DOCTOR OF PHILOSOPHY

The Measurement of Maximal Bite Force in Human Beings

Alibrahim, Anas

Award date:
2015

Awarding institution:
University of Dundee

THE MEASUREMENT OF MAXIMAL BITE FORCE IN HUMAN BEINGS

ANAS ALIBRAHIM

BDS, MDSc

A thesis submitted for the degree of

Doctor of Philosophy

University of Dundee

March, 2015

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

ٱقْرَأْ بِٱسْمِ رَبِّكَ ٱلَّذِى خَلَقَ (١)

Recite in the name of your Lord who created -

خَلَقَ ٱلْإِنسَٰنَ مِنْ عَلَقٍ (٢)

Created man from a clinging substance.

ٱقْرَأْ وَرَبُّكَ ٱلْأَكْرَمُ (٣)

Recite, and your Lord is the most Generous -

ٱلَّذِى عَلَّمَ بِٱلْقَلَمِ (٤)

Who taught by the pen -

عَلَّمَ ٱلْإِنسَٰنَ مَا لَمْ يَعْلَمْ (٥)

Taught man that which he knew not.

Table of Contents

Acknowledgements

First, I would like to thank both my supervisors for their time, guidance, help and support. I am very grateful to **Professor Samuel W. Cadden** for his words of encouragement, sharing his knowledge, and input and advice; in particular the time he spent reviewing the written work is greatly appreciated. I am grateful to **Dr Mervyn F. Lyons** for helping me to set up the study and for inspiring me to pursue this subject. I would like to thank **Dr Mounir Atassi** for his help in setting up experiments, in particular the time he spent with me in the lab.

I would like to thank the Prosthodontics Department, College of Dentistry, Jordan University of Science and Technology for their sponsorship and for giving me the opportunity to further my studies. I would also like to thank the staff and dental nurses at Dundee Dental School for their support throughout the course.

I would like to thank the research subjects (my colleagues and friends) who gave their valuable time to participate in experiments.

I would also like to thank my family and friends; in particular my parents, **Nayef and Atefah**, without their love, prayers, encouragement and support I would not be able to achieve all this, thank you.

Finally, and most importantly, I would like to thank my wife, **Hannah**, for her unwavering love and constant support. Without her encouragement, dedication, quiet patience, and confidence in me, this would not have been possible.

Declaration

I, Anas Alibrahim, hereby declare that I am the author of this thesis and that all references cited have been consulted by myself. I was the principal investigator in all studies described in this thesis. This work has not previously been submitted for a higher degree in this or any other university.

Anas Alibrahim

Certificate

I hereby certify that Anas Alibrahim has fulfilled the conditions of Ordinance 39 of the University of Dundee and is qualified to submit this thesis for the Doctor of Philosophy.

Professor Samuel W. Cadden

Publications

At the time of writing, the following publications have arisen either directly or indirectly as a result of the work described in this thesis:

Directly:

Alibrahim AN, Lyons MF & Cadden SW. Pressure Versus Strain-Gauge Transducers for Bite-Force Measurement. *Journal of Dental Research*: **93** (Spec Iss C), 191933, 2014.

Indirectly:

Chinni SS, Al-Ibrahim A & Forgie AH. A simple, safe, reliable and reproducible mechanism for producing experimental bitemarks. *Journal of Forensic Odonto-Stomatology*: **31**, 22-29, 2014.

To my parents, Nayef and Atefah

To my parents in-law, Anas and Lama

To my wife and daughter, Hannah and Judy

May god bless you all

Abstract

Background: Registering a true maximum bite force on the most commonly-used force transducers is problematic. It is often believed that this is related mainly to discomfort and the fear of breaking teeth.

Objectives: The aim of the project was to compare the suitability of different bite force measuring transducers including ones which were designed to improve subject comfort. The transducers used were a traditional strain-gauge transducer with and without covering with ethylene vinyl acetate (EVA) sheets, and a newly-developed pressure transducer.

Methods: Five separate studies were performed in this project. The experiments were carried out on human volunteer subjects (aged 24 to 41 years). They were all dentate with no missing anterior teeth and with no crowns on these teeth. The following procedures were used in some or all of the studies: measurement of MVBF, electrical stimulation of the masseter muscle, and EMG recording from two pairs of jaw closing muscles.

Results: The highest MVBF values were recorded on the pressure transducer, mean (± S.D.) 464 N ± 224 N; followed by the strain-gauge transducer with EVA sheets, 243 ± 80 N; and last of all the strain-gauge transducer with silicone indices, 165 ± 35 N; or acrylic indices, 163 ± 82 N. Significantly higher maximum potential bite forces were predicted by twitch interpolation for the pressure transducer (730 ± 199 N) than for the strain-gauge transducer with EVA sheets, 354 ± 67 N (Paired t test, $P < 0.05$). Significantly higher EMGs of the masseter and anterior temporalis muscles were found to be associated with MVBFs on the pressure transducer than with MVBFs on the strain-gauge transducer with EVA sheets (Paired t test, $P < 0.05$).

Conclusions: It is concluded that: a) the pressure transducer system and to a lesser extent the strain-gauge transducer covered with EVA sheets seemed to overcome the fear associated with biting on the hard surfaces of the strain-gauge transducer alone; b) the pressure transducer may have some multi-directional capabilities which allow for total bite forces, or at least larger parts of them, to be recorded than on a uni-directional strain-gauge transducer.

Chapter 1: Introduction

1.1 General

Dentists and oral physiologists have long been interested in bite force as it is an indicator of the functional state of the masticatory system (see Hagberg, 1987; Bakke, 2006). It results from the combined action of the jaw closing muscles and is modified by jaw biomechanics and reflexes. The skeletal, muscular, dental, and nervous systems all have an effect on bite force, and the condition of these systems will influence the biting ability of a human (e.g. see Ow et al., 1989; Rentes et al., 2002; Duygu Koc et al., 2010).

It has been argued that there are two main factors that might prevent subjects from registering the true maximum bite forces which their jaw closing muscles are capable of producing when biting on hard surfaces. First, the discomfort and the fear of breaking cusps and edges of teeth and dental restorations (Braun et al., 1995; Lyons et al., 1996; Fernandes et al., 2003). Secondly, the possible initiation of a significant negative modulation of jaw closing muscle activity and thus biting forces triggered by activation of sensory receptors within the periodontium, and / or the possible prevention of a significant positive modulation of jaw closing muscle activity and thus biting forces also triggered by these receptors (van der Glas et al., 1985; Paphangkorakit and Osborn, 1998; Serra and Manns, 2013).

1.2 Why is Bite Force Measured?

Measurement of maximum voluntary bite force (MVBF) has been used in dentistry for various reasons: to understand the underlying mechanics of mastication (see Carlsson, 1974; Bates et al., 1975; Bakke, 2006), to evaluate the physiological characteristics of jaw muscles (e.g. Sasaki et al., 1989; Bakke et al., 1992; Lyons et al., 1996; Tortopidis et al., 1999), to study the effect of different physical factors such as gender, age, height, and weight on occlusal forces (e.g. Kiliaridis et al., 1993; Braun et al., 1995), and to provide reference values for studies on the biomechanics of prosthetic devices (see Şahin et al., 2002). Furthermore, measurement of MVBF has been considered by some to be clinically important in the assessment of the performance and therapeutic effects of prosthetic devices (e.g. Haraldson et al., 1979; Lassila et al., 1985; Müller et al., 2001), and in the diagnosis and treatment of temporomandibular disorders (TMD; e.g. Helkimo et al., 1975; Pereira et al., 2007).

Many studies have shown that patients with disturbances of the craniomandibular system, such as pain from masticatory muscles and / or temporomandibular joints, have lower MVBFs than healthy subjects (see Molin, 1972; Helkimo et al., 1975; Hagberg, 1987). In a study by Molin (1972), a group of TMD patients produced only one half to two thirds of the forces produced by heathy control subjects. Tortopidis et al (1999) found that MVBF was lower in edentulous TMD patients compared to healthy edentulous patients. Moreover, it was found that MVBF increased in TMD patients after management of symptoms during treatment (e.g. Helkimo et al., 1975).

1.3 History

Interest in bite force has a long history. Borelli, in 1681 (cited by Brawley and Sedwick, 1938; Duxbury et al., 1973; Duygu Koc et al., 2010), was the first to perform an experimental study, measuring intraoral forces, using his own designed gnathodynamometer. He attached different weights to a cord, which was placed over the mandibular molar teeth while the mouth was opened, and with the closing of the mouth, up to 200 kg (1961 N) were lifted. In 1893, Black (cited by Rowlett, 1933; Brawley and Sedwick, 1938; Duygu Koc et al., 2010) designed a new type of gnathodynamometer, which he used to measure intraoral forces due to vertical jaw movements. Subsequently, several workers continued to study bite force and designed different types of measuring devices, including the lever-spring, manometer-spring and lever, and micrometered devices (see Brawley and Sedwick, 1938; Ortu, 2002; Duygu Koc et al., 2010).

At the present time, a variety of methods and devices are available for the measurement of bite force, ranging from conventional mechanical devices to more advanced electronic transducers (see Bates et al., 1975; Hagberg, 1987; Duygu Koc et al., 2010). Most of these electronic transducers base their function on the action of electrical resistance strain-gauges (e.g. Molin, 1972; Tortopidis et al., 1999; Fernandes et al., 2003).

More recently, computerised occlusal analysis systems with pressure sensitive foils have been developed for the measurement of bite force and occlusal contact area. Examples of these systems are the T-scan system and Prescale system (e.g. Maness et al., 1987; Shinogaya et al., 2000; Iwase et al., 2006; Babu and Nayar, 2007).

1.4 Influential Factors on MVBF Measurement

A wide range of MVBF values have been reported in previous studies. This can be attributed to several factors that can influence the measurement of MVBF (see Hagberg, 1987; Bakke, 2006; Duygu Koc et al., 2010). These factors can be categorized into subject-device related factors and subject related factors. The subject-device related factors include: the amount of jaw separation as determined by the thickness of the bite force measuring device, and the type of measurement (anterior vs. posterior and unilateral vs. bilateral) as determined by the design and the position of the bite force measuring device. The subject related factors include: gender, age, craniofacial variables, dental status, periodontal condition, presence of malocclusion, and presence of TMD.

1.4.1 Subject-device Related Factors

1.4.1.1 The amount of jaw separation (transducer thickness)

A number of studies have reported that there is a trend for an increase in MVBF up to a jaw separation of 15-20 mm between anterior teeth and 9-11 mm between posterior teeth (e.g. Manns et al., 1979; Mackenna and Türker, 1983).

These ranges of jaw separation almost certainly correspond to the optimum length of the jaw closing muscle sarcomeres at which they are most able to produce the highest bite forces (Mackenna and Türker, 1983, Manns et al., 1979, Paphangkorakit and Osborn, 1997).

1.4.1.2 Type of measurement

MVBF can be measured unilaterally or bilaterally and between anterior or posterior teeth. Higher MVBFs have been reported between posterior teeth than between anterior teeth (e.g. Helkimo et al., 1977; Tortopidis et al., 1998b). This has been attributed mainly to the shorter distance from the fulcrum which gives a mechanical advantage to the jaw closing muscles (see Hagberg, 1987; van Eijden, 1991) and to the larger root area of posterior teeth (Gibbs et al., 2002; Bakke, 2006). Higher MVBFs were reported in bilateral measurements than in unilateral measurements (e.g. Tortopidis et al., 1998b; van der Bilt et al., 2008). This has been attributed mainly to the reduced occlusal support in unilateral measurements (Shinogaya et al., 2000).

1.4.2 Subject Related Factors

1.4.2.1 Gender

It is generally accepted that the MVBF in males is higher than in females (Helkimo et al., 1977; Shinogaya et al., 2001; Koç et al., 2011). In a study by Helkimo et al (1977), molar and incisor MVBFs were measured in a sample of Skolt Lapps using a specially designed strain-gauge metal transducer. It was found that the mean MVBF values were higher in males than in females in both the molar and the incisor regions. The mean MVBF in males was 176 N in the incisor region and 382 N in the molar region. On the other hand, the mean MVBF in females was 108 N in the incisor region and 216 N in the molar region.

In another study by Shinogaya et al (2001), the mean MVBF as measured with the Prescale system was significantly higher in a group of young Japanese males (1617 N) than in a similar age group of young Japanese females (1101 N). Many other studies have also confirmed the above findings, with higher MVBF values recorded in males than females (e.g. Ikebe et al., 2005; Calderon et al., 2006; Palinkas et al., 2010; Koç et al., 2011).

The higher MVBF values in males may be related to the greater muscular potential in men due to several physiological differences. It has been found that the masseter muscle in males has a larger diameter and cross-sectional area of type II muscle fibres (see Tuxen et al., 1999; Hatch et al., 2001; Duygu Koc et al., 2010). It has also been found that males have larger jaw dimensions than females (Bakke, 2006). Koç et al (2011) suggested that the lower MVBF in females is possibly because of the significantly lower pressure pain threshold, and pressure pain intolerance, during maximum biting. Furthermore, it has been found that the MVBF increases with age after puberty at greater rates in males than in females (Braun et al., 1996).

Other authors have related the higher MVBF in males to the larger size of the dentition (Ferrario et al., 2004a). These authors stated that the larger size of teeth in males is associated with a larger periodontal ligament area which can withstand higher biting forces. However, it should be noted that there is no conclusive evidence for a significant role for periodontal sensory receptors, and their associated inhibitory or excitatory (positive) reflexes, in the control of maximum bite force (see Hellsing, 1980; Orchardson and Cadden, 1998; Kleinfelder and Ludwig, 2002; Morita et al., 2003).

1.4.2.2 Age

Bite force could be considered an important factor in more fully understanding the normal ageing process and its associated changes (Palinkas et al., 2010). It has been shown that MVBF increases with age and growth through childhood, stays relatively constant from about 20 years to 40 years, and then declines (Bakke, 2006). In a study by Kiliardis et al (1993), the relation between MVBF and age, in a sample of growing healthy subjects, was investigated. The MVBF measurements revealed a positive correlation between MVBF and age in both sexes. In another study, Bakke et al (1990) studied the MVBF in a sample of healthy subjects (aged 8 to 68 years). The authors found that the MVBF increased with age until 25 years. They also found that the level of the MVBF decreased significantly after this age in women, whereas only a slight decrease occurred in men until the age of 45 years.

Indeed, skeletal muscle atrophy and declining strength are mostly inevitable consequences of ageing (Ikebe et al., 2005). The loss of skeletal muscle mass may be related to some age-related changes in tissue secretion or responsiveness to trophic hormonal factors (Baumgartner et al., 1999). Other reasons have also been suggested such as the changes in the dietary intake and the lack of exercise i.e. disuse atrophy (Baumgartner et al., 1998). With regard to the jaw closing muscles, it has been found that the cross-sectional areas of the masseter and the medial pterygoid muscle reduce significantly with ageing (Newton et al., 1993). This reduction in the muscles' mass will likely be associated with a decrease in the maximal mechanical output of these muscles, i.e. a decrease in the maximum bite force.

1.4.2.3 Craniofacial variables

Many studies have shown a relationship between bite force and the different variables of craniofacial morphology (e.g. Ringqvist, 1973; Kiliaridis et al., 1993; Waltimo et al., 1994; Bonakdarchian et al., 2009). Generally speaking, there are three basic facial types: short (brachyfacial), average (mesofacial), and long (dolichofacial).

It has been found in several studies that the people with short faces usually have the highest MVBFs followed by the people with the average faces and lastly the people with the long faces (e.g. Proffit et al., 1983; van Spronsen, 2010; Custodio et al., 2011). Abu Alhaija et al (2010) assessed the MVBFs in a sample of Jordanian dental students with three different facial patterns: short face, average face, and long face. The MVBF was measured using a digital occlusal force gauge (GM10, Nagano Keiki, Japan). The authors found that the group with the short faces recorded the highest MVBF values (mean = 680 N), followed by the group with the average faces (mean = 593 N), and finally the group with the long faces (mean = 454 N). In a previous study by Proffit et al (1983), it was found that the long-faced individuals had significantly lower MVBF than the individuals with the average vertical facial dimensions. In agreement with the above studies, Farella et al (2003) found that the short-faced subjects have thicker and stronger masseter muscles than the long-faced subjects.

The short face type is usually associated with reduced facial heights, deep anterior overbite, and acute gonial angle. The long face type is usually associated with excessive vertical facial growth, increased mandibular inclination, anterior open bite, and increased gonial angle (Serrao et al., 2003; Abu Alhaija et al., 2010; Custodio et al., 2011). It has been suggested that the bite force may reflect the geometry of the lever system of the mandible; in that when the ramus of the mandible is more vertical and the gonial angle is relatively acute, the mandibular elevator muscles will have a greater mechanical advantage and will produce higher biting forces (see Bakke, 2006; Duygu Koc et al., 2010).

1.4.2.4 Dental status

It has been shown in many studies that there is a significant relationship between the MVBF and the number of the natural teeth present (see Helkimo et al., 1977; Bakke et al., 1990; Duygu Koc et al., 2010). Helkimo et al (1977) found that greater MVBF values were associated with greater numbers of natural teeth present, and that the MVBF was significantly smaller in denture wearers than in subjects with full natural dentition. In another study, Miyaura et al (2000) compared the MVBFs in subjects with full natural dentition, fixed partial dentures, removable partial dentures, and complete dentures. They found that the MVBF was highest in the full dentition group (mean = 491 N), followed by the group with the fixed partial denture (mean = 394 N), and then the group with the removable partial denture (mean = 174 N), and finally the complete denture group (mean = 55 N). Similar results have also been found by other workers who have compared the MVBFs in subjects with different states of dentition and with different types of dental prosthesis (see Lassila et al., 1985; Hagberg, 1987; Sonnesen and Bakke, 2005).

Tooth loss in the molar region has a more negative influence on the level of the MVBF than loss in the anterior teeth region (Gibbs et al., 2002; Bakke, 2006). In a study by Shinogaya et al (2000), the first and the second molars contributed to more than half of the total MVBF as recorded with the dental Prescale system. Perhaps, as discussed earlier, this is due to the fact that the molars have a more favourable position, i.e. shorter distance from the fulcrum, larger root areas, and larger periodontal support areas (see Hagberg, 1987). Correspondingly, occlusal tooth contacts are more frequent between the molars than the anterior teeth particularly during maximum clenching (Shinogaya et al., 2000; Bakke, 2006).

The number and the area of the occlusal contacts could be more important determinants of the MVBF than the number of teeth present. Hatch et al (2001) reported that the MVBF was greatly influenced by the number of the occlusal contacts. This is in agreement with the results of Bakke et al (1990) who found that 10 to 20% of the variation in the MVBF was explained by the variable number of occlusal contacts.

There is more than one possible explanation for the relation between the MVBF and the occlusal contacts: a) tooth contacts permit better force distribution over the teeth, thus reducing the potential perception of pain and permitting higher biting forces to be produced; b) good occlusal stability may result in stronger masticatory muscles with greater force output; and / or c) stronger masticatory muscles with higher biting forces may enhance better occlusal stability and more tooth contacts to develop (Ingervall and Minder, 1997).

1.4.2.5 Periodontal condition

The effect of the periodontal condition on the level of the MVBF in humans is controversial. Some studies have reported that lower levels of MVBF are associated with reduced periodontal tissue support (e.g. Williams et al., 1987; Alkan et al., 2006). However, other studies have reported that the effect of the periodontal condition on the level of the MVBF is negligible (e.g. Kleinfelder and Ludwig, 2002; Morita et al., 2003).

Alkan et al (2006) compared the MVBF and occlusal contact area of chronic periodontitis patients with control subjects with healthy dentition. The MVBF and occlusal contact areas were measured using the dental Prescale system. The authors found that both the MVBF and occlusal contact area values were significantly greater in the healthy control subjects (904 N, 25 mm^2) than the chronic periodontitis patients (668 N, 19 mm^2).

By contrast, Kleinfelder and Ludwig (2002) failed to find any significant correlations between the periodontal indices and the level of MVBF. In another study, Morita et al (2003) found a significant negative correlation between the MVBF and the clinical attachment loss but not with the probing pocket depth and the bleeding on probing.

An explanation for the proposed effect of the periodontal condition on the level of the MVBF, is that the sensory inputs from the receptors in the periodontium play a key role in the control of the bite force (Alkan et al., 2006). However, as mentioned earlier, this explanation is controversial as some studies have denied that there is a significant role for the periodontal sensory receptors in the control of maximum bite force (see Hellsing, 1980; Orchardson and Cadden, 1998; Kleinfelder and Ludwig, 2002; Morita et al., 2003).

1.4.2.6 Presence of malocclusion

A relationship between the MVBF and malocclusion is said to exist. It has been reported in many studies that the MVBF is often reduced in subjects with malocclusions (e.g. Throckmorton et al., 1996; Sonnesen et al., 2001; Bakke, 2006). In a recent study by Sathyanarayana et al (2012), MVBF was assessed in adult subjects with different forms of malocclusions and compared to that of control subjects with normal occlusions. The authors concluded that the MVBF significantly correlated with the vertical facial morphology whereas a weak correlation was found between the MVBF and the malocclusions which are linked to the sagittal facial morphology. In agreement with the above study, Trawitzki et al (2011) found that there was no significant difference in MVBFs between subjects with class II and those with class III dentofacial deformities, although the values for both groups were lower than those of control subjects.

It might be concluded that malocclusion might negatively affect the MVBF especially when it is associated with a reduced number of occlusal contacts. However, the MVBF does not seem to vary significantly between the different classes of malocclusions and no systematic relationship between the two has been found (Sonnesen and Bakke, 2005).

1.4.2.7 Presence of TMD

TMD refer to the signs and symptoms associated with pain and functional-structural disturbances of the masticatory system, especially of temporomandibular joint and jaw closing muscles, or both.

As discussed earlier, many studies have shown that TMD patients have lower MVBFs than healthy subjects (see Molin, 1972; Helkimo et al., 1975; Hagberg, 1987). This has been attributed mainly to muscle tenderness and pain in the temporomandibular joint (Kogawa et al., 2006; Pizolato et al., 2007). However, in a study by Pereira-Cenci et al (2007), no difference in MVBFs was found between TMD patients and healthy control subjects. This could be attributed to the variation in severity of symptoms in TMD patients recruited in different studies.

As also discussed earlier, a number of studies have reported an increase in the level of MVBF in TMD patients after treatment and palliation of symptoms (e.g.

Helkimo et al., 1975; Pereira et al., 2009). Thus, the measurement of MVBF may be a useful indicator in the diagnosis and treatment of TMD.

1.5 Bite Force Recording Devices

As mentioned earlier, a variety of systems and devices are available at the present time for the measurement of MVBF. These include strain-gauge transducers, pressure sensitive foils (e.g. T Scan and Prescale systems), load cells, digital occlusal force-meters, and pressure transducers.

1.5.1 Strain-gauge Transducers

Strain-gauge metal force tranducers have been used in many bite force studies (see Manly and Vinton, 1951; Garner and Kotwal, 1973; Lindqvist and Ringqvist, 1973; Bates et al., 1975; Lyons and Baxendale, 1990). Different designs of these transducers have been described previously (e.g. Linderholm and Wennström, 1970; Sasaki et al., 1989; Lyons and Baxendale, 1990; Lyons et al., 1996). One of the earliest designs was that described by Linderholm and Wennström (1970). Their transducer consisted of two steel bars which were formed into bite plates at one end, and were joined by a wedge-formed steel part at the other end. Strain-gauges were applied to the steel bars and connected in a Wheatstone bridge circuit. With the transducer connected to a potentiometer writer, it was possible to record the load on the bite plates.

The theory of operation for the strain-gauge transducer is that any change in resistance of strain-gauges that follows loading the transducer i.e. bending the strain-gauges, will result in a change in electric potential or voltage. This change in voltage can then be calibrated with a known weight to indicate the applied load.

Although strain-gauge transducers have proved to be accurate for the measurement of MVBF, it is still difficult to record a true maximum bite force. It has been suggested that this is mainly due to discomfort and to the fear of breaking cusps and edges of teeth and dental restorations when biting on the hard surfaces of the transducers (Braun et al., 1995; Lyons et al., 1996; Fernandes et al., 2003). Thus, some workers have attempted to make biting on the strain-gauge transducers a more comfortable procedure by covering the metal surfaces with different materials such as acrylic resin, gauze, gutta percha, and polyvinyl chloride (PVC; e.g. Molin, 1972; Tortopidis et al., 1998a; Tortopidis et al., 1999; Shinogaya et al., 2000). However, although using the protective covers might have reduced the discomfort to some degree, it has not totally overcome the fear and the discomfort associated with biting on the hard surfaces (Lyons et al., 1996; Fernandes et al., 2003).

1.5.2 Pressure Sensitive Foils

It has been argued that the evaluation of bite force and the area of occlusal contact in the intercuspal position is of considerable importance as most of tooth contact during masticatication occurs near this position (Pameijer et al., 1969; Hidaka et al., 1999). To that end, computerised occlusal analysis systems with pressure sensitive foils have been developed for studying the bite force and the occlusal contact area in the intercuspal position. The T Scan system and the Prescale system are examples of these systems.

1.5.2.1 T Scan system

The T Scan system is a computerized occlusal analysis system which was developed by the Tekscan company to assist in occlusal analysis by providing information on the timing and distribution of occlusal contacts as well as the magnitude of bite force. The first generation of the T Scan system consisted of a piezoelectric foil sensor, sensor handle and cable, system unit, and software for recording and analyzing the data (Maness et al., 1987; Lyons et al., 1992). The newer versions of the T Scan system consist of a sensor and handle which plugs directly into the USB port of a Windows-based PC or laptop.

