
<td>van Kampen et al, 2004 Geertman et al, 1994</td>
</tr>
<tr>
<td></td>
<td>Not significantly different</td>
<td>Garrett et al, 1998</td>
</tr>
<tr>
<td>Total EMG activity</td>
<td>Not significantly modified</td>
<td>Garrett et al, 1998</td>
</tr>
<tr>
<td></td>
<td>Higher</td>
<td>Karkazis, 2002</td>
</tr>
</tbody>
</table>
Table 2.1 Reported chewing ability questionnaire (Ow et al 1998).

<table>
<thead>
<tr>
<th>Question</th>
<th>Response Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>How well can you chew?</td>
<td>A. Well</td>
</tr>
<tr>
<td></td>
<td>B. Fairly well</td>
</tr>
<tr>
<td></td>
<td>C. Poorly</td>
</tr>
<tr>
<td>Can you chew?</td>
<td>A. Hard and soft foods</td>
</tr>
<tr>
<td></td>
<td>B. Only soft foods</td>
</tr>
<tr>
<td>Do you prefer to eat?</td>
<td>A. Hard and soft foods</td>
</tr>
<tr>
<td></td>
<td>B. Only soft foods</td>
</tr>
<tr>
<td>Which side do you prefer to chew?</td>
<td>A. One side (left or right?)</td>
</tr>
<tr>
<td></td>
<td>B. Both sides</td>
</tr>
<tr>
<td>Is it hard to open your mouth when chewing?</td>
<td>A. Yes, often</td>
</tr>
<tr>
<td></td>
<td>B. Yes sometimes</td>
</tr>
<tr>
<td></td>
<td>C. No</td>
</tr>
<tr>
<td>Do you feel pain in the jaws of face when chewing?</td>
<td>A. Yes, often</td>
</tr>
<tr>
<td></td>
<td>B. Yes, sometimes</td>
</tr>
<tr>
<td></td>
<td>C. No</td>
</tr>
</tbody>
</table>
Table 2.2 Reported parafunction questionnaire (Miyake et al 2004).

<table>
<thead>
<tr>
<th>Reported Parafunctions</th>
<th>Response Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping on one side</td>
<td>Yes</td>
</tr>
<tr>
<td>Leaning on the palm</td>
<td>Yes</td>
</tr>
<tr>
<td>Gum chewing</td>
<td>Yes</td>
</tr>
<tr>
<td>Chewing on one side</td>
<td>Yes</td>
</tr>
<tr>
<td>Tongue, cheek or lip biting</td>
<td>Yes</td>
</tr>
<tr>
<td>Bruxing</td>
<td>Yes</td>
</tr>
<tr>
<td>Nail biting</td>
<td>Yes</td>
</tr>
<tr>
<td>Clenching</td>
<td>Yes</td>
</tr>
<tr>
<td>Biting foreign objects</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 3.1 Age and gender composition of the study population.

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (mean)</th>
<th>Age std</th>
<th>Age (median)</th>
<th>Females (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND/ND</td>
<td>62.4</td>
<td>3.43</td>
<td>61</td>
<td>60</td>
</tr>
<tr>
<td>CD/ND</td>
<td>71</td>
<td>13.63</td>
<td>77</td>
<td>60</td>
</tr>
<tr>
<td>CD/CD</td>
<td>58.6</td>
<td>10.31</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>CD/OD</td>
<td>61.4</td>
<td>7.89</td>
<td>58</td>
<td>100</td>
</tr>
<tr>
<td>CD/FD</td>
<td>59</td>
<td>10.36</td>
<td>57</td>
<td>60</td>
</tr>
<tr>
<td>All groups</td>
<td>62.5</td>
<td>10.00</td>
<td>61</td>
<td>60</td>
</tr>
</tbody>
</table>

Legend: ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Table 3.2 Reported chewing ability questionnaire results: percentage of subjects answers/question/group.

<table>
<thead>
<tr>
<th>Group</th>
<th>Question/answer/percentage</th>
<th>How well can you chew?</th>
<th>Can you chew?</th>
<th>Do you prefer to eat?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Well (3 pts)</td>
<td>Fairly well (2 pts)</td>
<td>Poorly (1 pt)</td>
</tr>
<tr>
<td>ND/ND</td>
<td></td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CD/ND</td>
<td></td>
<td>40</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>CD/CD</td>
<td></td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CD/OD</td>
<td></td>
<td>40</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>CD/FD</td>
<td></td>
<td>60</td>
<td>40</td>
<td>0</td>
</tr>
</tbody>
</table>

Legend: ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Table 3.2 (continued) Reported chewing ability questionnaire results: percentage of subjects answers/question/group.