The sensor foil is made up of several layers of electrically conductive inks on a polyester film substrate. The top and bottom surface of the sensor are printed with thin conductive strips which form an X - Y grid of more than 1500 sensing points. The spacing of the grid lines determines the degree of the planar resolution. The thickness of the sensor foil is about 100 microns and it is held in a rigid plastic supporting handle for intra-oral use. The theory of operation for the T Scan sensor is that any increase in pressure will lead to a decrease in the electrical resistance. The electronics in the handle scan the sensor and look at each contact point to determine the resistance and thus the pressure or force.

Lyons et al (1992) evaluated the T Scan system and tested the accuracy of the system in measuring bite force. They concluded that the system did not measure bite force accurately, but that it was still useful as a clinical tool in the determination of the position of contact points. Another disadvantage of the T Scan system is the inflexibility of the sensor foil. It has been found that this inflexibility can lead to uncontrolled shifts of the mandible which would result in incorrect data and misleading reproduction of occlusal contacts (Patyk et al., 1989; Hidaka et al., 1999).

1.5.2.2 Dental Prescale system

The Dental Prescale system (Dental Prescale, Fuji Film Co., Tokyo, Japan) is a computerised occlusal analysis system used for the measurement and analysis of bite force (N), occlusal contact area (mm^2), and bite pressure (MPa). It was developed in an attempt to overcome the limitations of strain-gauge tranducers such as the discomfort associated with biting on metal beams and the fear of breaking teeth or restorations. It consists of a horse-shoe shaped Prescale pressure sensitive foil, a pressure distribution mapping software (FPD, Fujifilm Co., Tokyo, Japan), and a suitable scanner (see Shinogaya et al., 2000; Duygu Koc et al., 2010).

When the foil is subjected to occlusal load a graded colour-producing chemical reaction occurs and the intensity of the colour is proportionally related to the amount of pressure. The foil contains a layer of microcapsules of different sizes which contain a colourless dye, and a developer layer. When subjected to pressure above 5 MPa the largest and thinnest capsules start to break and release the dye; with increasing pressure the smaller and thicker capsules break and release their dye. The released dye reacts with the developer and this reaction gives a red colour. With increasing pressure, the red colour becomes more intense. The pressure sensitive foil is then analyzed in a scanner. The scanner reads the area and the colour intensity of the red dots in order to calculate bite force and occlusal contact area using the pressure distribution mapping software (Suzuki et al., 1997; Ando et al., 2009; Duygu Koc et al., 2010).

The dental Prescale system has been tested in many bite force studies on fully dentate, partially dentate, and edentulous patients (e.g. Matsui et al., 1996; Suzuki et al., 1997; Shinogaya et al., 1999). The main advantages of the dental Prescale system are: a) the ability to measure MVBF close to the intercuspal position; b) the ability to calculate bite force from every tooth in recordings with trivial disturbance to occlusion; c) the ability to measure the occlusal contact area; d) that it is more convenient and comfortable for subjects than strain-gauge transducers; e) it's good reproducibility; and f) that it is an easy procedure (Bakke, 2006; Ando et al., 2009; Duygu Koc et al., 2010). The main disadvantages are: a) some technical limitations in the computerized scanning system which leads to overestimation of the MVBF; b) it not being possible to carry out continuous measurements; and c) it is time consuming (Shinogaya et al., 2000).

1.5.3 Load Cells

Different shapes and designs of load cells have been used in bite force studies. However, they all share the same concept, which is that the resistance changes with an increase in the applied force. One example of load cells is the FSR™ № 151 force sensing resistor from Interlink Electronics Inc. This sensor is a circular conductive polymer pressure-sensing resistor. It consists of two thermoplastic sheets; the bottom sheet is deposited with two conducting interdigitated electrodes, and the top sheet is coated with a semi-conductive Polyetherimide ink. The basic feature of this sensor it that it is piezoresistive, i.e. its resistance decreases with increasing applied pressure. The main function of the thermoplastic sheets is to protect and insulate the sensor from moisture and temperature changes. The diameter of this circular sensor is 12 mm and the thickness is 0.25 mm.

The FSR™ № 151 force sensing resistor has been used in many bite force studies (e.g. Fernandes et al., 2003; Gonçalves et al., 2011; Simone Guimarães Farias Gomes et al., 2011; William Custodio et al., 2011). In a recent study by Gonçalves et al (2011), the FSR™ № 151 force sensing resistor was used to measure the influence of female hormonal fluctuation during the menstrual cycle on MVBF. In this study, two FSR™ № 151 force sensing resistors were used to measure the MVBF bilaterally in the first molar region. In order to protect the sensors from deformities during biting, each sensor was covered by a 1.0 mm thick metal disk and a 1.7 mm thick rubber disk from each side. The overall thickness of the assembly was 5.65 mm. The outer wider rubber disk ensured a comfortable biting procedure during the experiment. The mean MVBF in this study was 465 N and there was no significant effect of hormonal fluctuation on the MVBF in the study sample.

In addition to their use in the measurement of biting forces in humans, load cells have also been used for the measurement of biting forces in animals (e.g. Bousdras et al., 2006; Freeman and Lemen, 2008). Freeman and Lemen (2008) developed a device for measuring bite force in small mammals. Their apparatus consisted of two parts; a piezo-resistive load cell and an electronic device for detecting the changes in the resistance of the sensor. The piezo-resistive sensor was a strip of thin plastic 10 mm wide, 150 mm long, and 0.2 mm thick. It was a Flexiforce sensor from Tekscan (Tekscan, Inc., South Boston, USA).

The piezoresistive material is the circular part at the tip of the sensor. It functions as a variable resistor, i.e. its resistance decreases when the force applied increases. The second part, which is the electronic device used for measuring the changes in the resistance of the sensor, was an electric circuit connected to a B2pe microcontroller (Parallax, Inc., Rocklin, California). In parallel with the Flexiforce sensor there was a small capacitor. The microcontroller charges the capacitor and then measures the time required to discharge the capacitor through the Flexiforce sensor. The time required for discharge will depend on the resistance of the sensor; the lower the resistance, the less time required. Flexiforce sensors can measure force up to 4500 N.

Freeman and Lemen (2008) concluded that Flexiforce sensors are inexpensive and easy to use. However, they found that these sensors are less accurate than other types of load cells.

1.5.4 Digital Occlusal Force-meters

Digital force gauges are useful in field studies and when a large number of participants are recruited. GM10 occlusal force-meter (GM10, Nagano Keiki, Japan) is one example of these devices that has been used in many bite force studies (e.g. Hasegawa et al., 2003; Kamegai et al., 2005; Abu Alhaija et al., 2010; Varga et al., 2011). This digital force gauge consists of a hydraulic pressure gauge and a biting element made of a vinyl material and encased in a disposable plastic tube. The thickness of the biting element is 5.4 mm, the length is 63.5 mm, and the width is 17 mm. The measurement range for this device is 0 – 1000 N. The accuracy and the repeatability of the GM10 force-meter has been confirmed by Nakano K et al (1994) and Sakaguchi et al (1996).

The main advantages of the GM10 occlusal force-meter are: a) portable; b) easy to use; c) soft biting element that enables safe, accurate, and comfortable MVBF recording; d) instantaneous digital measurement of bite force – as bite force is calculated and displayed digitally in Newtons; and e) bite force could be measured unilaterally or bilaterally. On the other hand, the main disadvantage is the inability to carry out continuous measurements.

1.5.5 Pressure Transducers

Pressure transducers have been developed for the measurement and analysis of bite force in view of the potential problems of strain-gauge metal transducers (Braun et al., 1995; Rentes et al., 2002; Winocur et al., 2007). The first design of pressure transducers was developed by Braun et al (1995). It consisted of a sterilizable, fibre-reinforced, rubber tube connected to a pressure sensor (Omega Model No. PX300 – 1KGV, Omega Engineering, Inc, Stamford, Conn). Pressure change was converted to an electrical signal and transferred to a digital strain indicator (Vishay/ Ellis – 20, Measurements Group, Inc, Raleigh, NC). In Braun et al's study, the mean MVBF in second premolar / first molar region was found to be 738 N. The authors explained these high values as follows:

1) The tube was relatively comfortable so the subjects were less reluctant to record true maximal forces.

2) During biting, the tube deformed elastically, conforming to the occlusal anatomy of teeth, and thereby providing more uniform force distribution. This deformation is important because it gives the subjects a degree of psychological security to exert their true maximum bite force.

3) The subjects were all dental students and this may have been a contributory factor for the higher MVBF values.

However, in the publication of this study, there are no details about the pressure range created by bite forces, the length and the diameter of the tube, the degree of rigidity of the tube and the type and viscosity of the fluid used to fill the tube.

Rentes et al (2002) used a pressure transducer to measure MVBF in children with primary dentitions. A different pressure sensor (MPX 5700, Motorola, SPS, Austin, TX, USA) than that used in the above study was used. The tube (7mm diameter) and the sensor were connected to an analogue to digital converter fed by an analog signal coming from the pressure sensor. The system was connected to a computer where software for reading the pressure changes had been installed.

According to the manufacturer’s instructions, the MPX 5700 pressure sensor is suitable only for the measurement of air pressure. They also state that any pressure media other than dry air might have adverse effects on sensor performance and long-term reliability. However, as air is compressible, there would be bounce and a lag time which is likely to be problematic in MVBF measurements. There would also be a significant effect of changes in temperature. However, there are no details in the publication of this study as to whether air or liquid was used to fill the tube.

Another design of pressure transducer was developed by Winocur et al (2007). Their custom-made rubber tube bite force measuring device consisted of a 20 cm long, 9.5 mm diameter, flexible rubber tube (Wing Foot 300, Good year, Akron, Ohio) which was filled with water and sealed to a manometer (Armaturenbau GmbH, Wesel – Ginderich, Germany, 63’ RKG 300 psi) at one end. In order to measure the MVBF, subjects were instructed to bite as hard as possible at the molar or incisor region, and the peak biting pressure was preserved by a special handle on the manometer dial. The measured pressure was then converted to a force value (N) according to a predefined calibration curve. In the authors' opinion, this system was safe, comfortable, and accurate in measuring MVBF. Furthermore, the authors claimed that the subjects recorded true maximal values because there was no fear of pain or dental fractures as with strain-gauge metal transducers.

1.6 Bite Force Measurement in Three Dimensions

1.6.1 The Three-dimensional Nature of Bite Force

The three-dimensional nature of bite force has been related to the different orientation of the jaw closing muscles elements in relation to the occlusal plane. Each muscle has different elements which are differently oriented, e.g. the masseter muscle has differently oriented superficial and deep elements. This would enable each of the jaw closing muscles elements to generate a force vector on the mandible with a different spatial orientation. Overall, an activation of the masseter and medial pterygoid muscles yields a forward force on the mandible. The temporalis muscle has an anterior part which is almost perpendicular to the occlusal plane and thus yields a vertical force and a posterior part which yields a backward force (Koolstra et al., 1988; van Eijden, 1991). Consequently, different combinations of action of the jaw closing muscles will lead to the application of the resultant force on the mandible in different magnitudes and directions.

Accordingly, it has been shown that bite force has both horizontal (anterior-posterior and medial-lateral) and vertical components, and that a total bite force should be the vector sum of all these components (Koolstra et al., 1988; van Eijden, 1991; Osborn and Mao, 1993; Mericske-Stern, 1998a).

1.6.2 The Use of Three-dimensional Transducers in the Assessment of the Multi-directional Nature of Bite Force

A variety of bite force transducers have been developed for the measurement of bite force. However, the majority of these transducers are unidirectional and allow for the measurement of bite force in only a single direction which is approximately the vertical direction (Linderholm and Wennström, 1970; Molin, 1972; Ringqvist, 1973; Helkimo et al., 1975; Pruim et al., 1978; Tortopidis et al., 1998b). To that end, multi-directional bite force transducers with the capability to record bite forces in horizontal and vertical directions have been developed (van Eijden et al., 1988; van Eijden, 1991; Osborn and Mao, 1993).

Van Eijden (1991) investigated the magnitude of MVBF at three different unilateral anteroposterior bite positions (canine, second premolar, and second molar) in several specified directions. For this purpose, he used a three-dimensional bite force measuring apparatus which was developed and used in an earlier study by the same and other workers (van Eijden et al., 1988). The bite force measuring apparatus consisted of a three-component piezoelectric force transducer (Kistler Instruments AG, Winterhur, Switzerland), dimensions 24 × 24 × 10 mm (length × width × height). The transducer had a working range of 5000 N in the axial (z) direction and 2500 N in the horizontal (x and y) directions.

At each bite position, subjects were instructed to maximally bite in 17 different predefined directions, thus making the total number of bites 51 (3 positions × 17 directions). Visual feedback, with simultaneous visualisation of both the actual and desired force direction on a computer screen, was used to indicate the desired bite direction. The output of the force transducer (three signals, one from each component) was recorded and digitised. Then, using a computer program, the magnitude of the MVBF was determined for each bite.

In addition, the moment arm length (resistance arm of bite force) produced in the sagittal plane was calculated by means of a lateral cephalometric radiograph. This was used to evaluate the efficiency of transfer of muscle to bite force. The moment arm length was defined as the perpendicular distance between the temporomandibular joint and the bite force vector.

The worker found a significant effect of both the bite position and force direction on the magnitude of MVBF. He found that, for each position, the highest mean MVBF values were achieved in vertical, posterior, and medial bite directions rather than that in corresponding anterior and lateral bite directions. The highest mean MVBF was achieved between the second molars in a postero-medial (10°) bite direction and was 724 N. The highest mean MVBF between second premolars was achieved in a vertical direction and was 583 N. The highest mean MVBF between canines was achieved in a posterior (10°) direction and was 485 N.

The moment arm length decreased from anterior to posterior bite positions and from anteriorly directed bites to posteriorly directed bites, thus indicating better efficiency of transfer of muscle to bite force.

The worker concluded that the highest possible bite force is not always associated with the direction which is perpendicular to the occlusal plane, and that the posteriorly and medially directed bite forces are generally higher than the corresponding anteriorly and laterally directed bite forces. This is in agreement with previous findings by Koolstra et al (1988) who described a three-dimensional mathematical model of the jaw closing system. They also concluded that the MVBF can be generated in a wide range of directions, and that the magnitude of MVBF largely depends on its direction.

Van Eijden et al might be the first group of workers who investigated the bite force in three dimensional aspects in depth (van Eijden et al., 1988; van Eijden, 1991). However, in the two studies where they built and used their three dimensional bite force measuring apparatus, there was not enough detail about the method in which the three dimensional force was calculated.

In a subsequent study, Osborn and Mao (1993) developed a 2 mm thick three dimensional force transducer. It consisted of a hollow H shaped steel housing to which two strain-gauge rosettes were attached. Each strain-gauge rosette contained three strain-gauges which were set at 45° intervals and cemented to the outer sides of the vertical arms of the H shape housing. Each strain-gauge was connected to ¼ Wheatstone bridge. The upper and lower surfaces of the crossbar of the H were 2 mm apart. When a load is applied to the crossbar of the H, the vertical bars of the H deform. This is accompanied by bending of the strain-gauges which results in a change of their resistance and subsequently a change in output voltage of the Wheatstone bridge. There were six outputs (one from each strain-gauge). These were converted to digital format by means of an Analog to Digital converter.

The change in resistance of the strain-gauges (expressed as change in voltage) is proportional to the amount of bending of the strain-gauges. By comparing the changes in resistance of the anterior strain-gauges to the changes in resistance of the posterior strain-gauges, the direction of bite force in the sagittal plane (anterior-posterior) could be calculated. By comparing the changes in resistance of the right side strain-gauges to the changes in resistance of the left side strain-gauges, the direction of bite force in the frontal plane (medial-lateral) could be calculated.

By comparing the output of the six strain-gauges, it was possible to formulate equations that enabled the calculation of the magnitude and the direction of bite force in the sagittal and the frontal planes. By means of personally written software, the magnitude and the direction of bite force were displayed on a computer screen.

The workers tested their device by positioning the transducer between the incisors with the cross bar of the H nearly horizontal. The workers found that subjects bit in a direction which was 10 -14° forward (anterior) of the vertical.

1.6.3 Recruitment of Differently Oriented Muscle Elements (Motor Units) at Different Jaw Openings and Biting Directions

During incisal biting, a number of masticatory muscles are involved in the production of bite force, primarily the superficial masseter (anteriorly directed) and the anterior temporalis (vertically oriented; Hylander, 1978). The direction of incisal bite force, in the sagittal plane, is therefore largely dependent on the ratio of activity between these two muscles (Osborn and Baragar, 1985). Bearing that in mind, Osborn and Mao (1993) attributed the anteriorly directed bite forces, found in their study sample, to the higher activity of the anteriorly oriented superficial masseter (as this yields a forward force on the mandible) than the vertically oriented anterior temporalis (as this yields a vertical force on the mandible). Thus, it was argued that a change in bite direction towards a more posterior direction would possibly be accompanied by an increased activity of the anterior temporalis or a bigger ratio between the activity in temporalis and masseter (temporalis / masseter). This was confirmed by electromyographic measurements in a later study by Paphangkorakit and Osborn (1997).

Using a three dimensional force transducer, Paphangkorakit and Osborn (1997) investigated the magnitude and direction of maximum incisal bite force at different jaw openings in ten subjects. Simultaneously, surface electromyographic (EMG) activity from the masseter and anterior temporalis muscles on both sides was recorded. The workers found:

a) The mean MVBF increased as the jaw was opened, reached a plateau between 14 and 28 mm of incisal separation, and then decreased as the jaw was further opened.

b) The direction of bite force, in respect to the lower occlusal plane, changed from anteriorly directed (11°) to posteriorly directed (5°) as the jaw opening was increased.

c) The ratio of EMG activity between the anterior temporalis and the masseter (temporalis/masseter) increased as the jaw opening was increased.

In agreement with these findings, a number of studies (e.g. Manns et al., 1979; Mackenna and Türker, 1983), as discussed earlier, reported a trend of an increase in MVBF as the jaw is opened, reaching a plateau at an optimal opening before it starts to decrease with further jaw opening. It has been proposed that the MVBF plateau starts when the sarcomeres of the masseter muscle reach their optimum length, and that this plateau lasts during further jaw opening, until those of the temporalis reach their optimum length while those of the masseter stretch beyond their optimum length (Paphangkorakit and Osborn, 1997). This indicates an increased involvement of the temporalis muscle as the jaw opening is increasing which has also been demonstrated by the increase in the ratio of EMG activity of the temporalis over the masseter (Lindauer et al., 1993; Paphangkorakit and Osborn, 1997).

This theory can also be extended to explain the change in bite force direction towards a more posterior direction with increasing jaw opening, since the superficial masseter (anteriorly oriented) becomes less involved and the anterior temporalis (vertically oriented) becomes more involved in the bite force production. Another possible explanation of the change in bite direction that is associated with jaw opening increase is the change in the position of the lower in relative to the upper bite points (Paphangkorakit and Osborn, 1997).

It should be noted that the above conclusions were drawn from studies where only EMG measurements of the masseter and temporalis muscles have been performed. The role of other jaw closing muscles (medial pterygoid) can also be influential on the magnitude and direction of bite force. However, unfortunately, these muscles are inaccessible for surface EMG measurement which makes the investigation of their role in bite force production a difficult task. Additionally, there is a role of suprahyoid muscles in jaw retrusion and depression which can also influence the bite force magnitude and direction, and thus it should be considered.

1.7 EMG in the Assessment of Bite Force

EMG is a physiological measure which is known to be proportionally related to muscle force production (see Inman et al., 1952; Basmajian and DeLuca, 1985). The relationship between muscle force production and EMG recording might be linear or non-linear depending on the muscle system. It has been reported in many studies that there is a linear relation between voluntary bite force and EMG activity of the jaw closing muscles especially at submaximal levels (e.g. Kawazoe et al., 1979; Bakke et al., 1989; Gonzalez et al., 2011). However, Haraldson et al (1985) found that this relationship was linear for the anterior temporalis muscle but not for the masseter muscle. In general, there is agreement that the integrated EMG of the jaw closing muscles increases linearly with bite force at submaximal contraction levels but starts to deviate from linearity as bite force increases towards the MVBF (Pruim et al., 1978; Tortopidis et al., 1998a).

EMG activity of the jaw closing muscles can be detected from surface recordings. A relationship can then be established between EMG activity and submaximal bite force and so an indirect estimation of the maximum bite force may be obtained. Fearraio et al (2004b) assessed the reliability of maximum bite force estimation as obtained from the submaximal EMG-force relationship. Participants in this study were asked to perform a maximum voluntary clench directly on their teeth and then four recordings of submaximal bite force (98 N, 196 N, 304 N and 392 N) were made on two strain-gauge metal transducers positioned on the left and right first mandibular molars. Simultaneously, surface EMG activity was recorded from the right and left masseter and anterior temporal muscles. For each subject, a linear regression was run between the submaximal bite forces and the corresponding EMG potentials. The EMG potentials recorded from the maximum voluntary clenches were then used to draw a best fitting line which was used to estimate the maximum bite force. On average, the estimated bilateral maximum bite force was approximately 700 N.

The authors in this study claimed that the estimates of maximum bite force were repeatable on a short term basis. However, the correlation between the two series of the estimates was not high. An important drawback of this study is that the authors estimated the maximum bite forces from EMG recordings of the maximum voluntary clenches while the teeth were together. Once the teeth are separated – as with the strain-gauge transducer – a change in the electromyographic-force relationship will occur. This fact has been reported by many authors (e.g. Mackenna and Türker, 1983; Lindauer et al., 1993), and can be attributed to the alterations in the muscle contractile properties due the changes in the length and thus to the relationship between electrical activity (which is unlikely to alter much with jaw position) and mechanical activity (which is).

Errors in the EMG recordings can happen due *inter alia* to the problems of short-circuiting when sweating occurs, or when the muscle belly is covered with hair-bearing skin (Tortopidis et al., 1998a). In addition, Bigland-Ritchie (1981) found that EMG activity is no longer an accurate indicator of bite force when muscle fatigue occurs. She found that when localized fatigue occurs, either the amplitude of EMG activity remains constant while bite force decreases, or the amplitude of EMG activity increases while bite force remains constant. This means that adequate rest periods are required between recordings if EMG to be used for the assessment of bite force.

1.8 Acoustic Myography (AMG) in the Assessment of Bite Force

Acoustic myography (AMG) is another physiological measure which is known to be proportionally related to muscle force production. It describes the sounds that are produced by the muscle when it contracts. The frequency of these sounds in humans is usually between 1 and 100 Hz (Bolton Ch et al., 1989).

Tortopidis et al (1998a) investigated the relationship between AMG and the level of force production in the masseter muscle. MVBF was measured between the anterior teeth, using a strain-gauge transducer. AMG was recorded using a piezoelectric crystal microphone which was placed over the belly of the masseter muscle. For each subject, MVBF was measured first, and then a series of four clenches were performed at 25, 50, 60 and 75% of the MVBF. AMG was measured simultaneously while performing the four clenches. In this study, the authors found a linear relationship between the AMG and the bite force at the four different submaximal bite force levels. They concluded that AMG might be a useful manner for the assessment of bite force. However, in a previous study by

Stiles and Pham (1991), AMG from the masseter and temporalis muscles failed to increase systematically with bite force. These authors found that AMG amplitude increased to a maximum at a low force level and then remained constant or decreased at higher forces. Other workers (Orizio et al., 1989) have found that AMG amplitude increased with increasing bite force, up to 80% of the MVBF and then decreased. Perhaps the differences in the above studies are because of some variations in the experimental methods such as the different types of force transducers, the different types of AMG recording devices, and the differences in the bite force levels under examination.

It might be concluded that AMG is a non-invasive way for the assessment of bite force. It offers some advantages over EMG: a) the relationship between AMG and muscle force is unaffected by muscle fatigue; and b) it is easier to filter out noise due to the very narrow bandwidth. However, it is still not considered as common as EMG in monitoring bite force, and extra care is required in the technique. It is suggested that AMG could be a useful tool for the assessment of bite force especially in fatigue studies and where EMG is difficult (Tortopidis et al., 1998a).

1.9 Twitch Interpolation in the Assessment of Maximum Potential Bite Force

The principle of twitch interpolation is that electrical stimuli are applied to a muscle (or a group of synergist muscles) at varying states of voluntary contraction. The momentary increase in force output from the muscles which results from the twitch produced by this stimulus is inversely proportional to the strength of the voluntary contraction. Thus, any given stimulus after all the muscle fibres have been activated and maximum contraction has been reached will not lead to any increase in the muscle force output (Merton, 1954; Lyons et al., 1996).

In 1996, Lyons et al investigated twitch interpolation as a non-invasive method for the assessment of maximum potential bite force (Lyons et al., 1996). The aim of this study was to apply twitch interpolation to the masseter muscle and to investigate the feasibility of this method in the assessment of the maximum potential bite forces in humans. First, MVBF was measured between anterior teeth using a strain-gauge metal transducer. Participants were then asked to perform a series of clenches at different voluntary bite force levels. While performing the clenches and at an unpredictable point of time, a twitch was elicited by a single transcutaneous electrical stimulus applied to one or both masseter muscles.

The authors found that, in all participants, the twitch forces produced by an electrical single stimulus were inversely and linearly related to the voluntary bite forces. Twitch forces were plotted against voluntary forces and extrapolation of the regression lines for the data to zero twitch force enabled the prediction of the maximum potential bite forces. MVBFs as measured by the strain-gauge metal transducer ranged from 153 to 593 N. On the other hand, maximum potential bite forces as predicted by the extrapolations ranged between 282 to

629 N. It was clear that extrapolation predicted a narrower and a higher range of maximum bite forces than MVBFs. It was concluded that twitch interpolation was useful in the prediction of maximum potential bite forces and whether the subjects were producing true maximum bite forces or not. Twitch interpolation is a promising non-invasive method which might be useful to define better the maximum bite force potential of humans.

1.10 Aims of Project

The overall aim of this project was to develop and test some better alternatives to the commonly-used strain-gauge transducer for measuring maximal bite forces. This would be done principally by employing softer and more flexible biting surfaces which would minimise many of the problems outlined above. The performance and practicality of these alternative designs would be compared to each other and to the standard strain-gauge transducer.

More specifically, the following questions would be addressed: a) Could higher MVBFs be recorded on the "improved" bite force transducers and if so, which of these transducers allowed for the highest MVBFs to be recorded? b) Were subjects more confident in the use of some transducers than others? c) Were any differences in the performance of force transducers related to their thicknesses? d) Were the MVBFs with different transducers closer to the maximal potential forces of the jaw closing muscles as assessed by the technique of twitch interpolation?

Chapter 2: General Materials & Methods

2.1 General

Five separate studies were performed in this project. They all took place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. All except one study required around one hour for each subject, completed in one visit. The fifth study required two visits, each of one hour duration. The following procedures were used in some or all of the studies: measurement of anterior maximum voluntary bite force (MVBF), electrical stimulation of the masseter muscle, and electromyographic (EMG) recording from the masseter and the anterior temporalis muscles. In all five studies, one or both of the two different bite force transducers (built for this project) was / were used. This chapter describes the two bite force transducers and calibration methods, and the bite force recording, the electrical stimulation, and the EMG recording techniques.

2.2 Subjects

The experiments were carried out on human volunteer subjects. They were all dentate with no missing anterior teeth and with no crowns or large composite restorations on these teeth, and the subjects did not report any symptoms of craniomandibular pain or dysfunction. Before taking part in the studies, each subject was asked to read and understand a participant information sheet and to sign a consent form. Ethical approvals (Appendix 1 and 2; reference numbers 13122 and 14040) were obtained from the University of Dundee Research Ethics Committee. All the studies conformed to the principles outlined in the Declaration of Helsinki.

The age range of the recruited subjects was 24 to 41 years. Previous studies had shown that bite force increases with age through childhood, stays relatively constant from 20 to 40 years, and then declines (Kiliaridis et al., 1993; Bakke, 2006). This indicates that the subjects were likely to be in the optimum age range for producing their MVBF when they took part in the experiments.

2.3 Bite Force Measuring Transducers

All of the bite force transducers used in this project were one of two different types – a strain-gauge transducer and a pressure transducer.

2.3.1 The Strain-gauge Transducer

The strain-gauge transducer consisted of two T-shaped metal beams with two strain-gauges attached to each side of one of the beams. The four strain-gauges were connected to form a Wheatstone bridge circuit. The overall thickness of the transducer was 8 mm (Fig. 2.1). This design has been described in detail previously by Lyons and Baxendale (1990).

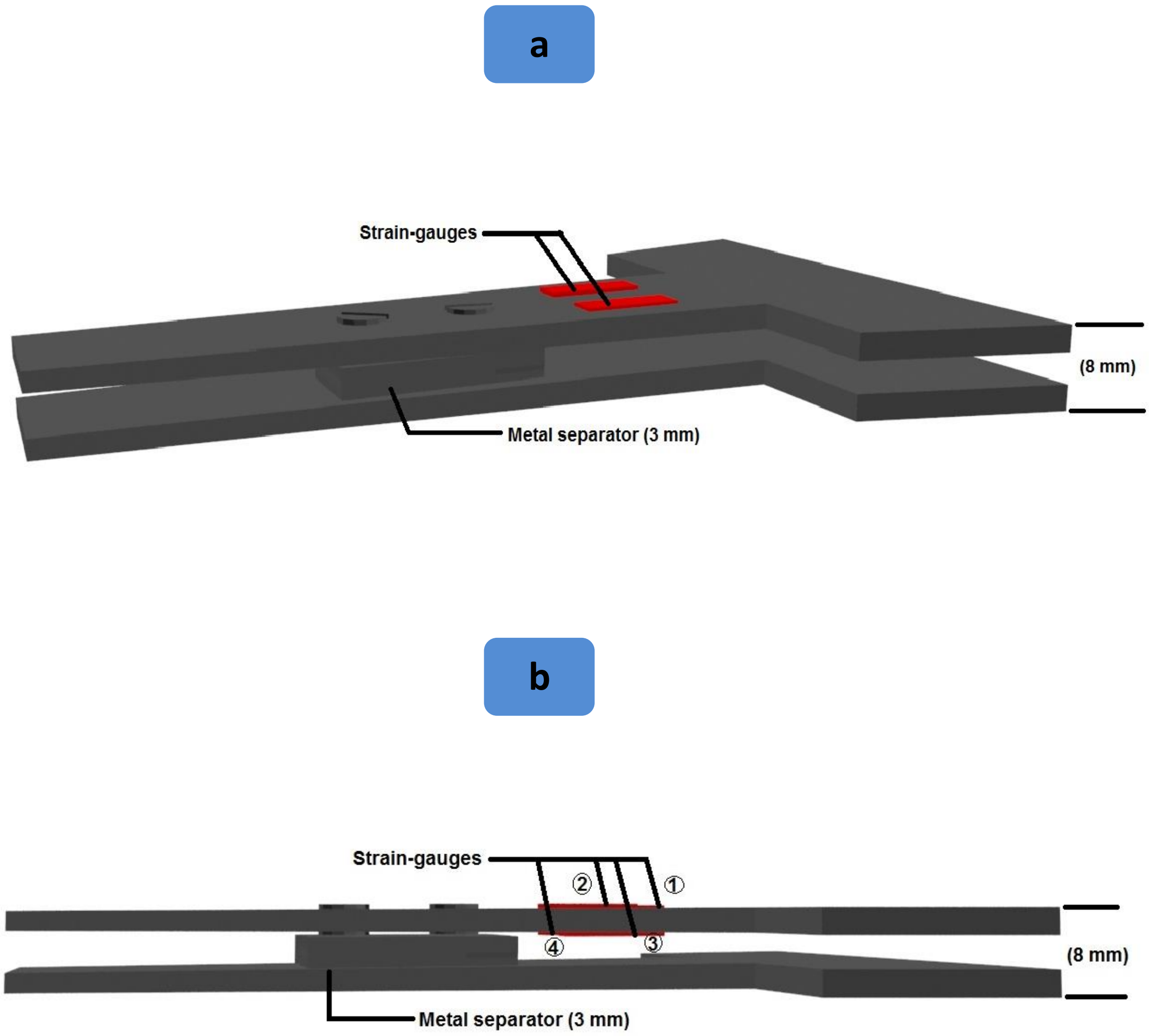

Figure 2.1: Illustrations of the strain-gauge force transducer: a) perspective view; b) side view.

The change in resistance of the strain-gauges following loading of the transducer i.e. bending of the beams, results in a change in output voltage. This voltage can then be calibrated with known weights to indicate applied load. A Neurolog bridge amplifier (NL 107, Digitimer, Letchworth Garden City, UK) was used to amplify the voltage changes of the transducer. These analogue signals were then digitised using a data acquisition interface (1401 Plus, Cambridge Electronic Design Limited, Cambridge, UK). Subsequent analysis was carried out using commercial software (Signal 2.16, Cambridge Electronic Design Limited, Cambridge, UK).

2.3.2 The Pressure Transducer

The pressure transducer consisted of a 270 mm long flexible polyvinyl chloride (PVC) tube (Model No. BRH3, Clarke International, UK) filled with water and connected to a 0 – 50 psi (0 – 344.7 kPa) range pressure sensor (PX 309, Omega Engineering Limited, Manchester, UK). In order to resist high bite forces without approximation of the tube walls, the PVC tube was reinforced by an inner flexible synthetic tube (Item No. a10090300ux0165, Sourcing Map, Kwai Chung, Hong Kong). Furthermore, in order to make the transducer more comfortable for biting, the PVC tube was covered by an outer soft silicone tube (NGP60 Clear Translucent Silicone Tube, Advanced Fluid Solutions, Essex, UK). The total thickness of the transducer was 19 mm (Fig. 2.2).

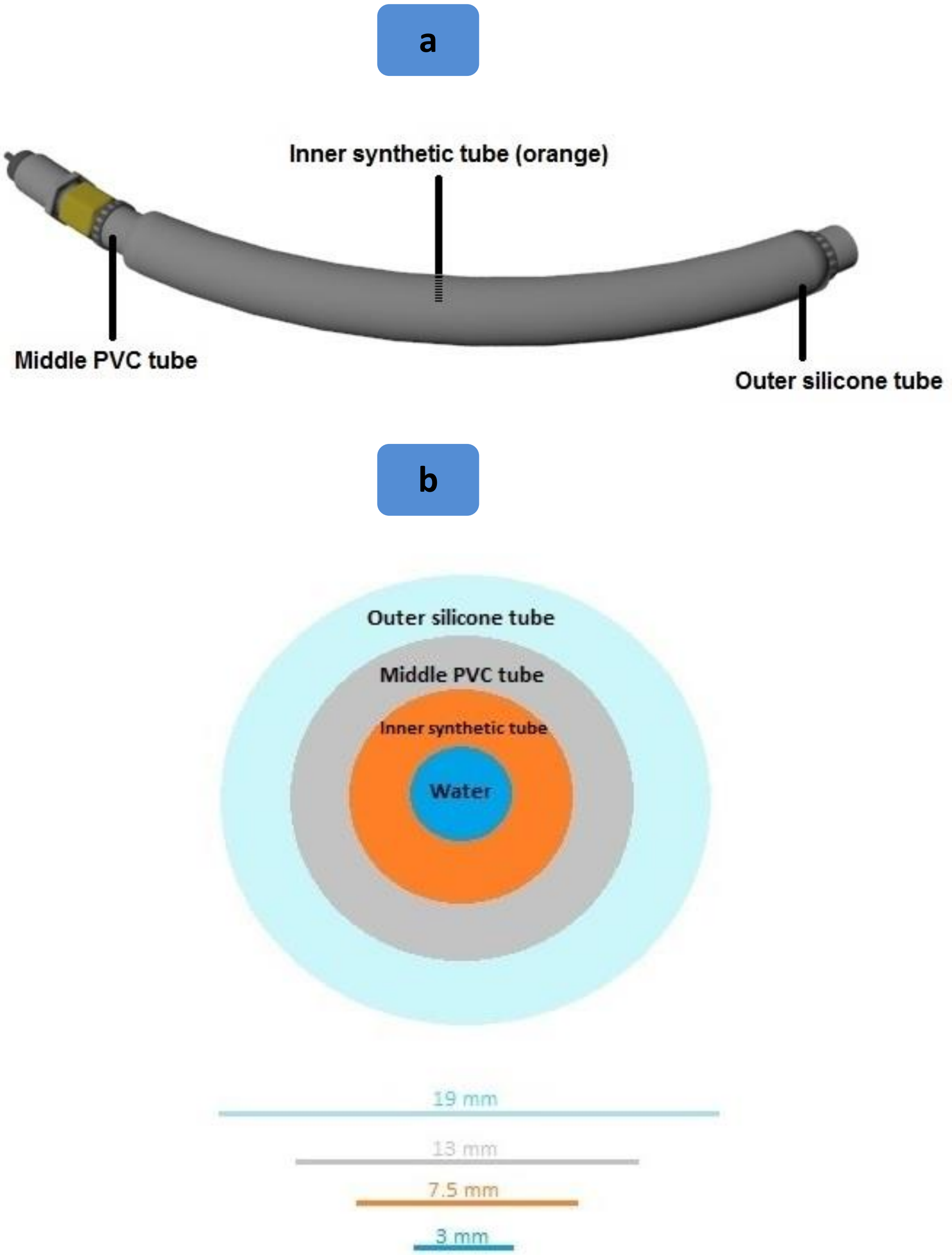

Figure 2.2: The pressure transducer: a) perspective view of the pressure transducer and attached tube; b) Illustration of the cross section of the pressure transducer. Note that: the inner synthetic tube is of 3 mm bore and 7.5 mm exterior diameter, the middle PVC tube is of 8 mm bore and 13 mm exterior diameter, the outer silicone tube is of 13 mm bore and 19 mm exterior diameter.

A Neurolog recorder amplifier (NL 107, Digitimer, Letchworth Garden City, UK) was modified by the manufacturers on request in order to be compatible with the pressure transducer (resistors R39 and R40 were changed to 15000 ohms in order to match the bridge resistance of the pressure transducer). The amplified voltage changes were again sent to a computer following analogue-to-digital conversion using a data acquisition interface (Micro 2 1401, Cambridge Electronic Design Limited, Cambridge, UK), and analyses were performed using Signal (Cambridge Electronic Design Limited, Cambridge, UK).

2.4 Calibration

Each of the two transducers was calibrated on each day of experimentation in order to avoid any error in the relationship between applied loads and the response of the transducer.

2.4.1 Calibration of the Strain-gauge Transducer

The consistent behaviour of this type of strain-gauge transducer has been confirmed in previous studies (e.g. Lyons and Baxendale, 1990; Lyons et al., 1996; Tortopidis et al., 1998b). A custom-made jig was used to apply known weights to the transducer while it was placed between the anterior teeth of a set of stone casts mounted in a semi adjustable articulator (Fig. 2.3). Weights of 5 kg, 10 kg, 15 kg, 17.5 kg, 15 kg, 10 kg, and 5 kg were successively applied to the transducer.

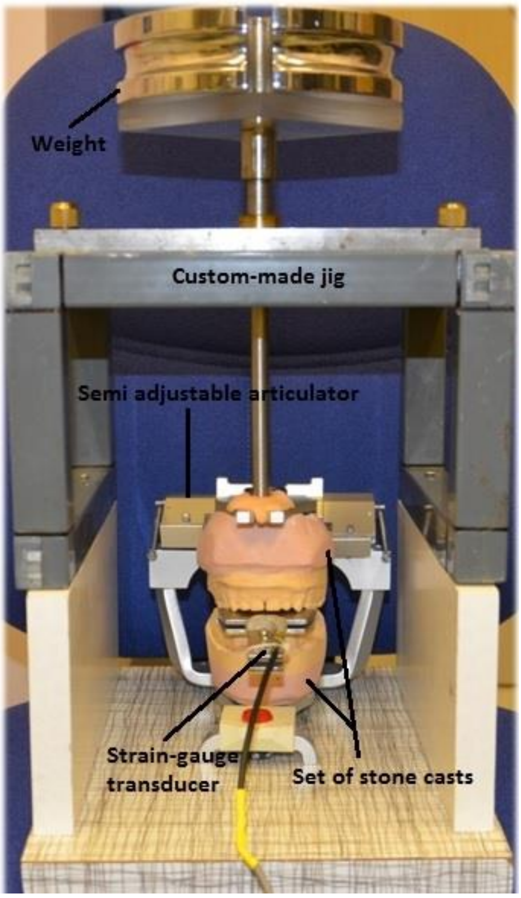

Figure 2.3: The custom-made jig used to apply weights for the calibration of the strain-gauge transducer.

On all occasions, a linear relationship was found between the applied loads and the response of the transducer. Microsoft® Excel® 2010 software was used to calculate regression line (Fig. 2.4). Linear regression was then applied to convert voltage changes associated with biting to force in Newtons.

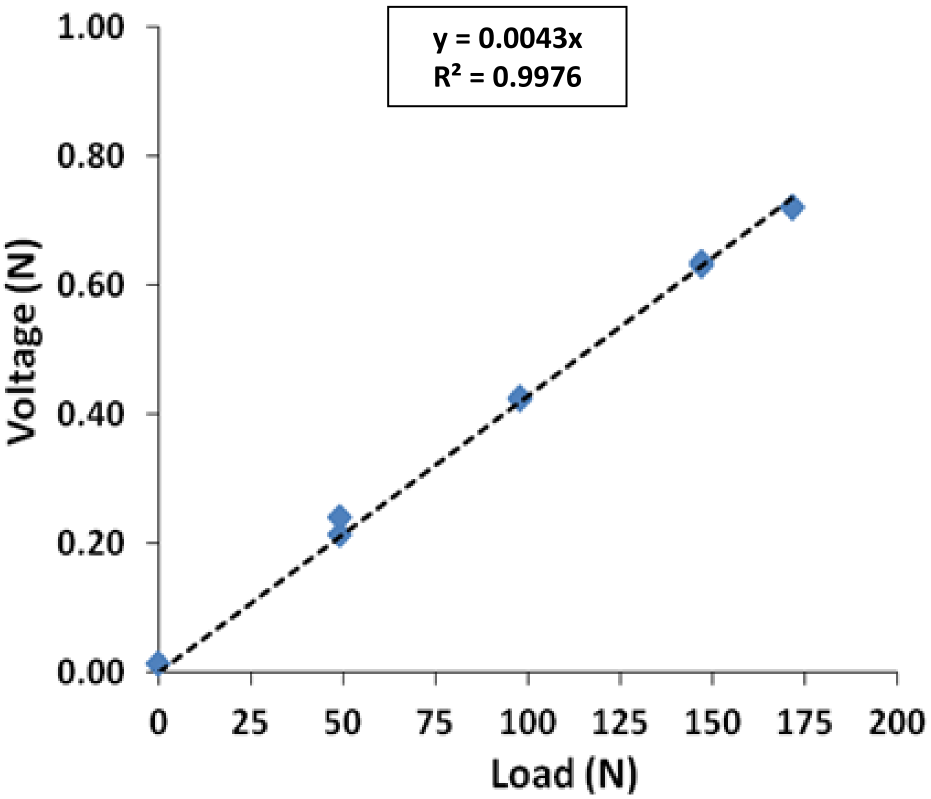

Figure 2.4: Example of calibration of the strain-gauge transducer. Equation and regression value are also shown.

2.4.2 Calibration of the Pressure Transducer

As this design of bite force transducer was newly developed for this project, it was even more important than usual to establish a method to check the consistency of the instrument and to do so over the whole range of forces to which the transducer was likely to be subjected. This was done by applying a wide range of forces (100 N, 200 N, 300 N, 400 N, 500 N, and 600 N) successively to the pressure transducer while it was placed between the anterior teeth of sets of casts mounted in a semi-adjustable articulator.

As no more than 40 kg of weights (392 N) could be applied safely on the custom made jig which was used for calibrating the strain-gauge transducer (mainly because it was difficult to control the tower of weights and prevent it from falling when a large number of weights were used), forces were applied by a universal testing machine (Instron Model 4469, Instron limited, High Wycombe, Buckingham, UK; Fig. 2.5a). The forces took the form of successive "ramp-and-hold" waveforms (Fig. 2.6). The Instron was programmed to produce the ramps between the different forces by moving its cross-head applicator downward at a speed of 1.5 mm/min. When each target force was reached, the cross-head was stopped, and the target force was maintained, using manual controls. Each target force was maintained until a steady response of the transducer was confirmed for this force; at that time, the movement of the cross-head was restarted until the next target force was achieved. The low speed (1.5 mm / min) was chosen as actual forces tended to fluctuate around target forces at a magnitude approximately proportionate to the cross-head speed, and thus it was easier to override these fluctuations using the manual control on the Instron, when the slowest speeds were used. It was checked that the responses of the transducer, using the above settings, were similar to the responses when calibrated using the custom-made jig and known weights up to 40 kg. As detailed elsewhere (section 2.4.3; Fig. 2.12), this was in fact, the case.

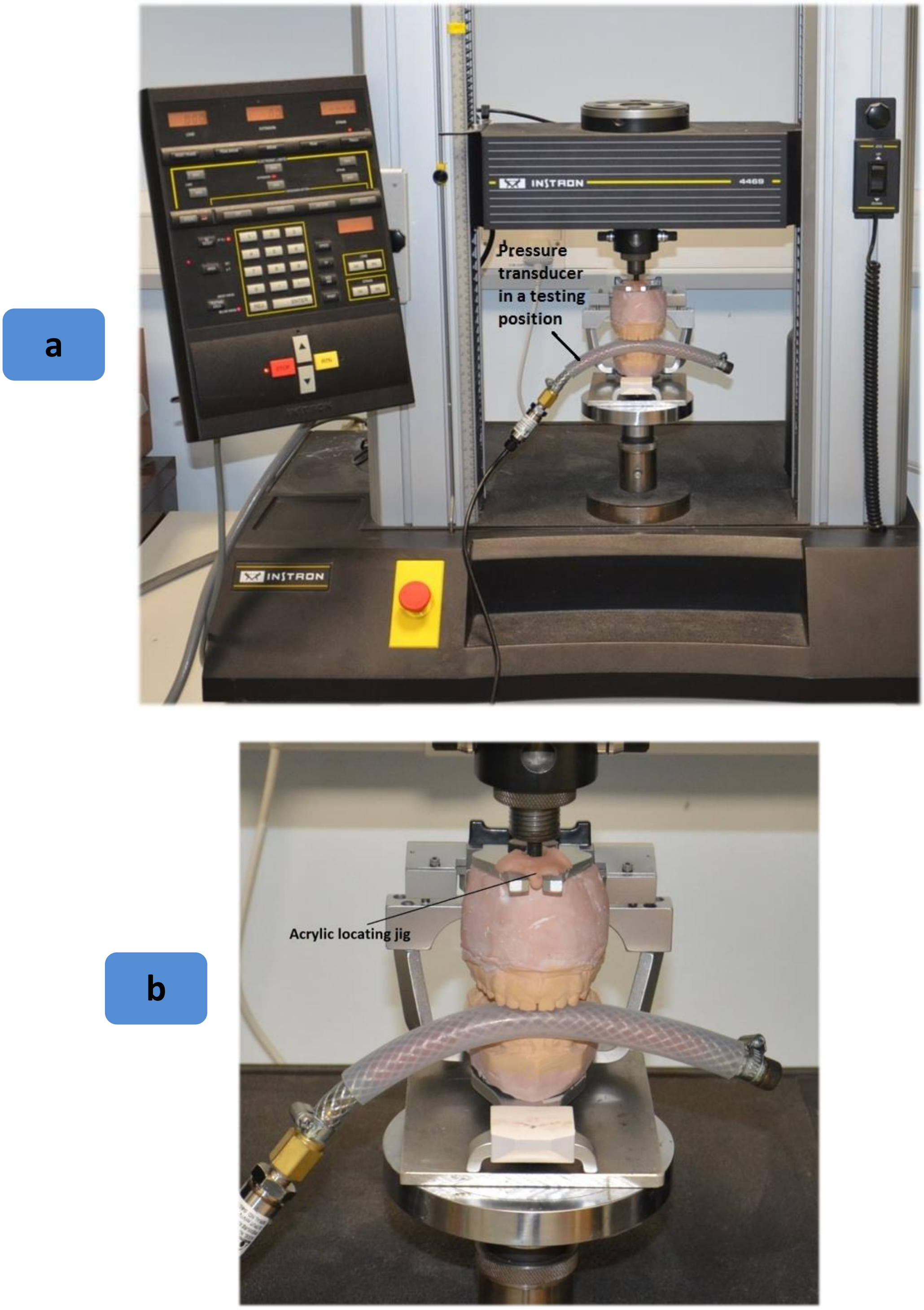

Figure 2.5: a) Instron testing machine used for the calibration of the pressure transducer; b) the acrylic locating jig used to ensure a consistent position of point of force application.

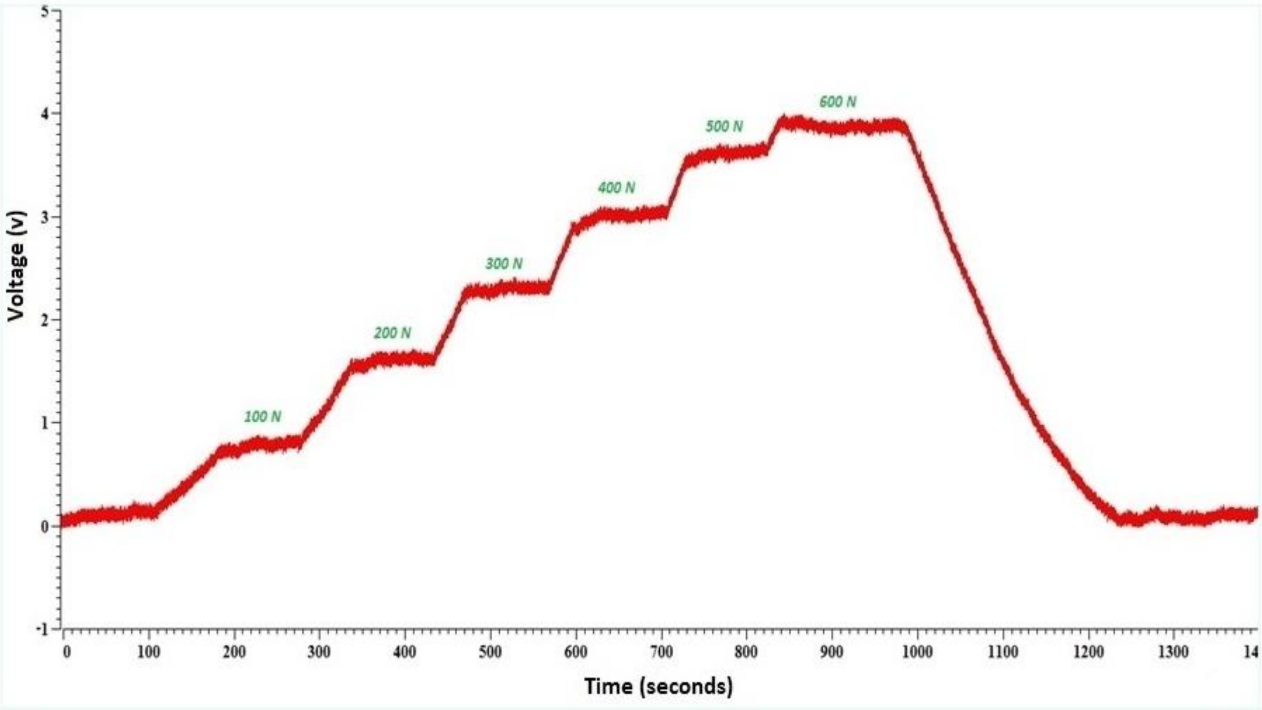

Figure 2.6: Example of calibration record for the pressure transducer.