<table>
<thead>
<tr>
<th>Group</th>
<th>Question/answer/percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Which side do you prefer to chew?</td>
</tr>
<tr>
<td></td>
<td>Both sides</td>
</tr>
<tr>
<td>ND/ND</td>
<td></td>
</tr>
<tr>
<td>CD/ND</td>
<td></td>
</tr>
<tr>
<td>CD/CD</td>
<td></td>
</tr>
<tr>
<td>CD/OD</td>
<td></td>
</tr>
<tr>
<td>CD/FD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>It is hard to open your mouth when chewing?</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
<tr>
<td>ND/ND</td>
<td>100</td>
</tr>
<tr>
<td>CD/ND</td>
<td>60</td>
</tr>
<tr>
<td>CD/CD</td>
<td>40</td>
</tr>
<tr>
<td>CD/OD</td>
<td>20</td>
</tr>
<tr>
<td>CD/FD</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Do you feel pain in the jaws or face when chewing?</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
<tr>
<td>ND/ND</td>
<td>100</td>
</tr>
<tr>
<td>CD/ND</td>
<td>80</td>
</tr>
<tr>
<td>CD/CD</td>
<td>60</td>
</tr>
<tr>
<td>CD/OD</td>
<td>80</td>
</tr>
<tr>
<td>CD/FD</td>
<td>100</td>
</tr>
</tbody>
</table>

Legend: ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis
Table 3.3 Reported parafunction questionnaire results: percentage of “Yes” answers/group for each question.

<table>
<thead>
<tr>
<th>Question/group</th>
<th>ND/ND</th>
<th>CD/ND</th>
<th>CD/CD</th>
<th>CD/OD</th>
<th>CD/FD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping on one side?</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Leaning on the palm?</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Gum chewing?</td>
<td>40</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Chewing on one side?</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Tongue, cheek, lip biting?</td>
<td>20</td>
<td>60</td>
<td>0</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Bruxism?</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nail biting?</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clenching?</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Biting foreign objects?</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total ‘yes’ responses from group of subjects</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>

Legend: ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Table 3.4 Power function analyses of the total duration of chewing versus model food firmness (% agar).

<table>
<thead>
<tr>
<th>Group</th>
<th>$c$</th>
<th>$n$</th>
<th>$R^2$</th>
<th>$\Delta % \text{ agar}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND/ND</td>
<td>13.8</td>
<td>0.414</td>
<td>0.987</td>
<td>2.66 x</td>
</tr>
<tr>
<td>All prosthodontically treated groups</td>
<td>17.4</td>
<td>0.472</td>
<td>0.996</td>
<td>2.36 x</td>
</tr>
<tr>
<td>CD/ND</td>
<td>28.1</td>
<td>0.386</td>
<td>0.991</td>
<td>2.85 x</td>
</tr>
<tr>
<td>CD/CD</td>
<td>13.0</td>
<td>0.601</td>
<td>0.985</td>
<td>1.96 x</td>
</tr>
<tr>
<td>CD/OD</td>
<td>20.6</td>
<td>0.379</td>
<td>0.960</td>
<td>2.91 x</td>
</tr>
<tr>
<td>CD/FD</td>
<td>12.2</td>
<td>0.520</td>
<td>0.977</td>
<td>2.18 x</td>
</tr>
</tbody>
</table>

Legend: $c$ – multiplicative constant; $n$ – exponent; $R^2$ – R-square goodness of fit of the data to a power function model; $\Delta \% \text{ agar}$ – change in agar necessary to increase the chewing duration by 50%; ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Table 3.5 Chewing frequency (chews/s) for the different subject groups