There were four different sets of casts (A, B, C, and D) and the loads were applied to each set on four different occasions. Sets of casts A, B, and C were without significant malocclusions. Set D was of a relatively small arch size and a class I malocclusion (Fig. 2.7). This allowed a check of the consistency of the response of the transducer on different occasions and also when used with different arch shapes and sizes, tooth morphology, and occlusion forms.

Figure 2.7: Occlusal view photos of sets of casts A, B, C, and D.

The response of the pressure transducer was found to be consistent for each set of casts between the four different occasions. The intra-class correlation coefficient (ICC) was 0.999, 0.997, 0.996, and 0.997 for the sets of casts A, B, C, and D respectively (Fig. 2.8). The response of the transducer was also found to be consistent when used with the different sets of casts i.e. different arch shapes and sizes, tooth morphology, and occlusion forms (ICC = 0.988; Fig. 2.9).

However, even with the high ICC value for the consistency of the response of the pressure transducer for the four different sets of casts on the four different occasions, it was clear that the results of set of casts D were rather different than the other sets of casts (see Fig. 2.9). Taking this into consideration, it was decided that it would be acceptable to use a control set of casts (set of casts B as its values were found the closest to the mean values of the four sets) for calibration in subsequent experiments. However, extra care was taken to recruit subjects with average arch shape and size and without significant malocclusions in order to reduce any chance of variation in calibration due to the effect of different arch shapes and sizes, tooth morphology, and occlusion forms between different subjects.

It had also been observed in some trial experiments in our laboratory that the effect of the different arch shapes and occlusion forms became larger when softer tubes were used with the pressure transducer. Thus, it is recommended that extra consideration should be given to this effect if softer tubing is to be used in future studies.

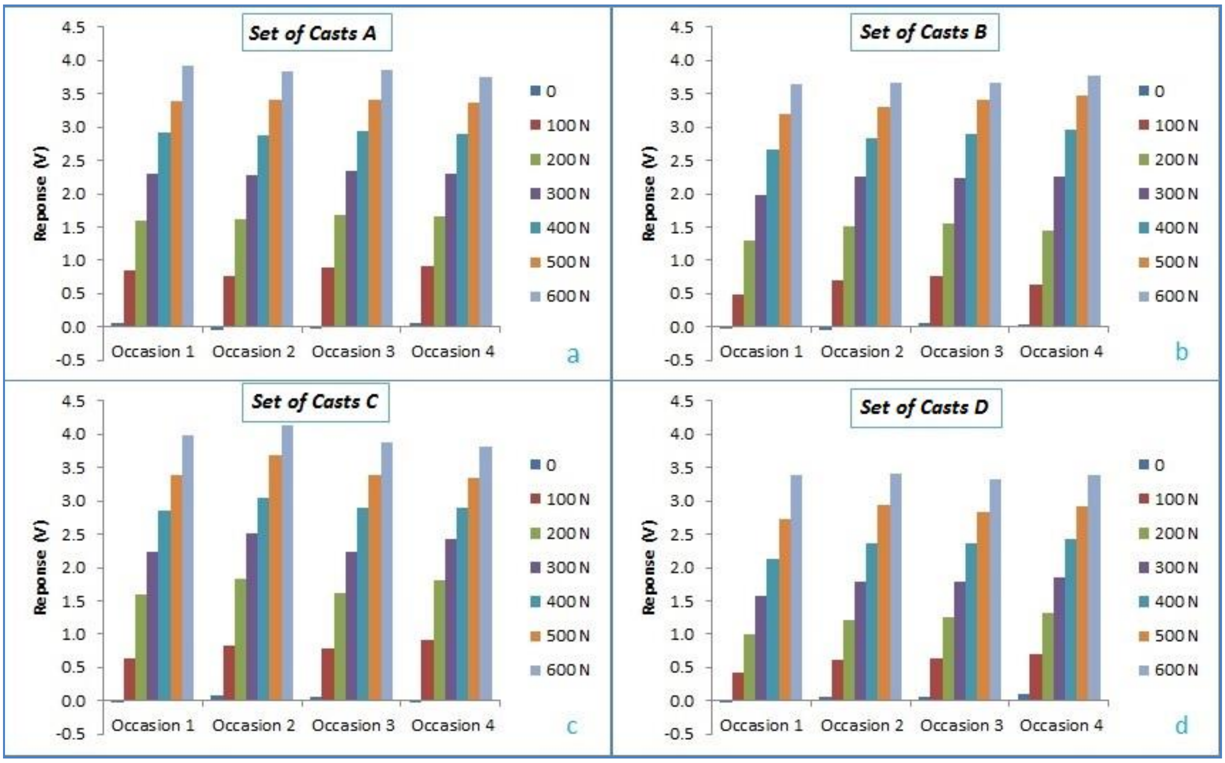

Figure 2.8: Consistency of the response of the pressure transducer (V) when loads (100, 200, 300, 400, 500, and 600 N) were applied with each set of teeth on the four different occasions; a- set of casts A; b- set of casts B; c- set of casts C; d- set of casts D.

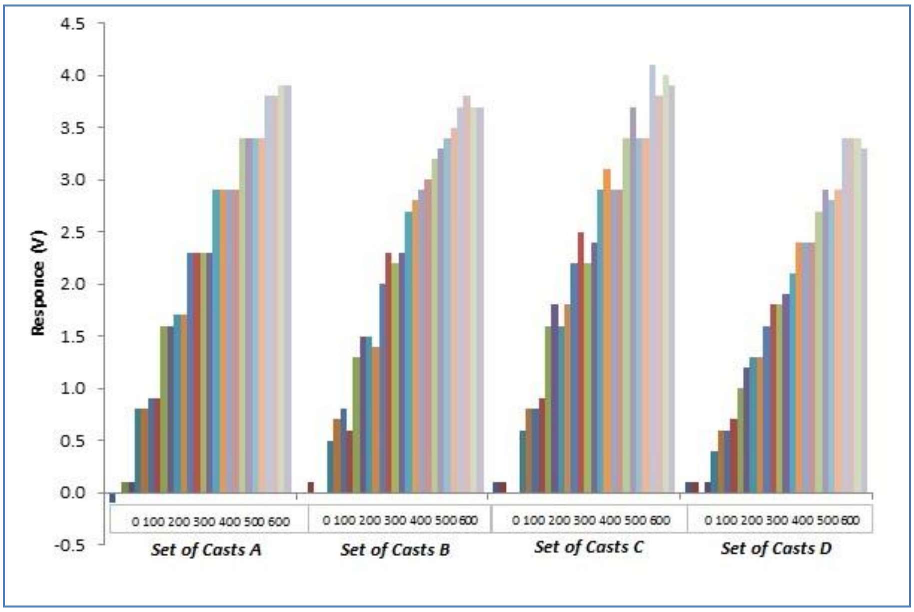

Figure 2.9: Consistency of the response of the pressure transducer (V) when loads (100, 200, 300, 400, 500, and 600 N) were applied with the four different sets of casts. Note that the graph represents the data from the four different occasions.

On all experimental occasions, a non-linear but consistent relationship was found between the applied loads and the response of the transducer. Microsoft® Excel® 2010 software was used to calculate regression line (Fig. 2.10). Second order polynomial regression was then applied to convert voltage changes associated with biting to force in Newtons.

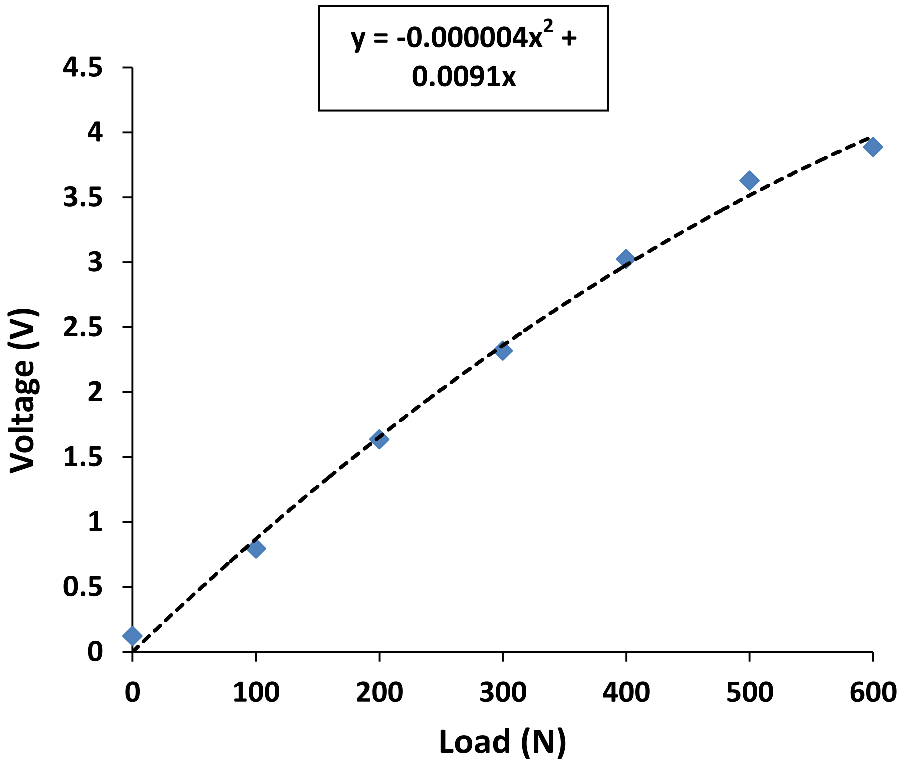

Figure 2.10: Example of calibration relationship for the pressure transducer. Note that the transducer produced a curve which was defined by a second order polynomial. Equation and regression value are also shown.

2.4.3 Additional Calibration Experiments

As two different pieces of equipment (the custom-made jig and the Instron) were used for the calibration of the two bite force measuring transducers, it was essential to check that each of the two transducers gave consistent responses, to the same applied loads, regardless of the calibration equipment used. Otherwise, the bite force values given by the two transducers would not be comparable.

To that end, it was decided to apply the same loads, used usually with the custom-made jig for the calibration of the strain-gauge transducer, but this time using the Instron testing machine. The responses of the strain-gauge transducer, to the same loads, using the two calibration equipments were found to be consistent (ICC = 0.997), and had a strong linear relationship with a high correlation coefficient value (r = 0.9962; Fig. 2.11).

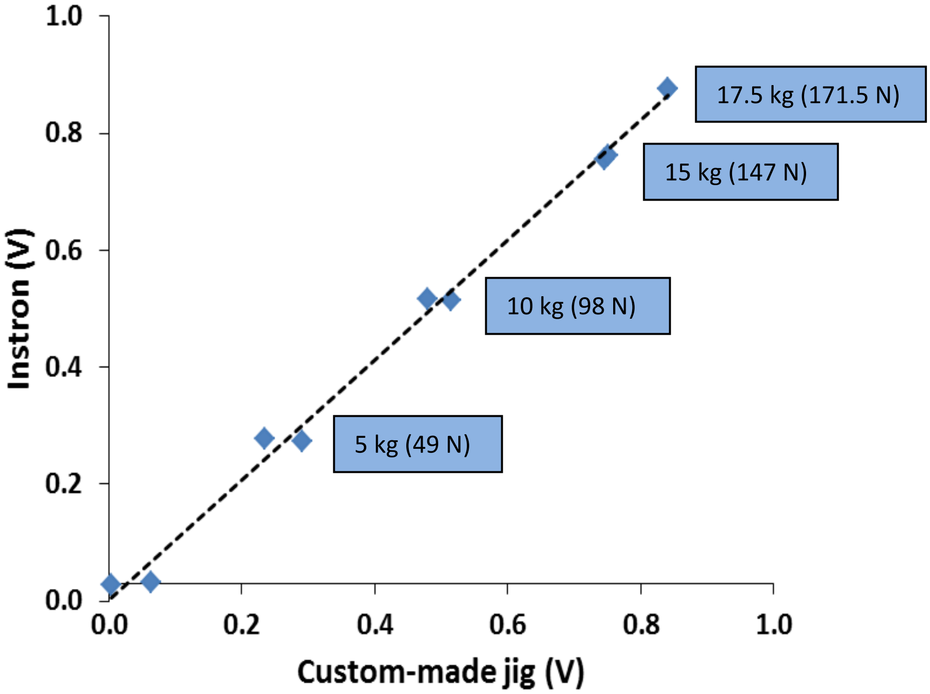

Figure 2.11: Response of the strain-gauge transducer to the applied loads: 5 kg (49 N), 10 kg (98 N), 15 kg (147 N), 17.5 kg (171.5 N), 15 kg (147 N), 10 KG (98 N), and 5 kg (49 N), using the two different calibration equipments [the custom-made jig (abscissa) and the Instron (ordinate)].

The same procedure was also performed with the pressure transducer. Loads of 10 kg (98 N), 20 kg (196 N), 30 kg (294 N), and 40 kg (392 N) were applied to the transducer using the custom-made jig on one occasion and the Instron testing machine on another occasion. The responses of the transducer were also found to be consistent with the two different types of calibration equipment (ICC = 0.997), and had a strong linear relationship (r = 0.9973; Fig 2.12).

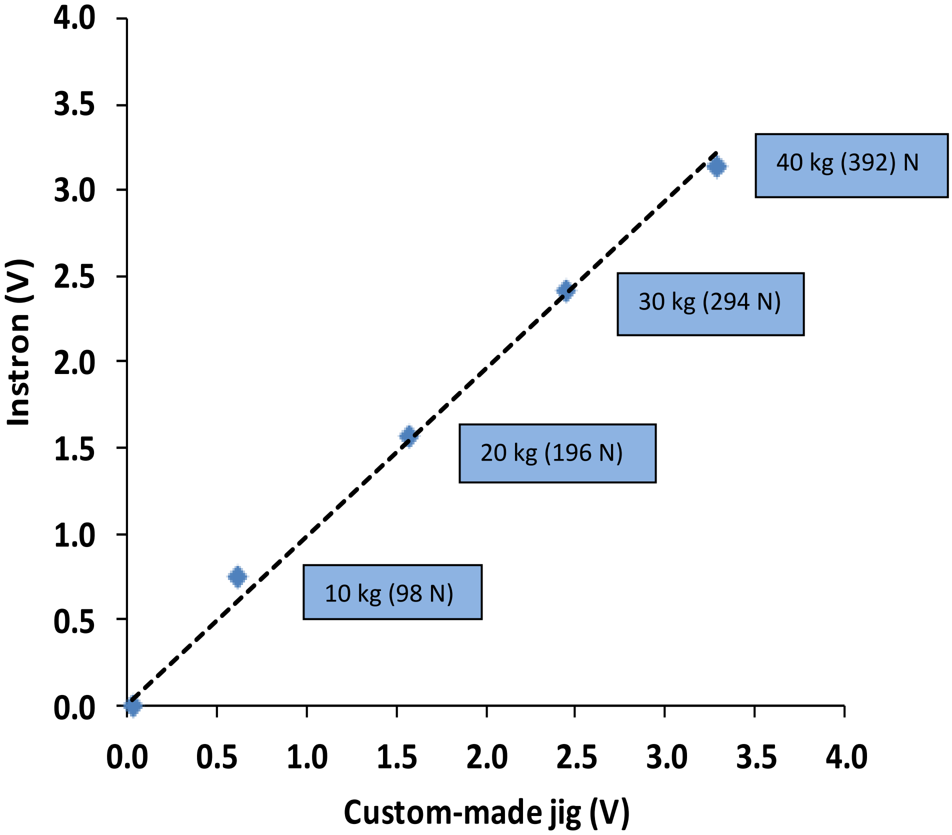

Figure 2.12: Response of the pressure transducer to the applied loads: 10 kg (98 N), 20 kg (196 N), 30 kg (294 N), and 40 kg (392 N) with the two different calibration equipments [the custom-made jig (abscissa) and the Instron (ordinate).

Although the linearity of the strain-gauge transducer was confirmed in previous studies (e.g. Lyons and Baxendale, 1990; Tortopidis et al., 1998b), one more calibration experiment was performed in order to assert this linearity up to high forces. Taking into account that previous studies reported a range from 120 N to 350 N of anterior MVBFs on this type of force transducer (e.g. Helkimo et al., 1977; Tortopidis et al., 1998b), the linearity of the strain-gauge transducer was checked up to 350 N. The Instron testing machine was employed to apply the forces 50 N, 100 N, 150 N, 200 N, 250 N, 300 N, and 350 N to the strain-gauge transducer while it was placed between the anterior teeth of a control set of casts mounted in a semi adjustable articulator. Again, the response of the strain-gauge transducer was found to be linear (r = 0.999, Fig. 2.13).

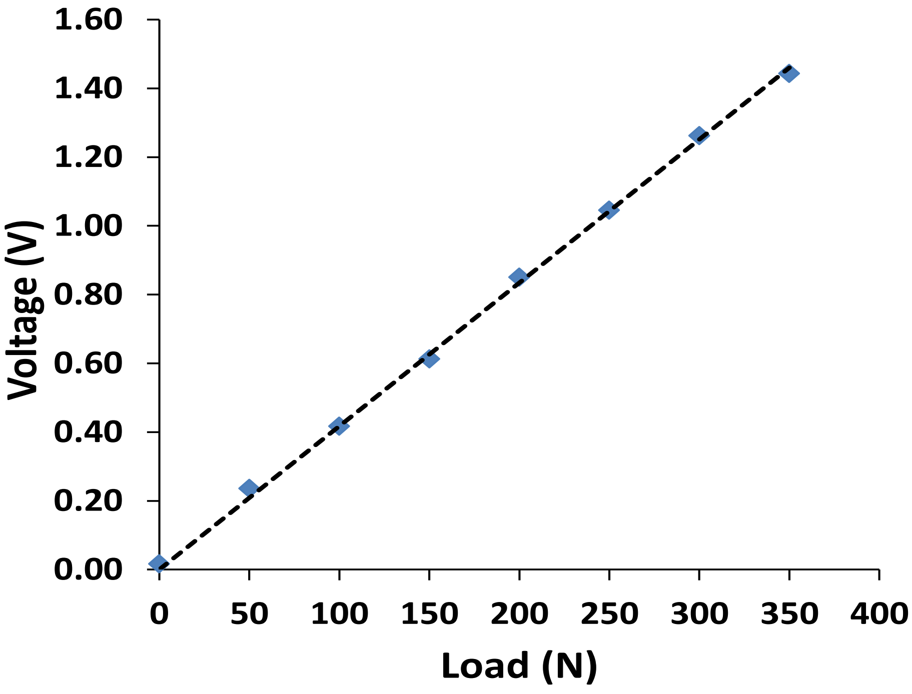

Fig 2.13: Linear relationship for the strain-gauge transducer up to 350 N.

2.5 Bite Force Recording Technique

In all the five studies described in this thesis, one or both of the two different bite force transducer/s was/were used. Three studies employed both the strain-gauge transducer and the pressure transducer. One study employed only the strain-gauge transducer but with three different covering materials. Another study also employed only the strain-gauge transducer but with three different thicknesses of covering.

For the measurement of anterior MVBF, each subject was asked to bite as hard as possible three times on each bite force transducer while the transducer was placed between the anterior teeth from canine to canine. The highest bite force was considered as the MVBF.

The order in which the different bite force transducers were used was randomized, and the subjects were required to rest for five minutes before changing to a different transducer. Before the use of each transducer, subjects were asked to undertake trial sub-maximal clenches in order to become familiar with the procedure. All the measurements were done while the subjects were seated upright in a dental chair. The bite force transducers were disinfected before the experiments by immersing them in a disinfectant solution for two minutes (Actichlor^{TM} Chlorine Releasing Disinfectant Tablets, Ecolab Limited, Leeds, UK).

2.6 Muscle Stimulation Technique

In those parts of the project where electrical muscle stimulation was required, this was applied to the right masseter muscle. The transcutaneous electrical stimuli were applied using a monopolar electrode configuration. A large (22 × 32 mm; skin contact size 20 × 20 mm), conductive self-adhesive hypoallergenic, surface electrocardiographic (ECG) electrode (Cat No. 23330, 3M™ Health Care Limited, Loughborough, Leicestershire, UK) was placed on the skin overlying the belly of the muscle and served as the cathode during the electrical stimulation. A square metal plate (50 × 50 mm) was fixed to the skin below the right lateral malleolus (ankle), and served as the indifferent anodal electrode. Full details about the technique are given in Chapter 6 (section 6.2).

2.7 Electromyography (EMG) Recording Technique

In those parts of the project where electromyography (EMG) was required, this was recorded bilaterally from the masseter and the anterior temporalis muscles. For this purpose, disposable self-adhesive surface electrodes (Product No. 720 00-S/25, Ambu® Neuroline 720, Ambu Ltd, Cambridgeshire, UK), dimensions (45 × 22 mm), skin contact size (30 × 22 mm), were used. Two electrodes were placed (i.e. in a bipolar configuration) on the skin overlying the bellies of each of the four muscles (i.e. two on each side). An additional electrode was placed on the left ear lobe and served as the common electrode. Full details about the EMG recording and processing techniques are given in Chapter 7 (section 7.2).

2.8 Statistical Analysis

IBM® SPSS® 21 statistical analysis software was used to perform statistical analysis. The following tests were employed: reliability analysis, Spearman's rank correlation, Pearson's correlation, Shapiro-Wilk, one sample t test, paired t test, Two-way ANOVA, repeated measures ANOVA with *post-hoc* Bonferroni-corrected paired t tests when $P < 0.05$, and Friedman test with *post-hoc* Bonferroni-corrected Wilcoxon signed-rank tests when $P < 0.05$. In all the tests, a P value < 0.05 was considered statistically significant. Full details are given about the tests in each relevant chapter.

Chapter 3: The Effect of Transducer Design on Maximum Voluntary Bite Force and the Possible Role of Subject Comfort

3.1 Introduction

As discussed in Chapter 1, strain-gauge transducers have proved to be accurate for the measurement of maximum voluntary bite force (MVBF). However, it is still difficult to be confident of registering a true maximum bite force using these transducers. It is often suggested that this is mainly due to discomfort and to the fear of breaking cusps of teeth and dental restorations when biting on the hard surfaces of the transducers (Braun et al., 1995; Lyons et al., 1996; Fernandes et al., 2003).

A further consideration relates to feedback from afferent nerves. There is some evidence that inhibitory factors triggered by activation of sensory receptors within the periodontium might be significant, especially when biting on hard surfaces. This may result in a reduction in the activity of the motor nerves which control the jaw closing muscles and consequently a lower bite force than the true maximum bite force of which the muscles are capable, will be achieved (Brodin et al., 1993; Paphangkorakit and Osborn, 1998; Alkan et al., 2006). However, it should be noted that the role of the periodontal sensory receptors in the control of bite force is controversial and many other studies have failed to verify this role or to find a significant correlation between the periodontal condition and the level of maximum bite force (see Hellsing, 1980; Orchardson and Cadden, 1998; Kleinfelder and Ludwig, 2002; Morita et al., 2003). For example, in a study by Hellsing (1980), anaesthesia of the periodontal receptors did not lead to noticeable changes in the level of MVBF.

Some workers have attempted to make biting on the strain-gauge transducers a more comfortable procedure by covering the steel surfaces with different materials such as acrylic resin, gauze, gutta percha, and polyvinyl chloride (PVC; e.g. Molin, 1972; Tortopidis et al., 1998a; Tortopidis et al., 1999; Shinogaya et al., 2000). However, unfortunately, none of these coverings seemed to overcome totally the discomfort associated with biting on the hard surfaces (Lyons et al., 1996; Fernandes et al., 2003).

To that end, the aim of this study was to investigate the use of a new soft, rubbery, covering material [ethylene vinyl acetate (EVA)], which is believed to be more comfortable for biting than the other, previously used, covering materials. The strain-gauge transducer with the EVA covering was compared to the strain-gauge transducer with silicone indices in order to investigate the effect of this on the recording of MVBF. It was proposed that covering the strain-gauge transducer with a soft, comfortable for biting, rubbery material (EVA sheets) would facilitate the production of higher (closer to true) MVBFs. The strain-gauge transducer covered with EVA sheets was also compared to the strain-gauge transducer covered with EVA sheets and silicone indices in order to investigate any possible extra comfort (or discomfort) effect of adding the silicone indices.

3.2 Materials and Methods

The study took place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. It required around one hour for each subject, to be completed in one visit.

3.2.1 Subjects

Ten subjects (six male; four female) were recruited. Their ages ranged from 24 to 41 years.

3.2.2 MVBF Measurements

Each subject was asked to bite as hard as possible three times on the three different types of bite force transducer while the transducer was placed between the anterior teeth from canine to canine. The highest bite force recorded was considered as the MVBF for each type of transducer. The three different types of bite force transducer were: (a) a strain-gauge transducer with silicone indices; (b) a strain-gauge transducer covered with EVA sheets; (c) a strain-gauge transducer covered with EVA sheets and silicone indices.

The order in which the three different transducers were used was randomized to avoid time-related effects, and the subjects were required to rest for five minutes before changing to a different transducer. Before the use of each transducer, subjects were asked to undertake trial sub-maximal clenches in order to become familiar with the procedure. All the measurements were done while the subjects were seated upright in a dental chair. The strain-gauge transducer and the EVA sheets were disinfected before the experiments by immersing them in a disinfectant solution for 2 minutes (made with Actichlor™ Chlorine Releasing Disinfectant Tablets, Ecolab Limited, Leeds, UK).

3.2.3 The Bite Force Transducers

3.2.3a The strain-gauge transducer with silicone indices

A detailed description of the steel strain-gauge transducer has been provided in Chapter 2 (section 2.3.1; page 41). For this type of bite force transducer, a condensation silicone impression material (Zetaplus, Zhermack SpA, Badia Polesine, Italy) was employed to make indices for each subject on the biting surfaces of the strain-gauge transducer (Fig. 3.1).

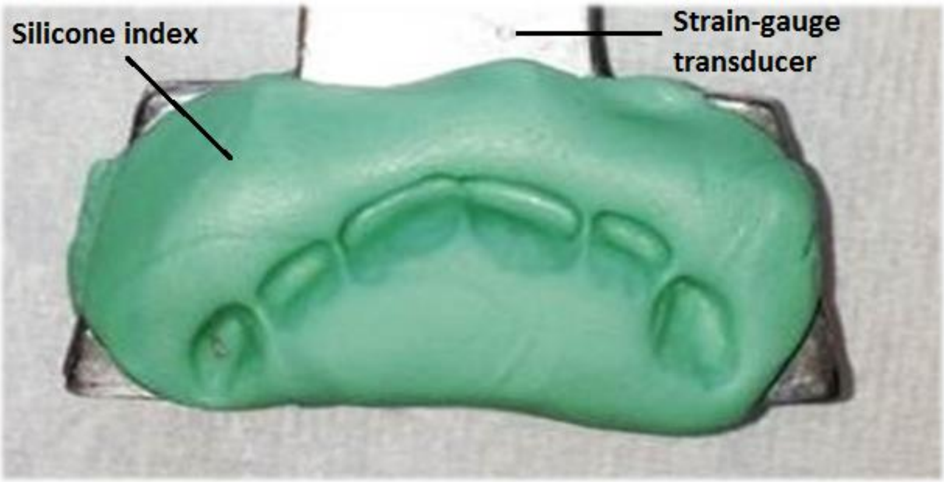

Figure 3.1: Example of a silicone index of upper anterior teeth on the strain-gauge transducer.

3.2.3b The strain-gauge transducer covered with EVA sheets

Two EVA sheets, 2mm thick, (Vacuum Blank Material, Bracon Limited, East Sussex, UK) were used to cover the biting surfaces of the strain-gauge transducer. The total thickness of the transducer with the two EVA sheets was 12 mm (Fig. 3.2).

Figure 3.2: A strain-gauge transducer covered with EVA sheets.

3.2.3c The strain-gauge transducer covered with EVA sheets and silicone indices

Two mm thick EVA sheets and silicone indices were used on the biting surfaces of the strain-gauge transducer (Fig. 3.3).

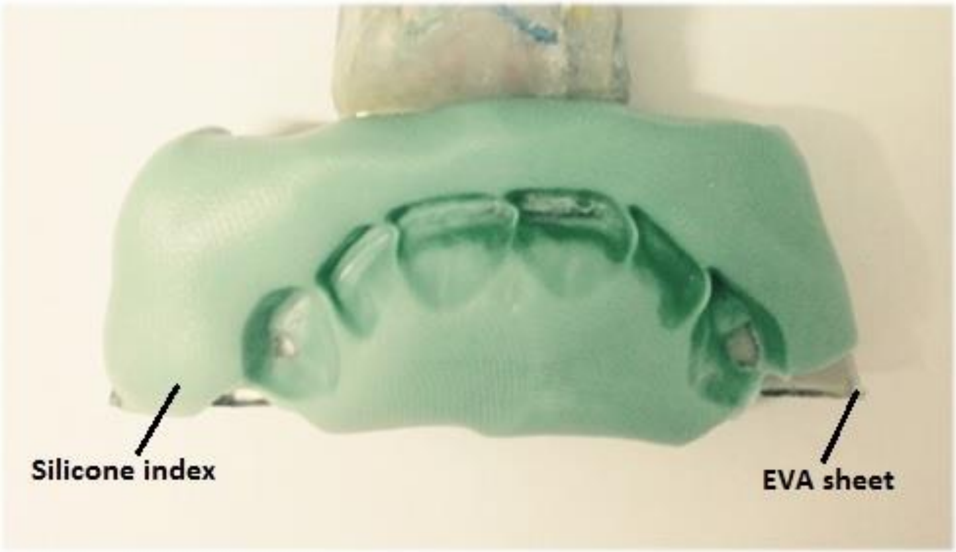

Figure 3.3: Example of a silicone index of upper anterior teeth on a strain-gauge transducer covered with EVA sheets.

3.2.4 Calibration

The strain-gauge transducer was calibrated on each day of experimentation. A detailed description of the calibration method has been provided in Chapter 2 (section 2.4.1; page 45). On all the experimental occasions, a linear relationship was found between the applied loads and the response of the instrument. Linear regression was used to calculate the best-fit line and the resulting equation was then applied to convert voltage changes associated with biting into forces in Newtons (see Fig. 2.4).

3.2.5 Statistical Analysis

IBM® SPSS® 21 statistical analysis software was used in this study. Repeated measures ANOVA was applied to examine whether there were any significant differences between the MVBFs recorded on the three different types of bite force transducer. When this yielded a significant ($P < 0.05$) result, *post-hoc* Bonferroni-corrected paired t-tests were used to determine if there were significant differences between each pair of transducers. Two-way ANOVA was applied to examine whether there were any significant differences between the MVBFs recorded in male and female subjects.

3.3 Results

Nine out of the ten subjects recorded higher MVBFs on the strain-gauge transducer covered with EVA sheets and on the strain-gauge transducer covered with EVA sheets and silicone indices than on the strain-gauge transducer with silicone indices. The mean MVBFs (± S.D.) on the three different transducers were: the strain-gauge transducer with silicone indices, 165 ± 35 N; the strain-gauge transducer covered with EVA sheets, 228 ± 61 N; and the strain-gauge transducer covered with EVA sheets and silicone indices, 248 ± 66 N (Fig. 3.4). Repeated measures ANOVA showed significant differences between the MVBF results for the three different types of bite force transducer ($P = 0.00014$). *Post hoc* tests showed a significant difference between the silicone indices and EVA sheets ($P = 0.0068$), and between the silicone indices and EVA sheets with silicone indices ($P = 0.0019$). However, there was not a significant difference between the EVA sheets with and without silicone indices ($P = 0.30$).

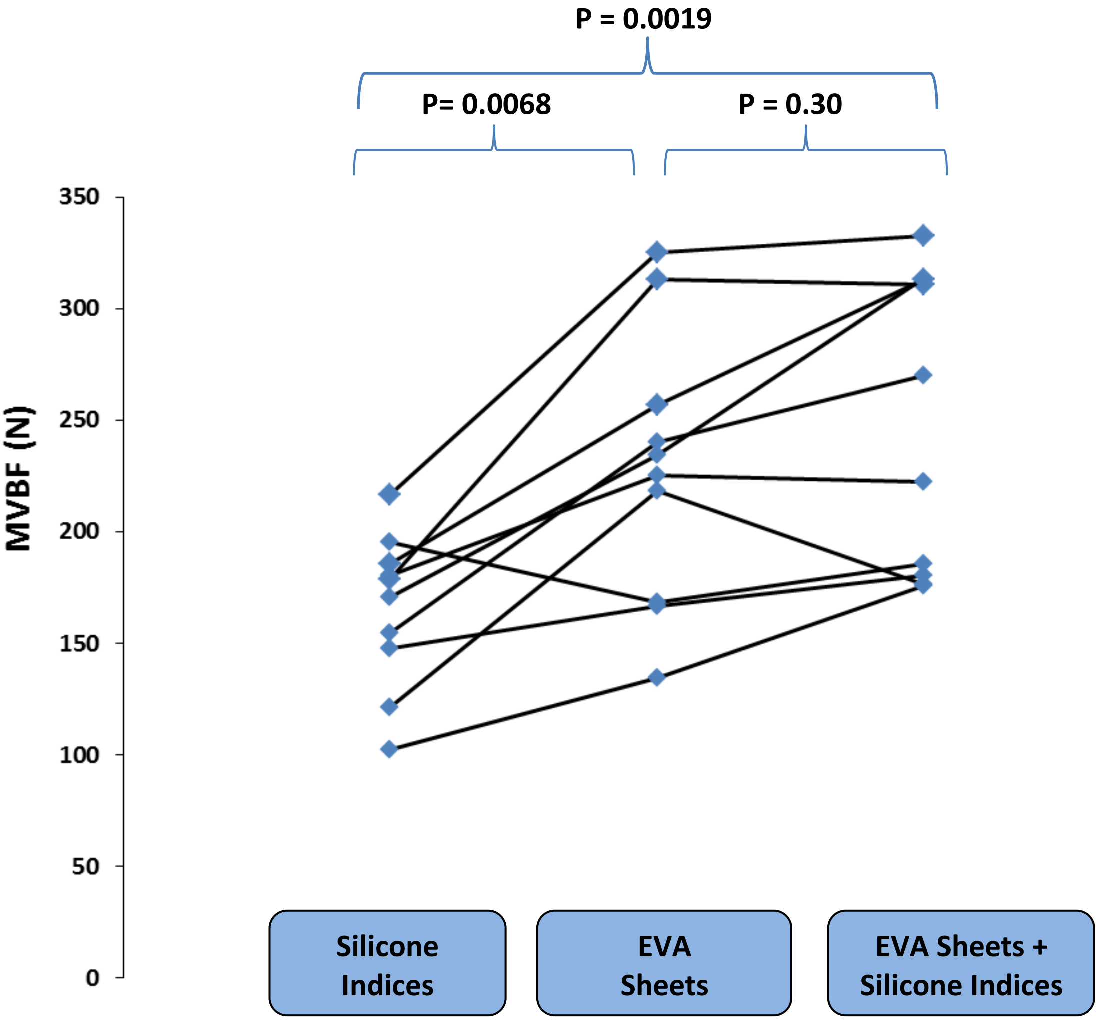

Figure 3.4: Scatter plot showing the MVBFs with each transducer by each subject. The data for individual subjects are linked by the lines between symbols. *Post hoc* tests (P) values between each pair of transducers are also shown. Note that only one subject recorded their highest MVBF on the strain-gauge transducer with silicone indices and he related this to the fact that he is used to breaking hard food in his diet.

On average, the MVBFs on the three different transducers were higher in male subjects [silicone indices (180 ± 22 N), EVA sheets (254 ± 59 N), EVA sheets and silicone indices 270 ± 62 N)] than in female subjects [silicone indices (143 ± 41 N), EVA sheets (190 ± 48 N), EVA sheets and silicone indices (202 ± 46 N)] (Fig. 3.5). Two-way ANOVA showed no interaction between sex and transducer type but there was a significant difference overall between the MVBF results of the male (237.4 ± 64.5 N) and female (178.5 ± 48.4 N) subjects (P = 0.035).

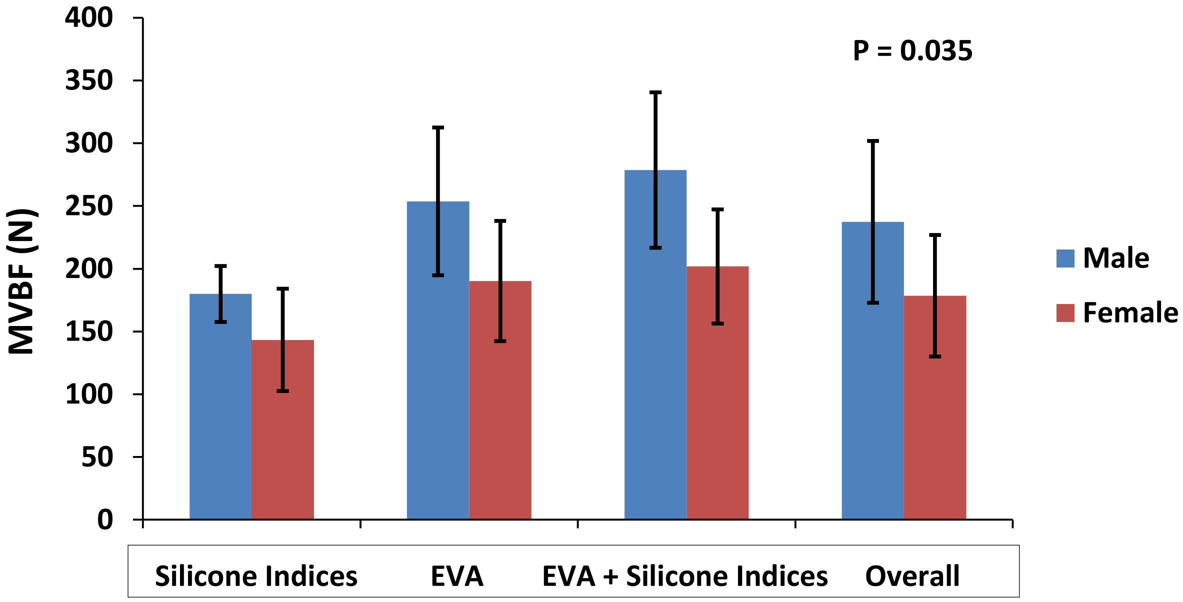

Figure 3.5: Mean MVBFs (± S.D.) on the three different types of bite force transducers in male vs. female subjects. P value for Two-way ANOVA between overall MVBFs in male and female subjects is also shown.

3.4 Discussion

The use of EVA sheets on the biting surfaces of the strain-gauge transducer resulted in significantly higher MVBFs than when only silicone indices were used. There are many possible explanations for this finding. Arguably the most obvious one is that the EVA sheets helped to improve comfort and to minimise the fear of damage to the teeth that is associated with biting on the hard steel surfaces, even if the steel is covered with silicone or acrylic indices as has been done in some previous studies (e.g. Lyons et al., 1996; Tortopidis et al., 1998b).

A second explanation can be linked to the possible inhibitory effects triggered by activation of sensory receptors within the periodontium, which are believed to be more apparent when biting on hard surfaces (Brodin et al., 1993; Paphangkorakit and Osborn, 1998; Serra and Manns, 2013). Paphangkorakit and Osborn (1998) suggested that biting on a soft or a rubbery surface would spread the bite force over a larger area of teeth (thus reducing the local stress). They argued that this would possibly result in a reduction in the inhibitory effects triggered by activation of sensory receptors, and thereby, higher bite forces can be achieved. However, as mentioned earlier, the role of the periodontal sensory receptors in the control of bite force is controversial and many other studies have reported contradictory findings on the ability of the sensory receptors to initiate either negative (inhibitory) or positive reflex modulations of maximum biting forces (see Hellsing, 1980; Orchardson and Cadden, 1998; Kleinfelder and Ludwig, 2002; Morita et al., 2003).

In agreement with the results of the present study, Serra and Manns (2013) found significantly higher MVBFs on a GM10 digital occlusal force gauge when a soft covering (made from leather and rubber) was employed on the biting surface of the instrument, than when the original semi-hard covering (provided by the manufacturer) was used. The workers attributed the higher MVBFs on the softer covering to the instant activation of inhibitory reflex mechanisms when the semi-hard covering was used and / or to the activation of positive reflex mechanisms when the soft covering was used.

A further possible explanation could be related to the thickness of the bite force transducer. A number of studies have reported a trend for an increase in the MVBF as the jaw is opened up to 15 - 20 mm incisal separation (e.g. Manns et al., 1979; Mackenna and Türker, 1983). As discussed in Chapter 1, this range of jaw opening probably corresponds to the optimum length of the jaw closing muscle sarcomeres at which they are most able to produce the highest bite force values (Duygu Koc et al., 2010). Taking this into consideration, it may be argued that the thickness of the strain-gauge transducer covered with EVA sheets (12 mm) was possibly more suitable for the production of higher MVBF than the thickness of the strain-gauge transducer with silicone indices (8 mm).

Employing silicone indices in addition to the EVA sheets did not add a significant positive effect to the recording of MVBF. However, acrylic or silicone indices can still be advantageously used in order to ensure a consistent position of biting between different sessions of experiments.

In agreement with previous studies (Helkimo et al., 1977; Shinogaya et al., 2001; Calderon et al., 2006; Palinkas et al., 2010), higher MVBFs were recorded in male than in female subjects. Again as discussed in Chapter 1, this could be attributed to the greater muscular potential in men due to several anatomical and physiological differences including: the larger diameter and cross-sectional area of the type II muscle fibres in the masseter muscle (Tuxen et al., 1999; Hatch et al., 2001), the larger jaw dimensions (Bakke, 2006), and the larger size of dentition and its associated larger periodontal ligament area (Ferrario et al., 2004a). Additionally, It has been suggested that the MVBF in women could also be related to the lower pressure pain threshold and pressure pain tolerance during maximum biting (Koç et al., 2011).

The range of MVBFs found in this study is within that (120 – 350 N) found between the anterior teeth in earlier bite force studies using the same basic type of bite force transducer (steel strain-gauge force transducer; e.g. Helkimo et al., 1977; Lyons and Baxendale, 1990; Tortopidis et al., 1998b). The next study will deal with an attempt to produce an even more comfortable transducer. The performance and practicality of the newly developed transducer and the strain-gauge transducer covered with EVA sheets will be compared. The next study will also include psychophysical measurements of the participants' subjective feelings about the use of the transducers, the absence of which was arguably a weakness in this study.

Chapter 4: A Comparison of Pressure and Strain-gauge Transducers for the Measurement of Maximum Voluntary Bite Force

4.1 Introduction

As described in Chapter 3, the use of ethylene vinyl acetate (EVA) sheets on the biting surfaces of the strain-gauge transducer resulted in significantly higher maximum voluntary bite forces (MVBFs) than when only silicone indices were used. Arguably the most obvious explanation for this finding is that the EVA sheets helped to improve comfort and to minimise the fear of damage to the teeth that is associated with biting on hard surfaces, even if the hard metal surfaces are covered with silicone or acrylic indices as had been done in some previous studies (e.g. Lyons et al., 1996; Tortopidis et al., 1998b; Tortopidis et al., 1999).

Pressure transducers, which utilise a fluid-filled tube connected to a pressure sensor, have been used in a few studies for the measurement of bite force (e.g. Braun et al., 1995; Rentes et al., 2002; Pereira et al., 2007). They have been developed mainly to overcome the problem that exists with strain-gauge transducers, of biting on hard surfaces. However, there is a lack of information from previous studies regarding the length and the diameter of the tube, the degree of rigidity of the tube, and the type and viscosity of the fluid used to fill the tube. Furthermore, no previous investigator has considered, in the calibration procedure, the effect of different arch shapes and tooth morphologies on recordings between different subjects. In principle, these variations in arch shapes and tooth morphology could result in differences in the area of contact between the teeth and the tube; as pressure is the ratio between force and area, the area of contact will affect the pressure produced by any given force and therefore should be considered.

The principal aim of this study was to compare the suitability of two bite force measuring transducers: firstly, the commonly-used strain-gauge transducer with EVA sheets as described in the previous chapter, and secondly, a newly-developed pressure transducer. These transducers were compared to each other and to the strain-gauge transducer with commonly-used acrylic indices in order to investigate their performance and practicality. The study also included psychophysical measurements by means of a visual analogue scale (VAS) on which the subjects indicated how confident they were that they had achieved a MVBF for each different transducer.

4.2 Materials and Methods

The study took place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. Experiments required around one hour for each subject and were completed in one visit.

4.2.1 Subjects

Fifteen subjects (twelve male; three female) were recruited. Their ages ranged from 24 to 41 years (mean = 32 years).

4.2.2 MVBF Measurements

Each subject was asked to bite as hard as possible three times on the three different types of bite force transducer while the transducer was placed between the anterior teeth from canine to canine. The highest bite force recorded was considered as the MVBF for each type of transducer. The three different types of bite force transducer were: (a) a strain-gauge transducer with acrylic indices; (b) a strain-gauge transducer covered with EVA sheets; (c) a pressure transducer-based system.

The order in which the three different transducers were used was randomized to avoid time-related effects, and the subjects were required to rest for five minutes before changing to a different transducer. Before the use of each transducer, subjects were asked to undertake trial sub-maximal clenches in order to become familiar with the procedure. All the measurements were done while the subjects were seated upright in a dental chair. The strain-gauge transducer, the EVA sheets, and the pressure transducer were disinfected before the experiments by immersing them for 2 minutes in a disinfectant solution (made with Actichlor™ Chlorine Releasing Disinfectant Tablets, Ecolab Limited, Leeds, UK).

4.2.3 The Bite Force Transducers

4.2.3a The strain-gauge transducer with acrylic indices

A detailed description of the strain-gauge transducer was given in Chapter 2 (section 2.3.1; page 41). For this type of bite force transducer, a hard, self-cured, acrylic material (Unodent, Unodent Limited, UK), usually used for re-lining dentures, was employed to make indices for each subject on the biting surfaces of the transducer (Fig. 4.1; Lyons et al., 1996).

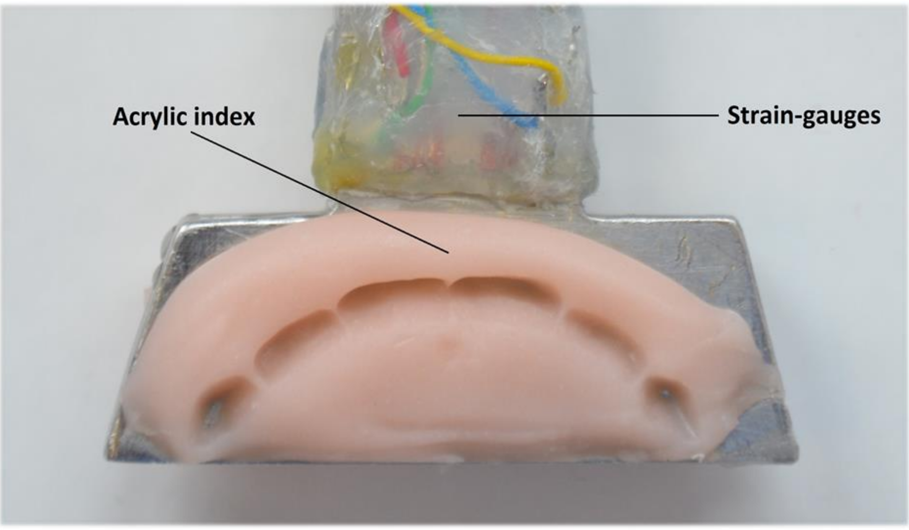

Figure 4.1: Example of an acrylic index of upper anterior teeth on the strain-gauge transducer. Note that the strain-gauges are covered in silicone rubber for insulation and protection.

4.2.3b The strain-gauge transducer covered with EVA sheets

Two mm thick EVA sheets (Vacuum Blank Material, Bracon Limited, East Sussex, UK) were used to cover the biting surfaces of the strain-gauge transducer. The total thickness of the transducer with the two EVA sheets was 12 mm (see Fig. 3.2; page 66).

4.2.3c The pressure transducer

A detailed description of the pressure transducer was given in Chapter 2 (section 2.3.2; page 43). Borders were marked on the tubing so that all the subjects bit within these borders during the experiment. This minimised the possibility that any inter-subject variations in the bite force signal output would be related to changes in the location of the teeth along the tube.

4.2.4 Calibration

4.2.4a Calibration of the strain-gauge transducer

The strain-gauge transducer was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.1; page 45). On all the experimental occasions, a linear relationship was found between the applied loads and the response of the instrument. Linear regression was used to calculate the best-fit line and the resulting equation was then applied to convert voltage changes associated with biting to forces in Newtons (see Fig. 2.4). The response of the instrument was found to be consistent between different occasions [Intra-Class Correlation Coefficient (ICC) = 0.998].

4.2.4b Calibration of the pressure transducer

The pressure transducer was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.2; page 47). On all the experimental occasions, a non-linear but consistent relationship was found between the applied loads and the response of the instrument. The best-fit curve generated by second order polynomial regression was calculated and the resulting equation was then applied to convert voltage changes associated with biting to forces in Newtons (see Fig. 2.10). The response of the instrument was found to be consistent between different occasions (ICC = 0.992).

4.2.5 VAS

Subjects were asked to respond by means of a 100 mm VAS as to how confident they were that they had achieved a maximum biting effort. The anchor points were "not confident at all" and "absolutely confident" (Appendix 3). Each subject responded on one VAS for each different type of transducer.

4.2.6 Statistical Analysis

IBM® SPSS® 21 statistical analysis software was used in this study. Reliability analysis was applied to examine the consistency of the response of the transducers using the ICC parameter. Repeated measures ANOVA was applied to examine whether there were any significant differences between the MVBFs recorded on the three different types of bite force transducer. When this yielded a significant result ($P < 0.05$), *post-hoc* Bonferroni-corrected paired t tests were used to determine if there were significant differences between each pair of transducers.

VAS data are often non-normally distributed, largely because of "floor" and "ceiling" effects. In the present study, the VAS data were found to be not normally distributed largely because of "ceiling" effects. Accordingly, a

Friedman, non-parametric, test was applied to examine whether there were any significant differences between the VAS results across the three different types of bite force transducer. When this yielded a significant result ($P < 0.05$), *post-hoc* Bonferroni-corrected Wilcoxon signed-rank tests were used to determine if there were any significant differences between the VAS scores from each pair of transducers.

4.3 Results

4.3.1 MVBF Measurements

Fourteen out of the fifteen subjects recorded their highest bite force while biting on the pressure transducer, followed by the strain-gauge transducer covered with EVA sheets and last of all the strain-gauge transducer with hard acrylic indices (Fig. 4.2). The mean MVBFs (± S.D.) on the three different transducers were: the pressure transducer, 359 ± 152 N; the strain-gauge transducer covered with EVA sheets, 239 ± 93 N; and the strain-gauge transducer with acrylic indices, 163 ± 82 N. Only one (male) subject recorded their highest MVBF on the strain-gauge transducer covered with EVA which was nearly identical with their MVBF on the strain-gauge transducer with acrylic indices (only 3 Newtons difference). He commented that he found the pressure transducer was “too thick to bite comfortably on it”.

Repeated measures ANOVA showed significant differences between the MVBF results for the three different types of bite force transducer ($P = 0.00015$). *Post hoc* tests showed significant differences between the acrylic indices and the pressure transducer (P = 0.00043), between the acrylic indices and the EVA sheets (P = 0.000062), and between the EVA sheets and the pressure transducer (P = 0.0045).