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND/ND</td>
<td>5</td>
<td>1.58</td>
<td>1.36</td>
<td>1.82</td>
</tr>
<tr>
<td>All prosthodontically treated groups</td>
<td>20</td>
<td>1.38</td>
<td>0.62</td>
<td>1.91</td>
</tr>
<tr>
<td>CD/ND</td>
<td>5</td>
<td>1.41</td>
<td>0.62</td>
<td>1.91</td>
</tr>
<tr>
<td>CD/CD</td>
<td>5</td>
<td>1.58</td>
<td>1.17</td>
<td>1.86</td>
</tr>
<tr>
<td>CD/OD</td>
<td>5</td>
<td>1.11</td>
<td>0.74</td>
<td>1.44</td>
</tr>
<tr>
<td>CD/FD</td>
<td>5</td>
<td>1.40</td>
<td>1.05</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Legend: N – number of subjects; ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Table 3.6 Power function analyses of the muscle work, based on scaled EMG area-under-curve versus model food firmness (% agar) of all study subjects.

<table>
<thead>
<tr>
<th>Group</th>
<th>c</th>
<th>n</th>
<th>R²</th>
<th>∆ % agar</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND/ND</td>
<td>0.258</td>
<td>0.372</td>
<td>0.998</td>
<td>2.97</td>
</tr>
<tr>
<td>All prosthodontically treated groups</td>
<td>0.695</td>
<td>0.338</td>
<td>0.998</td>
<td>3.31</td>
</tr>
<tr>
<td>CD/ND</td>
<td>0.749</td>
<td>0.191</td>
<td>0.95</td>
<td>8.35</td>
</tr>
<tr>
<td>CD/CD</td>
<td>0.576</td>
<td>0.391</td>
<td>0.986</td>
<td>2.82</td>
</tr>
<tr>
<td>CD/OD</td>
<td>0.666</td>
<td>0.380</td>
<td>0.920</td>
<td>2.90</td>
</tr>
<tr>
<td>CD/FD</td>
<td>0.810</td>
<td>0.389</td>
<td>0.989</td>
<td>2.83</td>
</tr>
</tbody>
</table>

Legend: c – multiplicative constant; n – exponent; R² – R-square goodness of fit of the data to a power function model; ∆% agar – change in agar resulting in 50% increase in work; ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Table 3.7 Power function analyses of the muscle work, based on scaled EMG area-under-curve versus model food firmness (% agar) of 5 dentate subjects. See Figure 3.23.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>c</th>
<th>n</th>
<th>$R^2$</th>
<th>$\Delta$ % agar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masseter, Working</td>
<td>0.096</td>
<td>0.461</td>
<td>0.998</td>
<td>2.40</td>
</tr>
<tr>
<td>Temporalis, Working</td>
<td>0.063</td>
<td>0.314</td>
<td>0.999</td>
<td>3.63</td>
</tr>
<tr>
<td>Masseter, Balancing</td>
<td>0.067</td>
<td>0.391</td>
<td>0.985</td>
<td>2.82</td>
</tr>
<tr>
<td>Temporalis, Balancing</td>
<td>0.042</td>
<td>0.322</td>
<td>0.976</td>
<td>3.52</td>
</tr>
</tbody>
</table>

Legend: c – multiplicative constant; n – exponent; $R^2$ – R-square goodness of fit of the data to a power function model; $\Delta$ % agar – change in agar resulting in 50% increase in work.
Table 3.8 Power function analyses of the muscle work, based on scaled EMG area-under-curve versus model food firmness (% agar) of 20 prosthodontically treated subjects. See Figure 3.29.

<table>
<thead>
<tr>
<th>Chewing Side</th>
<th>c</th>
<th>n</th>
<th>$R^2$</th>
<th>$\Delta$ % agar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working</td>
<td>0.415</td>
<td>0.305</td>
<td>0.993</td>
<td>3.77</td>
</tr>
<tr>
<td>Balancing</td>
<td>0.290</td>
<td>0.371</td>
<td>0.998</td>
<td>2.98</td>
</tr>
</tbody>
</table>

Legend: $c$ – multiplicative constant; $n$ – exponent; $R^2$ – R-square goodness of fit of the data to a power function model; $\Delta$% agar – change in agar resulting in 50% increase in work.
Table 3.9 Time occurrence of peak EMG activity in stated muscle re: time of peak EMG activity in working side masseter muscle (time = 0).