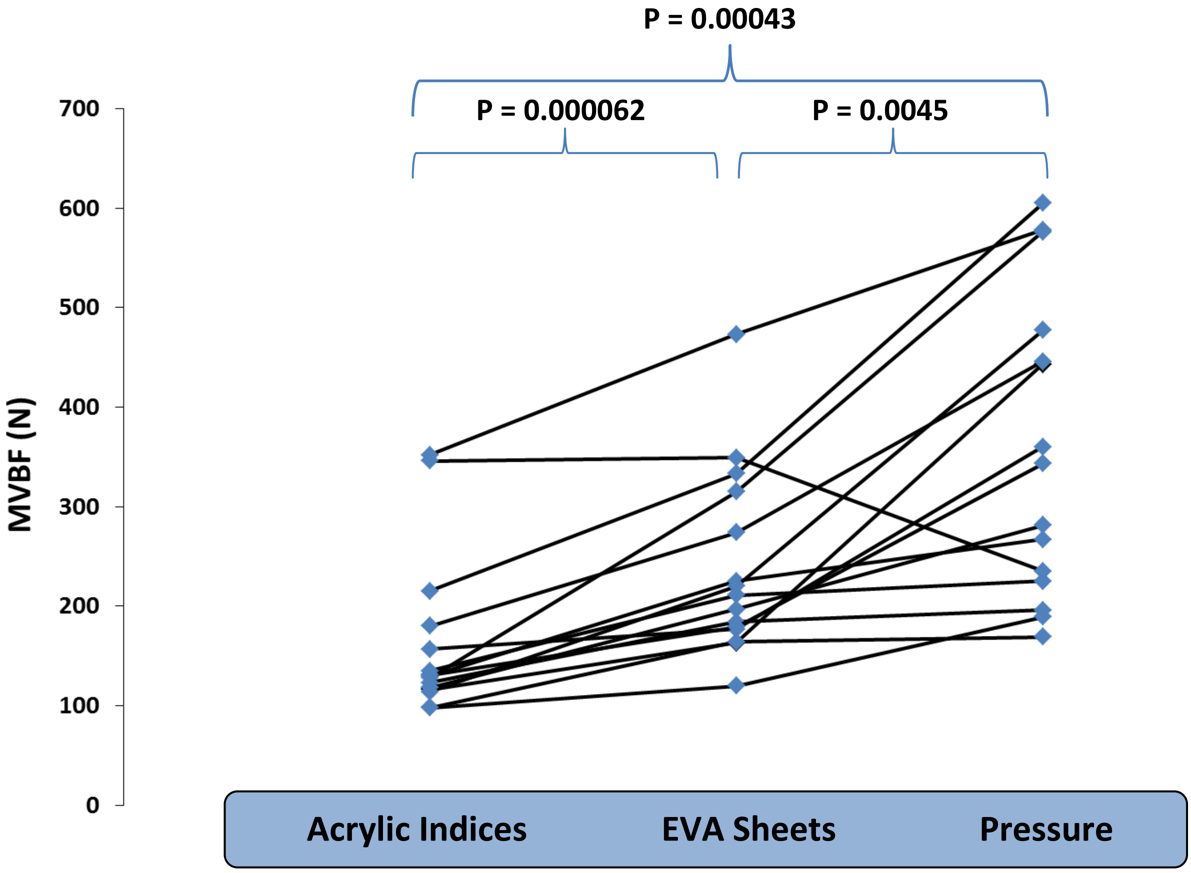

Figure 4.2: Scatter plot showing the MVBFs obtained with each transducer by each subject. The data for individual subjects are linked by the lines between symbols. P values for *post hoc* tests between each pair of transducers are also shown.

4.3.2 VAS Responses

Twelve out of the fifteen subjects noted the highest level of confidence with the pressure transducer, followed by the strain-gauge transducer covered with EVA sheets and last of all the strain-gauge transducer with hard acrylic indices (Fig. 4.3). The medians and full ranges of VAS scores for the three different transducers were: the pressure transducer, 95 mm (73.5 - 98 mm); the strain-gauge transducer covered with EVA sheets, 73 mm (38 - 98.5 mm); and the strain-gauge transducer with acrylic indices, 14 mm (1.5 - 92 mm).

A Friedman test showed significant differences between the VAS scores across the three different types of bite force transducer (P = 0.000095). *Post hoc* Wilcoxon tests showed a significant difference between the scores for the acrylic indices and the pressure transducer (P = 0.0040), and between the scores for the acrylic indices and the EVA sheets (P = 0.0020). The differences between the scores for the EVA sheets and the pressure transducer narrowly failed to achieve statistical significance (P = 0.051), with a trend for there to be higher scores with the pressure transducer.

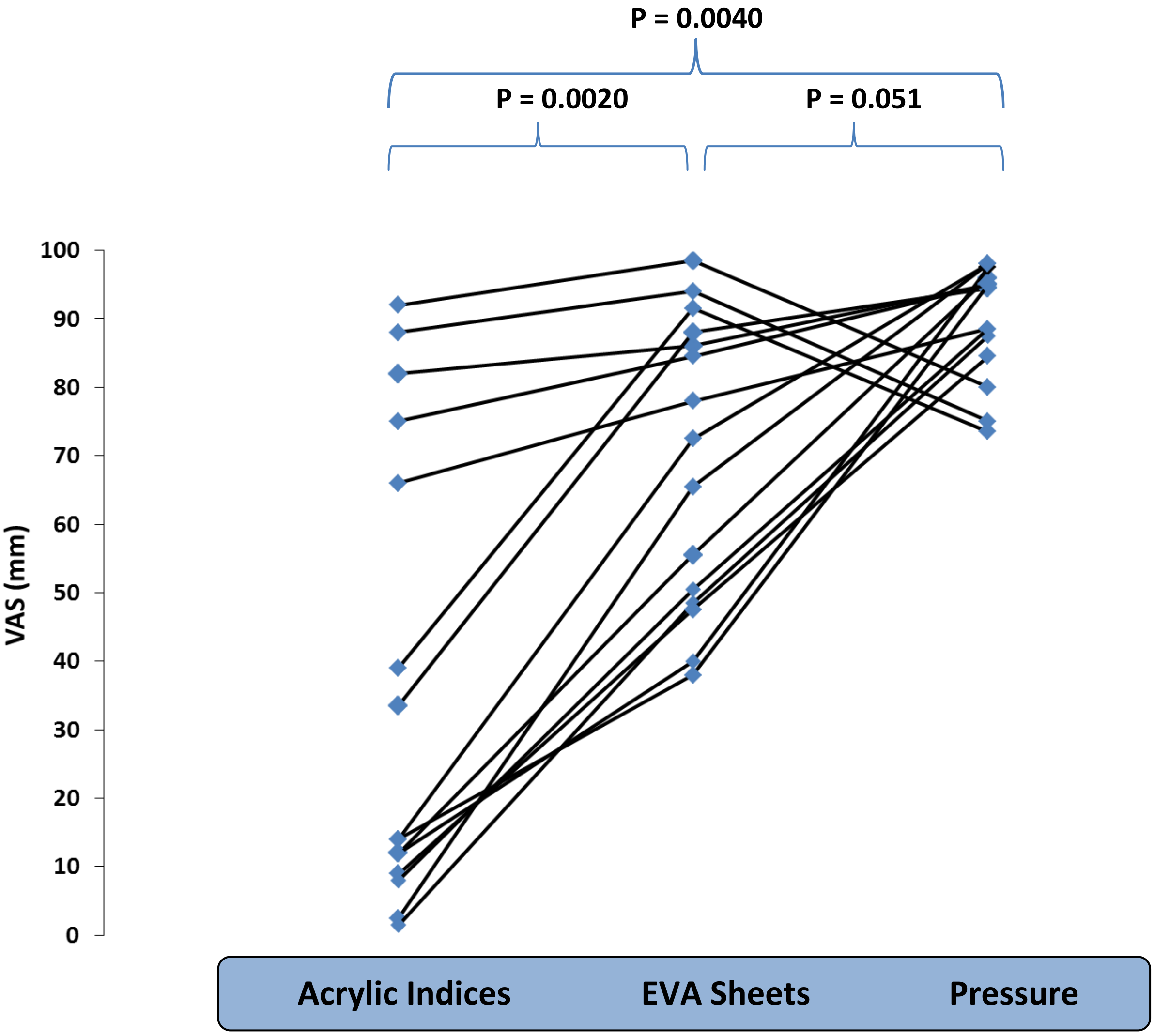

Fig. 4.3: Scatter plot showing the measurements of confidence (VAS data) with each transducer for each subject. The data for individual subjects are linked by the lines between symbols. P values for p*ost hoc* tests between each pair of transducers are also shown. The three subjects who noted low confidence levels in the pressure transducer related this to the bulkiness of the transducer.

4.4 Discussion

4.4.1 General

As discussed in Chapters 1 and 3, a true maximum bite force on the commonly-used strain-gauge transducer with acrylic indices is unlikely to be achieved, mainly due to discomfort and fear of breaking teeth and restorations (Braun et al., 1995; Lyons et al., 1996). It was therefore considered desirable to develop bite force transducers which avoided, or at least minimised, these drawbacks. Pressure transducers have been used previously for the measurement of bite force (e.g. Braun et al., 1995; Rentes et al., 2002; Pereira et al., 2007). Braun et al (1995) were amongst the first to develop a pressure transducer system and use it for the measurement of bite force. However, there was a lack of information in the publication of that study regarding the length, diameter and rigidity of the tube, and whether or not a liquid was used to fill the tube. The workers in that study used a PX300 Omega pressure sensor. When the same pressure sensor was tested in our laboratory by applying known forces (50 - 200 N) to a water filled rubber tube, the signal-to-noise ratio was far too low. This made detecting the pressure changes due to the applied forces inaccurate at best. When the reasons for this poor signal-to-noise ratio were investigated, it was found that PX300 Omega pressure sensor has a far higher pressure range (0 - 1000 psi; 0 - 6894.8 kPa) than that required in bite force measurement studies; the appropriate range for the pressure transducer, developed in the present study, proved to be between 5 and 20 psi (34.5 – 137.9 kPa). For that reason, the Omega Model No. PX309 with a pressure range of 0 - 50 psi was used in this study.

Rentes et al (2002) used a different pressure sensor (MPX 5700, Motorola, SPS, Austin, TX, USA) for their transducer (Rentes et al., 2002). However, this sensor is approved only for the measurement of air pressure and the authors gave no details on whether or not a liquid was used to fill the tube. As air is compressible, there would therefore be bounce and lag time in the measurement of bite force which is likely to be problematic if one assumes that a subject can hold their MVBF for only a short period of time. There would also be a significant effect with changes in temperature.

As far as one can tell from the published information, none of the above workers considered the potential effect of different arch shapes and tooth morphologies when calibrating the transducer (see Chapter 2; section 2.4.2). However, with our transducer, the differences in the areas of contact between the teeth and the tube when used with the different sets of casts were minimal and had little effect on the output of the pressure transducer. It was therefore considered acceptable to use a control set of casts for the calibration on each day of experimentation in subsequent studies. However, with a softer version of the pressure transducer, with one layer of tubing, the differences in the areas of contact, when used with different sets of casts, were substantial and had a considerable effect on the output of the pressure transducer (see Chapter 2). Accordingly, the effect of different arch shapes and tooth morphologies should be taken into consideration whenever a pressure based system is used for the measurement of bite force, as this will vary with the resilience of the tube.

4.4.2 MVBFs Recorded on the Different Transducers

The results of this study indicate that both the strain-gauge transducer covered with EVA sheets and the pressure transducer, are more suitable transducers for the measurement of MVBF than the strain-gauge transducer with acrylic indices. However, the highest bite forces were achieved on the pressure transducer.

The range of MVBFs recorded, in this study, on the strain-gauge transducer is within that (120 – 350 N) found between the anterior teeth in earlier bite force studies using the same type of bite force transducer (e.g. Helkimo et al., 1977; Lyons and Baxendale, 1990; Tortopidis et al., 1998b). Braun et al (1995) reported higher values of MVBFs on their pressure transducer than on the one developed in this study. This difference is most likely to be because they measured the MVBF in the second premolar-first molar region, whereas in this study it was measured between the anterior teeth. In agreement with this, many studies (see Bates et al., 1975; Tortopidis et al., 1998b; Duygu Koc et al., 2010) have reported higher MVBFs between the posterior teeth than between the anterior teeth. This, as discussed in Chapter 1, has been explained mainly by the larger root area of posterior teeth (Gibbs et al., 2002; Bakke, 2006) and the shorter distance from the fulcrum which gives a mechanical advantage to the jaw-closing muscles (see Hagberg, 1987; van Eijden, 1991).

4.4.3 Possible Explanations for the Different MVBFs from the Different Transducers

A number of considerations might help to explain the different MVBFs obtained with the different transducers. These are discussed below and are not mutually exclusive.

4.4.3.1 Transducer thickness

One factor that might have affected the MVBFs was the difference in total thickness of the three transducers. Manns et al (1979) and Mackenna et al

(1983) reported that MVBF increases up to a jaw separation of 15-20 mm between anterior teeth and 9-11 mm between posterior teeth. This might be considered one of the possible explanations for the higher MVBFs recorded on the pressure transducer (19 mm thickness) compared to the strain-gauge transducer covered with EVA sheets (12 mm thickness) and the strain-gauge transducer with acrylic indices (8 mm thickness). However, it should be pointed out that the compressibility of the tube when a high bite force is applied makes it very difficult to assess the effect of transducer thickness on MVBF.

4.4.3.2 Nature of biting surfaces

The responses on the Visual Analogue Scale (VAS) showing greater confidence in the pressure transducer than in the strain-gauge transducer, are consistent with the notion that the higher MVBFs on the pressure transducer could be attributed to the subjects believing that they could achieve a maximum bite force with little or no discomfort or fear of breaking the teeth (see; Lyons et al., 1996; Bakke, 2006).

One other possible explanation for the higher MVBFs recorded on the pressure transducer could be the flexibility of the tubing which allows the tube to conform to the occlusal surfaces of the teeth. This would avoid the possibility of deformation of tooth structure which is likely when biting on a hard or on an inflexible surface (Braun et al., 1995). It may also be argued that the different nature of the biting surface for the pressure transducer possibly helped to initiate a significant positive and / or to delay or prevent a negative modulation of maximum biting forces by the sensory receptors within the periodontium, and this, as discussed in Chapter 3, could enhance the achievement of higher bite forces (Paphangkorakit and Osborn, 1998; Serra and Manns, 2013).

As discussed above, the increased confidence, the possible reduced discomfort and fear of breaking the teeth, the possible initiation of a significant positive modulation of maximum biting forces, and the possible prevention of a significant negative modulation of maximum biting forces, might have enhanced the production of higher MVBF on the pressure transducer than on the strain-gauge transducer. Thus, higher and closer to the true maximum bite forces of which the jaw closing muscles are capable, were recorded on the pressure transducer.

The difference that might exist between the true maximum bite force and the MVBF as recorded on a bite force transducer is referred to as the “spare capacity” of the jaw closing muscles (Lyons et al., 1996). This might be investigated by means of the technique of twitch interpolation (see Chapter 6).

4.4.3.3 Two- versus three-dimensional sensitivity

One other factor that might have contributed to the differences in MVBFs recorded using the strain-gauge transducer and the pressure transducer was the difference between the two transducers in terms of three dimensional capabilities. As discussed in Chapter 1, a number of studies have investigated the three dimensional nature of bite force and suggested that the bite force is composed of both horizontal and vertical components (van Eijden et al., 1988; van Eijden, 1991; Osborn and Mao, 1993).

The strain-gauge transducer is uni-directional and allows for the measurement of bite force in only a single direction, which is parallel to its measuring axis (approximately vertical; van Eijden et al., 1988; van Eijden, 1991). On the other hand, the pressure transducer is flexible and allows the subject to have a range of bite direction instead of being restricted to one direction (as is the case with the strain-gauge transducer). Thus, it may be argued that the pressure transducer possibly allows for the measurement of the total bite force (or a more representative part of it), whereas the strain-gauge transducer allows for the measurement of only the vertical component of bite force. Thus, it may be proposed that the higher MVBFs recorded, in this study, on the pressure transducer were possibly total bite forces (vector sum of the vertical and the horizontal components), while the lower MVBFs recorded on the strain-gauge transducer were only vertical components of bite forces (vertical bite forces).

However, unfortunately, there is not enough information on what proportion of the total bite force can be accounted for by each of the different components of bite force (the horizontal and vertical components). Only a few studies, by the same group of workers (Mericske-Stern et al., 1992; Mericske-Stern et al., 1996; Mericske-Stern, 1998a), investigated this in mandibular implant supported overdenture wearers using a three-dimensional bite force transducer. They found that the total bite forces were mainly composed of vertical and anterior-posterior horizontal components, and that the anterior-posterior horizontal components reached 10-50% of the vertical components during maximum biting, while they resembled or exceeded the vertical components during chewing. Thus, it is hard to conclude that the difference between the strain-gauge transducer and the pressure transducer in terms of three-dimensional capabilities would fully explain the large differences in MVBFs recorded using the different transducers.

4.4.3.4 Area of tooth contact

One further factor that might have contributed to the differences in MVBFs recorded using the strain-gauge transducer and the pressure transducer was the differences in the area and number of teeth involved in maximum biting. As discussed earlier, the flexibility of the pressure transducer would allow it to conform to the occlusal surfaces of the teeth. Thus, a larger area of teeth would be involved in maximum biting on the pressure transducer than on the strain-gauge transducer (Braun et al., 1995). Also, even with careful positioning of the pressure transducer between the anterior teeth from canine to canine, an involvement of the first premolars in the bite cannot be entirely excluded as some flattening of the tube occurs as the bite force is increased. This possible involvement of a larger area and number of teeth (more posterior teeth), as discussed earlier and also in Chapter 1, can give an advantage to the pressure transducer to allow for higher bite forces to be recorded than on the strain-gauge transducer (see Bates et al., 1975; Tortopidis et al., 1998b; Bakke, 2006; Duygu Koc et al., 2010).

It may also be argued that another possible explanation for the higher MVBFs on the pressure transducer could be related to some overestimation of MVBFs due to possible variations in calibration caused by the effect of different arch shapes and sizes, tooth morphology, and occlusion forms between different subjects. This, as discussed earlier, could affect the area of contact between the teeth and the tube, and thus the pressure changes created by biting forces. However, as demonstrated in Chapter 2, these variations were largely minimised by selectively recruiting the subjects with average arch sizes and without significant malocclusions.

4.4.4 Conclusions and Further Experiments

Within the limitations of this study, it was concluded that both the pressure transducer and the strain-gauge transducer covered with EVA sheets are more appropriate for the measurement of bite force than the commonly-used strain-gauge transducer with acrylic indices. The pressure transducer was found to be the transducer which consistently produced the highest MVBF values and VAS scores. It had good reliability and was inexpensive to fabricate.

Having discussed the possible explanations for the differences in MVBFs for the different transducers, the next stage of the project was to investigate which of these can be substantiated or eliminated. The next study was therefore to investigate the effect of changing the thickness of a bite force transducer on MVBF, within the range of the thickness difference between the strain-gauge transducer with EVA sheets (12 mm) and the pressure transducer (19 mm).

Chapter 5: An Assessment of the Effect of Increasing the Thickness of a Bite Force Transducer on Maximum Voluntary Bite Force

5.1 Introduction

As described in Chapter 4, higher maximum voluntary bite forces (MVBFs) were recorded on a 19 mm thick pressure transducer than on a 12 mm thick strain-gauge transducer covered with ethylene vinyl acetate (EVA) sheets. One factor that might have affected these results was the difference in total thickness of the two transducers.

As discussed in Chapters 1 and 3, a number of studies have reported a trend for an increase in the MVBFs as the jaw is opened up to 15 - 20 mm incisal separation (e.g. Manns et al., 1979; Mackenna and Türker, 1983). It has been suggested that this range of jaw openings probably corresponds to the optimum length of the jaw closing muscle sarcomeres over which the force output does not vary with length and the muscle force output is maximal (see Bakke, 2006; Duygu Koc et al., 2010).

Paphangkorakit and Osborn (1997) reported a wider range for the optimum incisal separation (14 – 28 mm). They argued that the maximum bite force plateau starts when the sarcomeres of the masseter muscle reach their optimum length, and that this plateau lasts during further jaw opening, until those of the temporalis reach their optimum length while those of the masseter stretch beyond their optimum length (Lindauer et al., 1993).

As discussed in Chapter 4, the proposed effect on MVBF, of the difference in total thickness of the strain-gauge transducer covered with EVA sheets (12 mm) and the pressure transducer (19 mm), and its associated change in the mount of incisal separation, is complicated by the fact that the pressure transducer is flexible and can lose up to half of its total thickness as the applied bite force is increased towards a maximum. However, the argument of a possible effect of the difference in total thickness of the two transducers can still be considered valid as a number of studies have reported that the force output of a muscle is largely dependent on the initial length of the muscle before contraction (Banus and Zetlin, 1938; Gordon et al., 1966; Mackenna and Türker, 1983).

The aim of this study was to investigate the effect on MVBF of increasing the thickness of a bite force transducer within the range of the thickness differences between the strain-gauge transducer with EVA sheets (12 mm) and the pressure transducer (19 mm). Thus it should be possible to either substantiate or refute the proposed effect of the difference in total thickness between the two transducers on MVBF.

5.2 Materials and Methods

The study took place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. It required around one hour for each subject in a single visit.

5.2.1 Subjects

Fourteen subjects (nine male; five female) were recruited. Their ages ranged from 24 to 38 years (mean = 31 years).

5.2.2 MVBF Measurements

Each subject was asked to bite as hard as possible three times on each of three, and in some cases four, (different thickness) strain-gauge transducers covered with EVA sheets while the transducer was placed between the anterior teeth from canine to canine. The highest bite force recorded was considered as the MVBF for each different thickness of transducer.

The order in which the different thickness transducers were used was randomized to avoid time-related effects, and the subjects were required to rest for five minutes before changing to a different transducer. Before the use of each of the different thickness transducers, subjects were asked to undertake trial sub-maximal clenches in order to become familiar with the procedure. All the measurements were done while the subjects were seated upright in a dental chair. The strain-gauge transducer, the polyethyleneterephthalate-glycol modified (PETG) sheets used to modify the thickness of the transducer, and the EVA sheets were disinfected before the experiments by immersing them in a disinfectant solution for 2 minutes (made with Actichlor™ Chlorine Releasing Disinfectant Tablets, Ecolab Limited, Leeds, UK).

5.2.3 The Bite Force Transducer

Detailed descriptions of the strain-gauge transducer and the strain-gauge transducer covered with EVA sheets were given in Chapter 2 (section 2.3.1; page 41) and Chapter 3 (section 3.2.3b; page 66), respectively.

A hard PETG material (Erkodur, Erkodent®, Pfalzgrafenweiler, Germany) of 1 mm thickness was employed to make 1 mm and 2 mm thickness sheets (Fig. 5.1). These sheets were then used under the EVA sheets in order to modify the thickness of the strain-gauge transducer covered with EVA sheets.

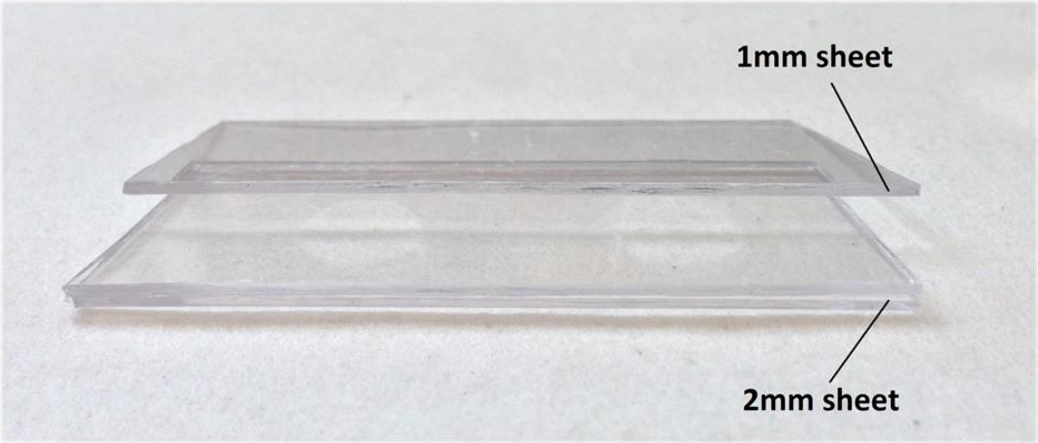

Figure 5.1: PETG sheets used to modify the thickness of the strain-gauge transducer covered with EVA sheets.

Four different thicknesses of the strain-gauge transducer covered with EVA sheets were used: (a) 12 mm, without PETG sheets; (b) 14 mm, with a 1 mm thick PETG sheet (under the EVA) attached to each of the biting surfaces of the strain-gauge transducer; (c) 16 mm, with a 2 mm thick PETG sheet (under the EVA) attached to each of the biting surfaces of the strain-gauge transducer; (d) 18 mm, with a 1 mm and a 2 mm thick PETG sheets (under the EVA) attached to each of the biting surfaces of the strain-gauge transducer.

5.2.4 Calibration

The strain-gauge transducer (without EVA or PETG sheets) was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.1; page 45). On all the experimental occasions, a linear relationship was found between the applied loads and the response of the transducer. Linear regression was used to calculate the best-fit line and the resulting equation was then applied to convert voltage changes associated with biting, into forces in Newtons (see Fig. 2.4).

5.2.5 Statistical Analysis

IBM® SPSS® 21 statistical analysis software was used in this study. Repeated measures ANOVA was undertaken to examine whether there were any significant differences between the MVBFs recorded on the different thickness bite force transducers. Spearman's rank correlation test was applied to assess the relationship between the transducer thickness and the MVBF. A P value < 0.05 was considered statistically significant.

5.3 Results

The mean MVBFs (± S.D.) on the three different thickness transducers [12, 14, 16 mm; number of subjects (n) = 14] were: the 12 mm thickness-transducer, 230 ± 82 N; the 14 mm thickness-transducer, 238 ± 72 N; and the 16 mm thickness-transducer, 254 ± 77 N (Fig. 5.2). Repeated measures ANOVA showed no significant differences between the MVBF results for the three (different thickness) transducers (P = 0.17). Spearman’s rank correlation test showed no significant correlation between the transducer thickness and the MVBF [Spearman’s Rho (rs) = 0.113, P = 0.48].

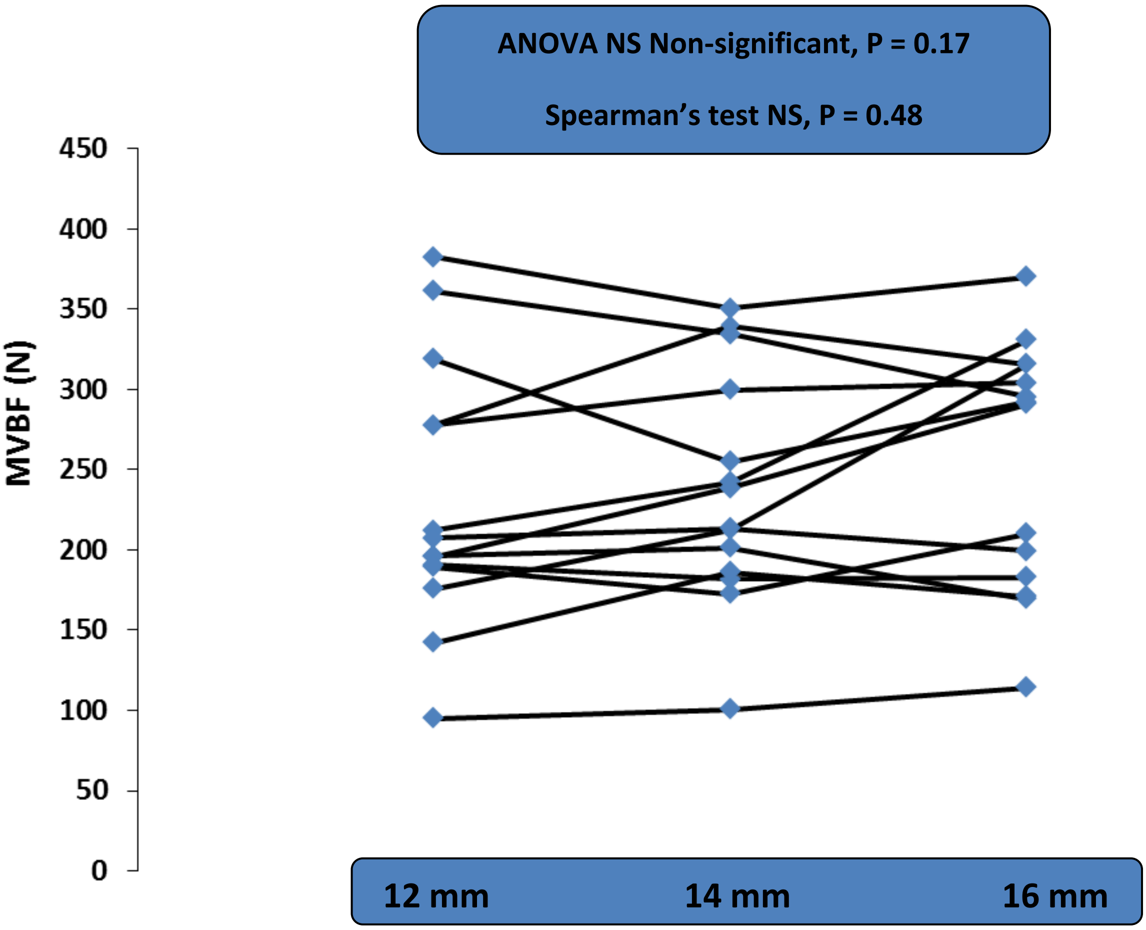

Figure 5.2: Scatter plot showing the MVBFs (N) obtained with each transducer thickness by each subject (n = 14). The data for individual subjects are linked by the lines between symbols. P values for repeated measures ANOVA and Spearman’s rank correlation test are also shown.

For the four subjects who used the four different thickness transducers (12, 14, 16, 18 mm; n =4), the mean MVBFs (± S.D.) on the different transducers were: the 12 mm thickness-transducer, 275 ± 95 N; the 14 mm thickness-transducer, 279 ± 73 N; the 16 mm thickness-transducer, 269 ± 66 N; and the 18 mm thickness-transducer, 290 ± 83 N (Fig. 5.3). Again, repeated measures ANOVA showed no significant differences between the MVBF results for the four (different thickness) transducers (P = 0.68), and Spearman's rank correlation test showed no significant correlation between the transducer thickness and the MVBF (rs = 0.036, P = 0.89).

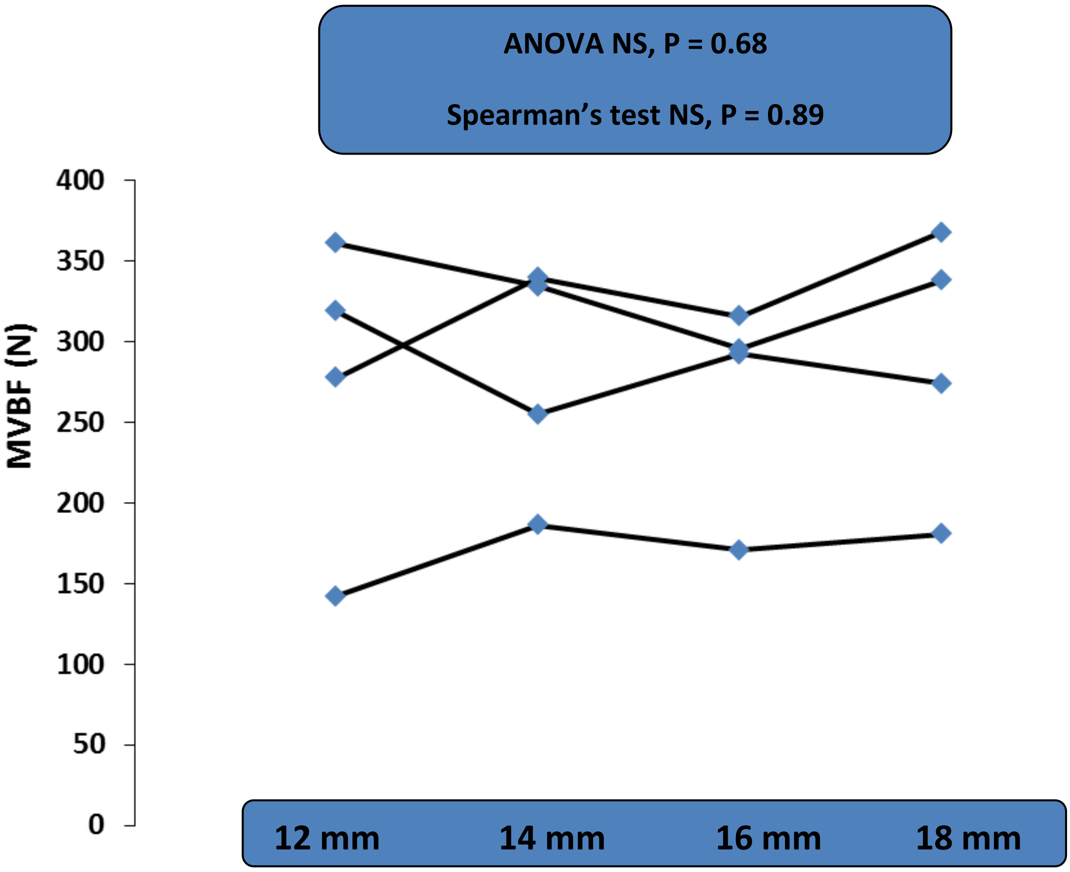

Figure 5.3: Scatter plot showing the MVBFs (N) obtained with each transducer thickness by each subject. The data for individual subjects are linked by the lines between symbols. P values for repeated measures ANOVA and Spearman’s rank correlation test are also shown in the figure. Note that the sample was small (n = 4).

5.4 Discussion

5.4.1 General

As discussed earlier, it is widely agreed that there is an optimal range of jaw opening (incisal separation) over which the jaw closing muscles are able to produce the highest MVBFs (see Hagberg, 1987; Bakke, 2006; Duygu Koc et al., 2010). This optimal range seems to start from 14 - 15 mm incisal separation

(Manns et al., 1979; Mackenna and Türker, 1983; Paphangkorakit and Osborn, 1997) and ends at about 20 mm (Manns et al., 1979; Mackenna and Türker, 1983) or even at a wider incisal separation (28 mm) as reported by Paphangkorakit and Osborn (1997).

Again, as mentioned earlier, the purpose of the present study was specifically to investigate the effect of increasing the thickness of a bite force transducer but only within the range of the thickness differences between the strain-gauge transducer covered with EVA sheets (12 mm) and the pressure transducer (19 mm). This was done in order to provide evidence to support (or disprove) the proposed effect of the difference in total thickness between the two transducers, on MVBF.

5.4.2 No Significant Effect for Changing the Transducer Thickness within the Range 12-18 mm

Although there was a trend for a slight increase in the mean MVBF value as the transducer thickness was increased, no significant differences were found between the MVBFs recorded on the three [different thickness (12, 14, 16 mm)] bite force transducers. In addition, no significant correlation was found between the transducer thickness and the MVBF.

Even with one more thickness of bite force transducer (18 mm) assessed in four of the subjects in order to make the transducer thickness more similar to the total thickness of the pressure transducer, no significant differences were found between the MVBFs recorded on the four [different thickness (12, 14, 16, and 18 mm)] transducers, and no significant correlation was found between the transducer thickness and the MVBF.

These findings are most likely because the four different thicknesses (12, 14, 16, and 18 mm) investigated in this study are all near to or within the optimal incisal separation ranges reported in earlier studies (e.g. Manns et al., 1979; Mackenna and Türker, 1983; Paphangkorakit and Osborn, 1997). Again, the investigated range of transducer thickness was limited to 12-18 mm because the purpose of the present study was to investigate only whether the difference in thickness between the strain-gauge transducer covered with EVA sheets (12 mm) and the pressure transducer (19 mm) might be a significant factor that affected the MVBFs recorded, in the previous study (Chapter 4), on the two transducers.

5.4.3 Conclusions and Further Experiments

Thus it might be concluded from the results of the present study that the difference in total thickness between the strain-gauge transducer covered with EVA sheets (12 mm) and the pressure transducer (19 mm), and its associated change in incisal separation, was not a significant factor that affected the MVBFs recorded in the previous study (Chapter 4), on the two transducers. Thus, the difference in total thickness between the two transducers cannot be considered any longer as a substantial explanation for the large differences in the MVBF recorded on the two transducers.

The next study will investigate another possible explanation (discomfort and spare capacity) for the difference in MVBFs recorded on the two transducers (see Chapter 4) by means of the technique of twitch interpolation.

Chapter 6: A Comparison of Maximum Voluntary and Maximum Potential Bite Forces Using the Technique of Twitch Interpolation

6.1 Introduction

As revealed in Chapter 5, the difference in total thickness between the 12 mm thick strain-gauge transducer covered with ethylene vinyl acetate (EVA) sheets and the 19 mm thick pressure transducer was not found to be a significant factor that would have contributed to the large differences in maximum voluntary bite forces (MVBFs) recorded using these different transducers in the previous study (Chapter 4). Another factor that might have contributed to the differences in bite forces (Chapter 4) was the amount of discomfort, or even expectation of discomfort, which might have left an unused "spare capacity" in the jaw closing muscles.

As discussed in previous chapters, registering a true maximum bite force is possibly limited by the fear of damaging the teeth and the discomfort associated with biting on hard surfaces (Lyons et al., 1996), as well as any inhibitory factors triggered by activation of sensory receptors within the periodontium. These may result in a reduction in the activity of the motor nerves which control the jaw closing muscles, and consequently the recording of a lower bite force than the true maximum possible (Brodin et al., 1993; Paphangkorakit and Osborn, 1998; Alkan et al., 2006).

Thus, it could be assumed that the higher MVBFs recorded on the more flexible, and presumably more comfortable, pressure transducer than on the strain-gauge transducer (Chapter 4) were closer to, or more representative of, the true maximum bite forces of which the jaw closing muscles are capable. This would also be in agreement with the psychophysical (visual analogue scale) responses of the participants' subjective feelings about the use of the two types of transducers in the previous study (Chapter 4), which indicated higher levels of confidence that the subjects had achieved a maximum biting effort with the pressure transducer than with the strain-gauge transducer.

The possibility that discomfort or some other factor leaves a "spare capacity" in the masticatory system can be investigated by means of the technique known as "twitch interpolation". The principle of twitch interpolation is that electrical stimuli are applied to a muscle (or a group of synergist muscles) at varying states of voluntary contraction. The momentary increase in force output from the muscles which results from the twitch produced by this stimulus is inversely proportional to the strength of the voluntary contraction. This, as previously shown for jaw muscles by Lyons et al. (1996), can be demonstrated by plotting twitch force against voluntary force, and then extrapolation of the regression line for the data to zero twitch force which should indicate the true maximum force potential of the group of muscles responsible for generating the force. This also means that any given stimulus after all the muscle fibres have been fully activated and maximum contraction has been reached, will not lead to any increase in the muscle force output (Merton, 1954; Lyons et al., 1996). Thus, the technique of twitch interpolation enables prediction of the true maximum force potential of a group of muscles and the assessment of whether a maximum voluntary force output of these muscles is a true maximum or not.

It has been argued that most normal individuals should be able to achieve full voluntary activation of their jaw closing muscles (Lyons et al., 1996). This is thought to be, at least in part, because of the scarcity of tendon organs in the masticatory system (see Matthews, 1975). These receptors are believed to cause tendon-organ reflex inhibition in other muscles in the body especially at eccentric contractions (Westing et al., 1990). However, even taking account of the scarcity of tendon organs, it is still difficult to conclude that it is possible to fully activate the jaw closing muscles voluntarily as there may be an inhibitory role for periodontal sensory receptors in the control of bite force, although whether this is significant is still unclear (see Chapters 1, 3, and 4; also Hellsing, 1980; Orchardson and Cadden, 1998; Kleinfelder and Ludwig, 2002; Morita et al., 2003).

The spare capacity, as defined in Chapter 4, is the difference that may exist between the maximum potential force output (which will be predicted by the technique of twitch interpolation in the present study) of a muscle or a group of synergist muscles e.g. the jaw closing system, and the maximum voluntary force output of this muscle or group of muscles e.g. MVBF on a bite force transducer (Lyons et al., 1996).

The aim of the present study was to investigate the jaw closing muscles' force output using the twitch interpolation technique and two of the bite force transducers used in the study described in Chapter 4: the strain-gauge transducer covered with EVA sheets and the pressure transducer. It was hypothesised that higher MVBFs would again be recorded on the pressure transducer, and that these would be closer to the maximum potential force outputs of the jaw closing muscles as predicted by the technique of twitch interpolation. Thus lower spare capacities would be associated with this transducer than with the strain-gauge transducer covered with EVA sheets. An additional aim of the study was to investigate whether full voluntary activation of the jaw closing muscles (i.e. no spare capacity) is possible using either of the two transducers.

6.2 Materials and Methods

The study took place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. It required two visits, each of one hour duration on the same day, for each subject.

6.2.1 Subjects

Ten male subjects were recruited. Their ages ranged from 31 to 36 years (mean = 33 years). Nine of the subjects recruited for this experiment had also participated in the previous experiment (Chapter 4).

6.2.2 MVBF Measurements

Each subject was asked to bite as hard as possible three times on the two different types of bite force transducer while the transducer was placed between the anterior teeth from canine to canine. The highest bite force recorded was considered as the MVBF for each type of transducer. The two different types of bite force transducer were: (a) a strain-gauge transducer covered with EVA sheets; (b) a pressure transducer-based system.

The order in which the two different transducers were used was randomized to avoid time-related effects, and the subjects were required to rest for five minutes before changing to a different transducer. Before the use of each transducer, subjects were asked to undertake trial sub-maximal clenches in order to become familiar with the procedure. All the measurements were done while the subjects were seated upright in a dental chair. The two different transducers and the EVA sheets were disinfected before the experiments by immersing them for 2 minutes in a disinfectant solution (made with Actichlor™ Chlorine Releasing Disinfectant Tablets, Ecolab Limited, Leeds, UK).

6.2.3 The Bite Force Transducers

6.2.3a The strain-gauge transducer covered with EVA sheets

A detailed description of the strain-gauge transducer covered with EVA sheets was given in Chapter 3 (section 3.2.3b; page 66).

6.2.3b The pressure transducer

A detailed description of the pressure transducer was given in Chapter 2 (section 2.3.2; page 43). Borders were marked on the tubing so that all the subjects bit within these borders during the experiment. This minimised the possibility that any inter-subject variations in the bite force signal output would be related to changes in the location of the teeth along the tube.

6.2.4 Calibration

6.2.4a Calibration of the strain-gauge transducer

The strain-gauge transducer was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.1; page 45). On all the experimental occasions, a linear relationship was found between the applied loads and the response of the instrument. Linear regression was used to calculate the best-fit line and the resulting equation was then applied to convert voltage changes associated with biting to forces in Newtons (see Fig. 2.4).

6.2.4b Calibration of the pressure transducer

The pressure transducer was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.2; page 47). On all the experimental occasions, a non-linear but consistent relationship was found between the applied loads and the response of the instrument. The best-fit curve generated by second order polynomial regression was calculated and the resulting equation was then applied to convert voltage changes associated with biting to forces in Newtons (see Fig. 2.10).

6.2.5 Muscle Stimulation Technique

In this study, electrical stimuli were applied to only one masseter muscle as this muscle had been found in the previous study by Lyons et al (1996), to be easily accessible for transcutaneous electrical stimulation, and was assumed to be sufficiently representative of the whole jaw closing system.

The transcutaneous electrical stimuli were applied to the right masseter muscle using a monopolar electrode configuration. A large (22 × 32 mm; skin contact size 20 × 20 mm), conductive, self-adhesive, hypoallergenic, surface electrocardiographic (ECG) electrode (Cat No. 23330, 3M^{TM} Health Care Limited, Loughborough, Leicestershire, UK) was placed on the skin overlying the belly of the muscle and served as the cathode during the electrical stimulation. A square metal plate (50 × 50 mm) was fixed to the skin below the right lateral malleolus (ankle), and served as the indifferent, anodal, electrode.

The electrical stimuli were delivered from an isolated, constant-current stimulator (DS7, Digitimer, Welwyn Garden City, UK), with an output current range of 0 – 100 milli-Amps (mA), and a maximum capacity of 400 V. The stimuli applied for twitch production were all single one millisecond (1 ms) duration rectangular wave pulses, and in most parts of the protocol (see below), of 40 mA intensity. The intensity 40 mA was chosen as it had been found in the previous study by Lyons et al (1996), to be within the optimum range of stimulus intensities. Higher intensities, e.g. 50 mA, were reported to be very uncomfortable to subjects, whereas intensities lower than 30 mA were reported to be inadequate in terms of the twitch contractions they produced (Lyons et al., 1996).

6.2.6 Experimental Protocols

As mentioned earlier, the study required two visits, each of one hour duration on the same day for each subject.

The first visit involved:

a- Measuring the MVBF for each subject using both the strain-gauge transducer covered with EVA sheets and the pressure transducer.

b- Establishing a stimulus / response relationship for the twitch forces produced by the right masseter muscle (as a representative of the jaw closing muscles) by applying a graded series of transcutaneous electrical stimuli at increasing intensities up to 40 mA while the muscle is at rest.

The second visit involved:

a - The subject being asked to perform a series of clenches on the strain-gauge transducer covered with EVA sheets at 20%, 40%, 60%, 80%, 100%, 100%, 80%, 60%, 40%, and 20% of their MVBF (recorded on the same transducer in the first visit) with the aid of visual feedback of the force record. Each force level was maintained for up to 5 seconds. While performing the clenches, and at an unpredictable point of time, a twitch was elicited by a single 1 ms, 40 mA, electrical stimulus applied to the right masseter muscle. The twitch force was measured from the pre-stimulus actual force to the peak force (Fig. 6.1).

b - The subject being asked to perform a series of clenches on the pressure transducer at 20%, 40%, 60%, 80%, 100%, 100%, 80%, 60%, 40%, and 20% of their MVBF (recorded on the same transducer in the first visit) with the aid of visual feedback of the force record. Each force level was maintained for up to 5 seconds. While performing the clenches, and at an unpredictable point of time, a twitch was elicited by a single 1 ms duration, 40 mA intensity, electrical stimulus applied to the right masseter muscle. The twitch force was measured from the pre-stimulus actual force to the peak force.

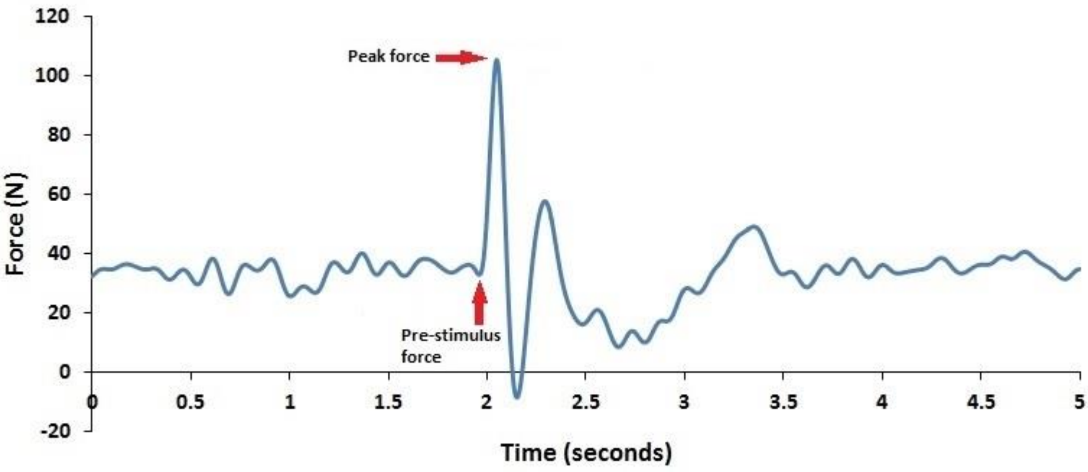

Figure 6.1: Example of a force record in which the subject was asked to perform and maintain a clench at approximately 20% of their MVBF on the strain-gauge transducer covered with EVA sheets. The timing of the stimulus and the pre-stimulus force are indicated by the bottom red arrow. The peak force is indicated by the top red arrow. The twitch force was measured as the difference between the peak force and the pre-stimulus force. The negative deflection after the twitch force was due to elastic recoil of the force transducer.

The order in which the subjects performed the above procedures “a” and “b” was randomized to avoid time-related effects. Silicone indices of the anterior teeth were made for each subject on both transducers in order to standardise the biting position on each of the transducers through the two sessions.

The visual feedback of the force recording was provided using a two channel digital oscilloscope (TDS 340 A, Tektronix, Inc., Wilsonville, U.S.A) which indicated the actual (feedback signal) and the desired levels (fixed target line) of bite force. During the experiments, the subjects were asked to approximate these two lines to the best of their ability.

6.2.7 Data and Statistical Analyses

Microsoft® Excel® 2010 software was used to calculate regression lines for the twitch forces produced at the different voluntary force levels in each subject for each type of bite force transducer. Then, extrapolation of these regression lines to zero twitch force enabled the prediction of the maximum potential bite forces in each subject for each of the two transducers.

IBM® SPSS® 21 statistical analysis software was used in this study. The Shapiro-Wilk test was used to assess the normality of the MVBF and the percentage spare capacity data. Pearson's correlation coefficient (Pearson's r) was used to assess the relationships between: (a) the different voluntary force levels and the twitch forces; (b) the MVBFs and the percentage spare capacities. Paired t tests were applied to examine whether there were any significant differences between: (a) the MVBFs recorded on the two different types of bite force transducer; (b) the maximum potential bite forces associated with the two different types of bite force transducer; (c) the percentage spare capacities (see next paragraph) associated with the two different types of bite force transducer. A P value < 0.05 was considered statistically significant.

The absolute spare capacity in each subject for each of the two transducers was measured as the difference (in Newtons) between the maximum potential bite force and the MVBF. The spare capacity was also expressed as a percentage of the maximum potential bite force. The percentage spare capacity reflected the proportion of muscle fibres or motor units (of all the jaw closing muscles) which were not fully activated during the maximum voluntary contraction. The maximum potential bite forces and spare capacities were calculated only when significant negative correlations between the different voluntary force levels and the twitch forces were found in each subject with the use of the two transducers. As a negative spare capacity is not possible, any such measurements (due to possible chance of error in the estimation of the maximum potential bite forces) were recorded as zero (see Results below).

6.3 Results

6.3.1 MVBFs

All ten subjects recorded higher MVBFs on the pressure transducer than on the strain-gauge transducer covered with EVA sheets (Fig. 6.2). The mean MVBFs (± S.D.) on the two transducers were: the strain-gauge transducer covered with EVA sheets, 277 ± 76 N; and the pressure transducer, 552 ± 243 N. A paired t test showed a significant difference between these MVBF results for the two different types of bite force transducer ($P = 0.0037$).