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>ND/ND</th>
<th>CD/xx</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muscle</strong></td>
<td><strong>mean</strong></td>
<td><strong>sd</strong></td>
</tr>
<tr>
<td>WMM</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>WTA</td>
<td>-13.85</td>
<td>8.74</td>
</tr>
<tr>
<td>BMM</td>
<td>-50.15</td>
<td>31.93</td>
</tr>
<tr>
<td>BTA</td>
<td>1.41</td>
<td>16.43</td>
</tr>
<tr>
<td>BDA</td>
<td>-386.48</td>
<td>94.47</td>
</tr>
</tbody>
</table>

Table 3.10 Time occurrence of peak EMG activity in stated muscle re: time of peak EMG activity in working side masseter muscle (time = 0).

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>CD/CD</th>
<th>CD/FD</th>
<th>CD/ND</th>
<th>CD/OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>mean</td>
<td>sd</td>
<td>mean</td>
<td>sd</td>
</tr>
<tr>
<td>WMM</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>WTA</td>
<td>-12.29</td>
<td>28.31</td>
<td>-2.81</td>
<td>22.43</td>
</tr>
<tr>
<td>BMM</td>
<td>-53.56</td>
<td>32.82</td>
<td>-33.54</td>
<td>53.12</td>
</tr>
<tr>
<td>BTA</td>
<td>-61.56</td>
<td>86.6</td>
<td>-33.6</td>
<td>35.43</td>
</tr>
<tr>
<td>WDA</td>
<td>-281.2</td>
<td>78.87</td>
<td>-337.71</td>
<td>79.97</td>
</tr>
<tr>
<td>BDA</td>
<td>-317.26</td>
<td>82.34</td>
<td>-422.94</td>
<td>78.98</td>
</tr>
</tbody>
</table>

Fig. 2.1 Testing results of 7% agar samples loaded to fracture, in order to evaluate the consistency of mechanical properties. ▲ – fracture point.
Fig. 2.2 Linear regression plot for stress fracture by agar concentration.
Fig. 2.3 EMG electrodes positioning: parallel with the muscle fibers (schematically represented in red), on the bulkiest part of the muscle belly, as determined by palpation, when subject is contracting the muscle.
Fig. 2.4 Raw EMG data for the six muscles investigated, as they appear on the computer screen after recording a masticatory sequence (right side intentional chewing, 1.75% agar). TA-R – right anterior temporalis; TA-L – left anterior temporalis; MM-R – right superficial masseter; MM-L – left superficial masseter; DA-R – right anterior digastric; DA-L – left anterior digastric.
Fig. 2.5 Combined rms (root mean squares) data (all six muscles tested during one masticatory sequence), processed in Labview software, and illustrated in Igor Pro software.
Fig. 2.6 a Expanded rms sequence allowing identification of different muscle waves, rough estimation of peak timing, and delimitation of individual chewing cycles (data processed in Labview software, and illustrated in Igor Pro. TA-R – right anterior temporalis; TA-L – left anterior temporalis; MM-R – right superficial masseter; MM-L – left superficial masseter; DA-R – right anterior digastric; DA-L – left anterior digastric.
Fig. 2.6b Expanded rms sequence, with the first chewing cycle delimited between cursors, and ready to be recorded. TA-R – right anterior temporalis; TA-L – left anterior temporalis; MM-R – right superficial masseter; MM-L – left superficial masseter; DA-R – right anterior digastric; DA-L – left anterior digastric.
Fig. 2.6 c Expanded rms sequence, with the second chewing cycle delimited between cursors, and ready to be recorded. TA-R – right anterior temporalis; TA-L – left anterior temporalis; MM-R – right superficial masseter; MM-L – left superficial masseter; DA-R – right anterior digastric; DA-L – left anterior digastric.
Fig. 3.1 Age composition of the study population. ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Fig. 3.2 Reported parafunction questionnaire results: percentage of “Yes” answers/group for each question. 
ND/ND – upper and lower natural dentition; CD/ND – upper conventional full denture, lower natural dentition; CD/CD – upper and lower conventional full dentures; CD/OD – upper conventional full denture, lower implant-supported overdenture; CD/FD – upper conventional full denture, lower implant-supported fixed prosthesis.
Fig. 3.3 Total duration of chewing in the dentate group. Error bars denote ± 1 standard error of the mean. ND/ND – dentate group.
Fig. 3.4 Total duration of chewing for the dentate group versus the prosthodontically treated patients. Error bars denote ± 1 standard error of the mean. CD/XX – prosthodontically treated subjects, including all individuals in the study having an upper conventional full denture; ND/ND – dentate group.
Fig. 3.5 Total duration of chewing for the prosthodontically treated subjects. Error bars denote ± 1 standard error of the mean. CD/ND – conventional full denture/natural dentition group; CD/OD – conventional full denture/implant-supported overdenture group; CD/CD – conventional full denture/conventional full denture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group.
Fig. 3.6 Chewing frequency for the dentate group. Error bars denote ± 1 standard error of the mean. 
*ND/ND* – dentate group.
Fig. 3.7 Chewing frequency for the dentate group versus the prosthodontically treated patients. Error bars denote ± 1 standard error of the mean. ND/ND – dentate group; CD/XX – prosthodontically treated subjects, including all individuals in the study having an upper conventional full denture.
Fig. 3.8 Chewing frequency for the prosthodontically treated subjects. Error bars denote ± 1 standard error of the mean. CD/CD – conventional full denture/conventional full denture group; CD/ND – conventional full denture/natural dentition group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/OD – conventional full denture/implant-supported overdenture group.
Fig. 3.9 Duration of single chew for dentate subjects. Error bars denote ± 1 standard error of the mean. *ND/ND* — dentate group.
Fig. 3.10 Duration of single chew for dentate subjects. Error bars denote ± 1 standard error of the mean. ND/ND – dentate group.
Fig. 3.11 Duration of single chew by agar concentration for dentate subjects versus prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. ND/ND – dentate group; CD/XX – prosthodontically treated group.
Fig. 3.12 Duration of single chew by chew number for dentate subjects versus prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. ND/ND – dentate group; CD/XX – prosthodontically treated group.
Fig. 3.13 Duration of single chew by agar concentration for prosthodontically treated subjects. Error bars denote ± 1 standard error of the mean. CD/OD – conventional full denture/implant-supported overdenture group; CD/ND – conventional full denture/natural dentition group CD/CD – conventional full denture/conventional full denture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group.
Fig. 3.14 Chew duration coefficient of variation by agar concentration. Error bars denote ± 1 standard error of the mean. CD/CD – conventional full denture/conventional full denture group; CD/ND – conventional full denture/natural dentition group; CD/OD – conventional full denture/implant-supported overdenture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; ND/ND – natural dentition group.
Fig. 3.15 Elevator duty by agar concentration for dentate subjects. Error bars denote ± 1 standard error of the mean. ND/ND – natural dentition group.
Fig. 3.16 Elevator duty by chew number for dentate subjects. Error bars denote ± 1 standard error of the mean. *ND/ND* – natural dentition group.
Fig. 3.17 Elevator duty by agar concentration for dentate subjects versus prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. CD/XX – prosthodontically treated group; ND/ND – natural dentition group.
Fig. 3.18 Elevator duty by chew number for dentate subjects versus prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. CD/XX – prosthodontically treated group; ND/ND – natural dentition group.
Fig. 3.19 Elevator duty by agar concentration for prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. CD/OD – conventional full denture/implant-supported overdenture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/CD – conventional full denture/conventional full denture group; CD/ND – conventional full denture/natural dentition group.
Fig. 3.20 Elevator duty by age for all groups. CD/OD – conventional full denture/implant-supported overdenture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/CD – conventional full denture/conventional full denture group; ND/ND – natural dentition/natural dentition; CD/ND – conventional full denture/natural dentition group.
Fig. 3.21 Mean muscle work/chew, as measured by scaled area under the EMG curve in dentate subjects. Error bars denote ± 1 standard error of the mean. ND/ND – natural dentition group.
Fig. 3.22 Mean muscle work/chew, as measured by scaled area under the EMG curve for the four jaw elevators, in dentate subjects, and prosthodontically treated individuals. WMM – working masseter; BMM – balancing masseter; WTA – Working temporalis anterior; BTA – balancing temporalis anterior; ND/ND – natural dentition group; CD/XX – prosthodontically treated individuals.
Fig 3.23 Mean muscle work/chew, as measured by scaled area under the EMG curve for the four jaw elevators, in dentate subjects. Error bars denote ± 1 standard error of the mean. WMM – working masseter; BMM – balancing masseter; WTA – Working temporalis anterior; BTA – balancing temporalis anterior.
Fig. 3.24 Mean muscle work/chew, as measured by scaled area under the EMG curve in dentate subjects versus prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. ND/ND – natural dentition group; CD/XX – prosthodontically treated subjects.
Fig. 3.25 Mean muscle work/chew, as measured by scaled area under the EMG curve in dentate subjects versus prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. ND/ND – natural dentition group; CD/XX – prosthodontically treated individuals.
Fig 3.26  Constant “c” and exponent “n” of the power functions for the relationship between muscle work and food firmness (% agar) by chew number. Error bars denote ± 1 standard error of the mean. ND/ND – natural dentition group; CD/XX – prosthodontically treated individuals.
Fig 3.27 Mean muscle work/chew, as measured by scaled area under the EMG curve in prosthodontically treated individuals. Error bars denote ± 1 standard error of the mean. CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/OD – conventional full denture/implant-supported overdenture group; CD/CD – conventional full denture group; CD/ND – conventional full denture/natural dentition group.
Fig. 3.28 Mean muscle work/chew, as measured by scaled area under the EMG curve for the four jaw elevators, in prosthodontically treated individuals. WMM – working masseter; BMM – balancing masseter; WTA – Working temporalis anterior; BTA – balancing temporalis anterior; CD/CD – conventional full denture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/ND – conventional full denture/natural dentition group; CD/OD – conventional full denture/implant-supported overdenture group.
Fig. 3.29 Mean muscle work/chew, as measured by scaled area under the EMG curve for the working side muscles versus the balancing side muscles in prosthodontically treated subjects. Error bars denote ± 1 standard error of the mean. WS – working side; BS – balancing side.
Fig. 3.30 Mean muscle work/chew, as measured by scaled area under the EMG curve in prosthodontically treated individuals. CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/OD – conventional full denture/implant-supported overdenture group; CD/CD – conventional full denture group; CD/ND – conventional full denture/natural dentition group.
Fig 3.31 Timing of masticatory muscles, based on peak activation and referenced to the timing of working masseter (considered equal to 0 by convention), for dentate subjects versus prosthodontically treated individuals. ND/ND – natural dentition group; CD/XX – prosthodontically treated individuals; WMM – working masseter; WTA – working temporalis anterior; BMM – balancing masseter; BTA – balancing temporalis anterior; WDA – working digastric anterior; BDA – balancing digastric anterior.
Fig. 3.32 Timing of masticatory muscles, based on peak activation and referenced to the timing of working masseter (considered equal to 0 by convention), for dentate subjects versus prosthodontically treated individuals, by agar concentration in the samples chewed. Error bars denote ± 1 standard error of the mean. ND/ND – natural dentition group; CD/XX – prosthodontically treated individuals; WMM – working masseter; WTA – working temporalis anterior; BMM – balancing masseter; BTA – balancing temporalis anterior; WDA – working digastric anterior; BDA – balancing digastric anterior.
Fig. 3.33 Timing of masticatory muscles, based on peak activation and referenced to the timing of working masseter (considered equal to 0 by convention), for dentate subjects, by chew number. Error bars denote ± 1 standard error of the mean. WMM – working masseter; WTA – working temporalis anterior; BMM – balancing masseter; BTA – balancing temporalis anterior; WDA – working digastric anterior; BDA – balancing digastric anterior.
Fig. 3.34 Timing of masticatory muscles, based on peak activation and referenced to the timing of working masseter (considered equal to 0 by convention), for prosthodontically treated subjects. WMM – working masseter; WTA – working temporalis anterior; BMM – balancing masseter; BTA – balancing temporalis anterior; WDA – working digastric anterior; BDA – balancing digastric anterior. CD/CD – conventional full denture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/ND – conventional full denture/natural dentition group; CD/OD – conventional full denture/implant-supported overdenture group.
Fig 3.35 Timing of jaw-opening masticatory muscles, based on peak activation and referenced to the timing of working masseter (considered equal to 0 by convention), for prosthodontically treated subjects, by chew number. Error bars denote ± 1 standard error of the mean. WMM – working masseter; CD/CD – conventional full denture group; CD/FD – conventional full denture/implant-supported fixed prosthesis group; CD/ND – conventional full denture/natural dentition group; CD/OD – conventional full denture/implant-supported overdenture group.
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