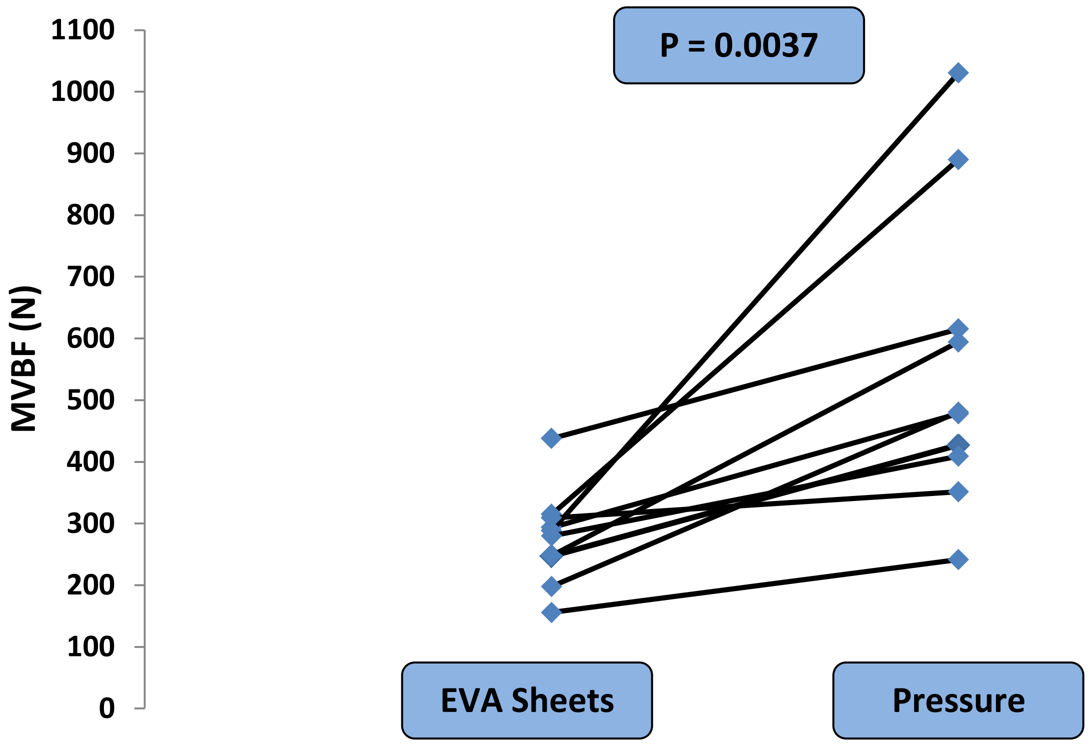

Figure 6.2: Scatter plot showing the MVBFs (N) obtained with the two different types of bite force transducer by each subject. The data for individual subjects are linked by the lines between symbols. The P value for a paired t test is also shown.

6.3.2 Maximum Potential Bite Forces

As mentioned above, the maximum potential bite forces and spare capacities were calculated only when significant negative correlations between the different voluntary force levels and the twitch forces were found in each subject with the use of the two transducers. Strong inverse linear relationships and significant negative correlations were found between the different voluntary force levels and the twitch forces in eight of the ten subjects with both types of bite force transducer [median Pearson’s r and range for the strain-gauge transducer covered with EVA sheets = (- 0.96, - 0.98 to -0.80), median Pearson's r and range for the pressure transducer = (- 0.92, - 0.98 to -0.72); Table 1; Fig. 6.3a and 6.3b]. However, in two of the subjects, the linear relationships between the different voluntary force levels and the twitch forces were found not to be statistically significant or sufficiently strong with the pressure transducer ($P = 0.18$; $r = -0.46$ and $P = 0.074$; $r = -0.59$; Fig. 6.4), although significant and strong linear relationships were found with the strain-gauge transducer covered with EVA sheets ($P = 0.000019$; $r = -0.95$ and $P = 0.00010$; $r = -0.93$). The data for these two subjects were therefore excluded in subsequent analyses.

Subject	Pearson's r EVA Sheets	P Value	Pearson's r Pressure	P Value
1	- 0.97	0.0000063	- 0.98	0.00000038
2	- 0.97	0.0000040	- 0.91	0.00023
3	- 0.97	0.0000055	- 0.94	0.000072
4	- 0.91	0.00021	- 0.92	0.00018
5	- 0.93	0.00011	- 0.95	0.000030
6	- 0.80	0.0051	- 0.91	0.00028
7	- 0.98	0.0000016	- 0.83	0.0030
8	- 0.95	0.000018	- 0.72	0.019
Median	**- 0.96**		**- 0.92**	
Range	**- 0.98** **-** **- 0.8**		**- 0.98** **-** **- 0.72**	

Table 1 Pearson's r values and P values for the relationships between the different voluntary force levels and the twitch forces in each subject (n = 8) for the two bite force transducers: the strain-gauge transducer covered with EVA sheets and the pressure transducer. Median Pearson's r value and range for each transducer are also shown.

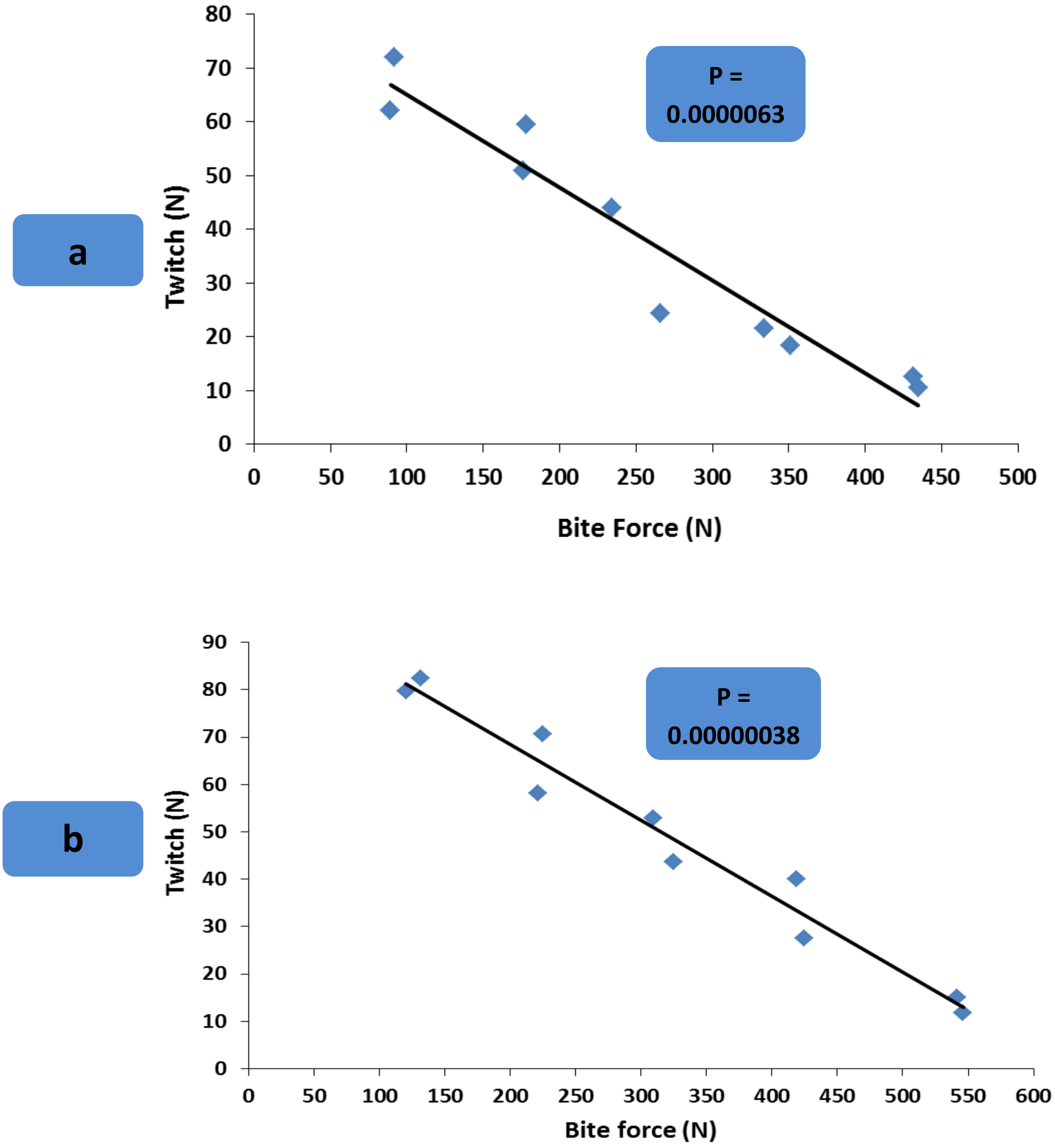

Figure 6.3: Scatter plots showing examples of strong inverse linear relationships between the different voluntary bite force levels and the twitch forces found in subject 1 (see Table 1) with the use of: (a) the strain-gauge transducer covered with EVA sheets (Pearson's r = - 0.97), and; (b) the pressure transducer (Pearson's r = - 0.98). P values for Pearson's correlation test are also shown.

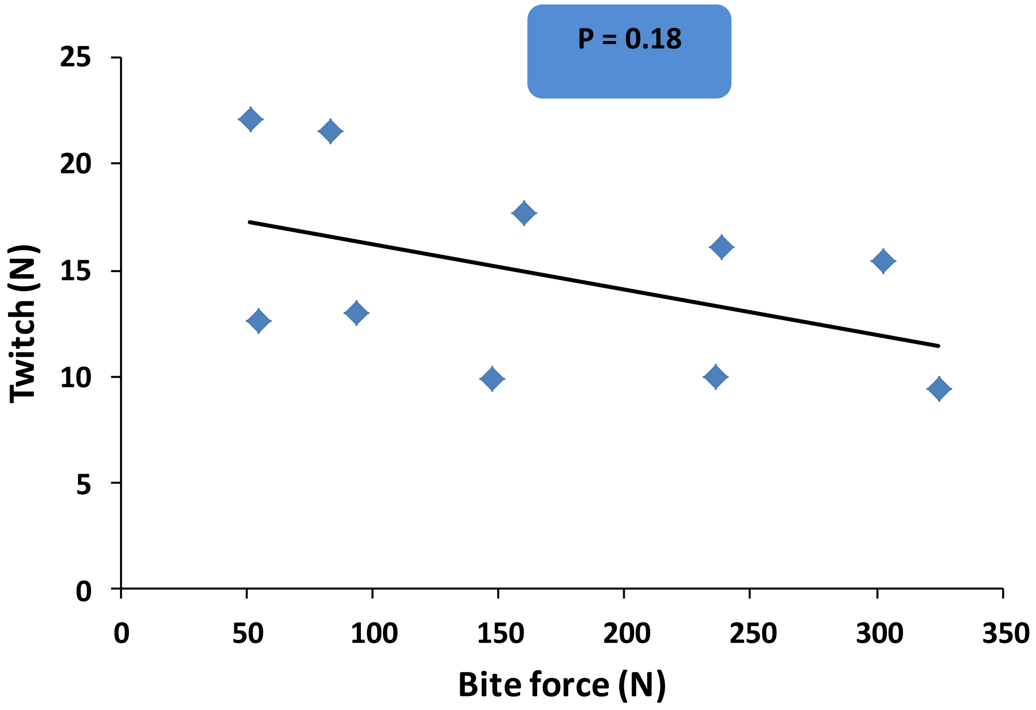

Figure 6.4: Scatter plot showing an example of a weak inverse linear relationship (Pearson's r = - 0.46) between the different voluntary bite force levels and the twitch forces found in one of the two subjects (for whom data were excluded in subsequent analyses) with the use of the pressure transducer. P value for Pearson's correlation test is also shown.

The maximum potential bite forces (as predicted by extrapolation of the regression lines between the different voluntary force levels and the twitch forces to zero twitch force) in all eight subjects were higher for the pressure transducer than for the strain-gauge transducer covered with EVA sheets (Fig. 6.5). The mean maximum potential bite forces (± S.D.) for the two transducers were: the strain-gauge transducer covered with EVA sheets, 354 ± 67 N; and the pressure transducer, 730 ± 199 N. A paired t test showed a significant difference between the maximum potential bite force results for the two different types of bite force transducer (P = 0.0013).

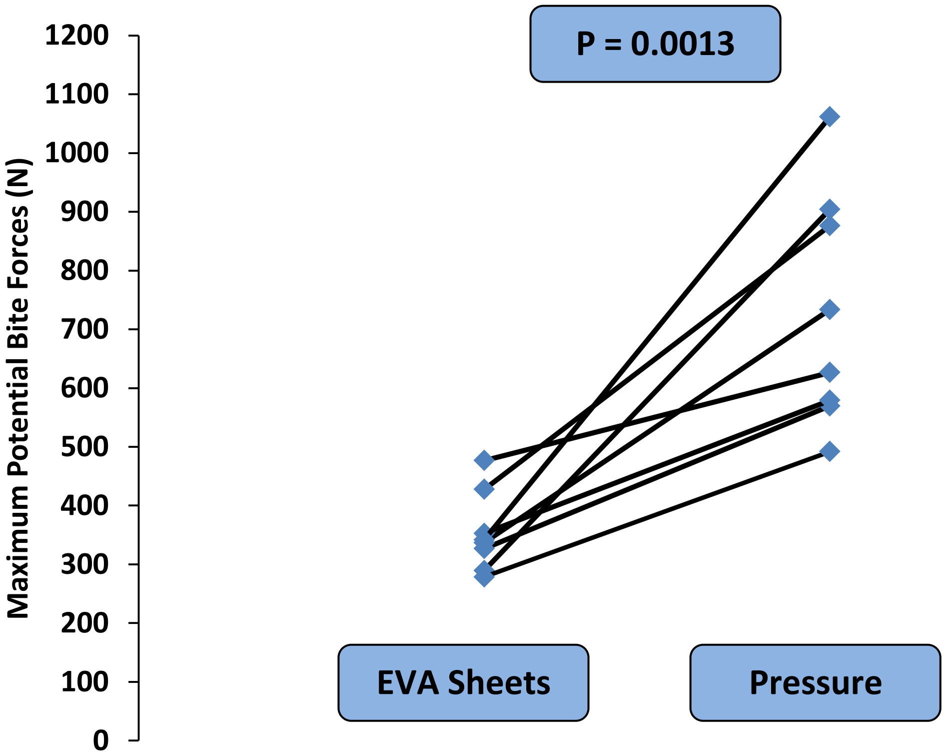

Figure 6.5: Scatter plot showing the maximum potential bite forces (N) predicted for each subject (n = 8) for the two different types of bite force transducer. The data for individual subjects are linked by the lines between symbols. The P value for the paired t test is also shown.

6.3.3 Absolute and Percentage Spare Capacities

6.3.3a Absolute spare capacities

On two occasions [one with the strain-gauge transducer (subject 3; Tables 2 and 3) and one with the pressure transducer (subject 7; Tables 2 and 3)], negative absolute and percentage spare capacities were predicted by the extrapolation. This, as mentioned earlier, is likely due to possible chance of error in the estimation of the maximum potential bite forces. As a negative spare capacity is not possible, these two measurements were recorded as zero (red font in Tables 2 and 3).

As defined earlier, the absolute spare capacity was measured as the difference (in Newtons) between the maximum potential bite force and the MVBF in each subject (n = 8) for each type of bite force transducer (Table 2). The mean absolute spare capacities (± S.D.) for the two transducers were: the strain-gauge transducer covered with EVA sheets, 65 ± 46 N; and the pressure transducer, 135 ± 180 N.

Subject	Absolute Spare Capacity (N) EVA Sheets	Absolute Spare Capacity (N) Pressure
1	39	11
2	80	142
3	0	14
4	139	253
5	53	31
6	59	101
7	31	0
8	119	525
Mean	**65**	**135**
Standard Deviation (S.D.)	**46**	**180**

Table 2 Absolute spare capacities (N) found in each subject (n = 8) for each type of bite force transducer. Mean absolute spare capacity and standard deviation for each transducer are also shown in the table.

6.3.3b Percentage spare capacities

As defined earlier, the percentage spare capacity was the spare capacity expressed as a percentage of the maximum potential bite force. The percentage spare capacity was calculated in each of the eight subjects for each type of bite force transducer (Table 3; Fig. 6.6). The mean percentage spare capacities (± S.D.) for the two transducers were: the strain-gauge transducer covered with EVA sheets, 18% ± 13%; and the pressure transducer, 18% ± 21%. A paired t test showed no significant difference between the percentage spare capacities for the two different types of bite force transducer (P = 0.96).

Subject	**Percentage Spare Capacity (%)** **EVA Sheets**	**Percentage Spare Capacity (%)** **Pressure**
1	8.1	1.8
2	24.4	25.0
3	0	1.6
4	41.3	34.5
5	15.6	3.0
6	16.8	17.5
7	11.1	0
8	27.7	59.9
Mean	**18.1**	**17.9**
Standard Deviation (S.D.)	**12.8**	**21.2**

Table 3 Percentage spare capacities found in each subject (n = 8) for each type of bite force transducer. Mean percentage spare capacity and standard deviation for each transducer are also shown in the table.

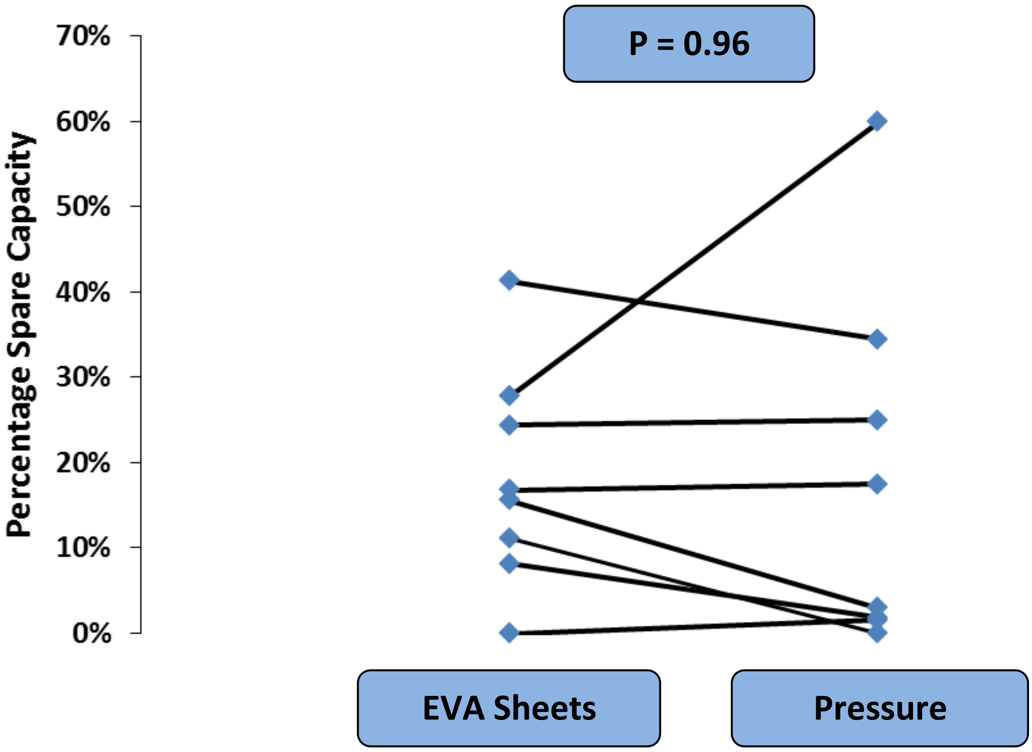

Figure 6.6: Scatter plot showing the percentage spare capacities found in each subject (n = 8) for each type of bite force transducer. The data for individual subjects are linked by the lines between symbols. The P value for a paired t test is also shown.

6.3.4 Relation between the MVBFs and the Percentage Spare Capacities

A Shapiro-Wilk test showed that both the MVBFs and the percentage spare capacities data were normally distributed. General trends towards negative correlations were found between the MVBFs (n = 8) and the percentage spare capacities with the use of both the strain-gauge transducer covered with EVA sheets (Pearson’s r = - 0.60; fig. 6.7a) and the pressure transducer (Pearson’s r = - 0.71; fig 6.7b). The trend towards a negative correlation was found to be statistically significant with the pressure transducer (P = 0.049), but not with the strain-gauge transducer covered with EVA sheets (P = 0.11).

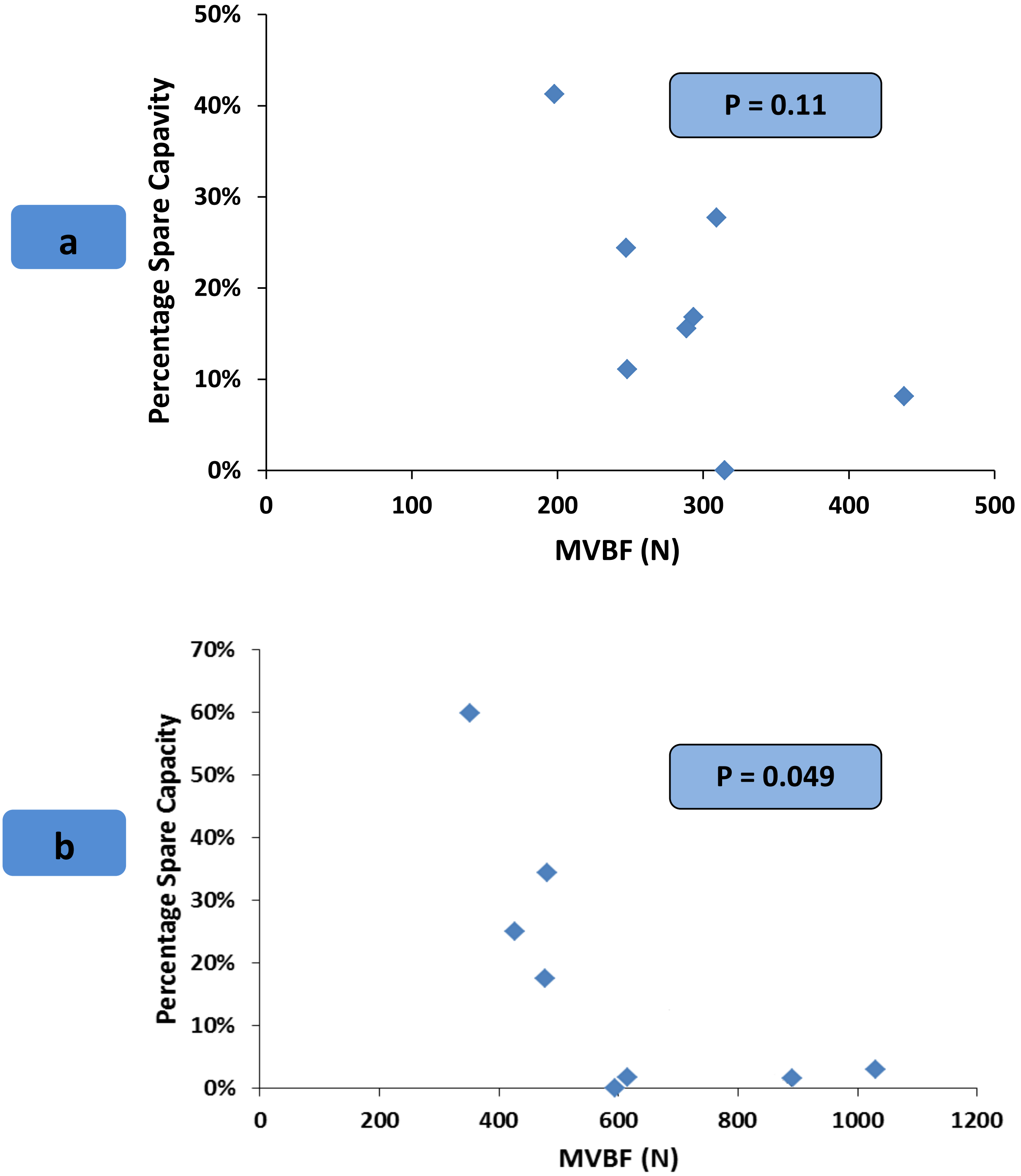

Figure 6.7: Scatter plots showing the negative correlations between the MVBFs and the percentage spare capacities found in the subjects (n = 8) with the use of: a) the strain-gauge transducer covered with EVA sheets (Pearson’s r = - 0.60); b) the pressure transducer (Pearson’s r = - 0.71). The P values for Pearson's correlation tests are also shown.

6.4 Discussion

6.4.1 General

As discussed earlier, the technique of twitch interpolation enables prediction of the maximum potential force of a muscle or a group of synergist muscles and the assessment of whether a maximum voluntary force output of this / these muscle(s) is a true maximum or not.

In a previous study by Lyons et al. (1996), it was assumed that for the technique of twitch interpolation, one masseter muscle or even parts of that muscle could be sufficiently representative of the whole jaw closing system. These workers provided partial support for their assumption with the fact that the values of the maximum potential bite forces and spare capacities (predicted by twitch interpolation in their study) using bilateral masseter stimulation, were similar to those obtained with stimulation of parts of just one masseter, and that they found a strong linear relation between twitch force and voluntary force at most of the stimulus intensities, particularly at higher ones. It was therefore decided to follow the same approach in this study and apply the electrical stimuli to only one masseter muscle.

6.4.2 Higher MVBFs on the Pressure Transducer

In agreement with the results of the previous study (Chapter 4), significantly higher MVBFs (n = 10) were recorded on the pressure transducer than on the strain-gauge transducer covered with EVA sheets. General trends towards higher

MVBFs on both transducers were found in this study than those on the same transducers in the previous study (Chapter 4). This might be attributed to two factors: first, only male subjects participated in this experiment (whereas three female subjects participated in the previous study) and males are believed to have higher MVBFs than females (see Chapters 1 and 3; also Hagberg, 1987; Bakke, 2006; Duygu Koc et al., 2010); second, the subjects may have gained confidence in biting on the transducers as they became more familiar with the transducers and the MVBF recording procedure (Mackenna and Türker, 1983; Chinni et al., 2014).

6.4.3 Higher Maximum Potential Bite Forces Predicted for the Pressure Transducer

The method of twitch interpolation predicted significantly higher maximum potential bite forces for the pressure transducer than for the strain-gauge transducer covered with EVA sheets.

Similar mean percentage spare capacities were found for the use of the pressure transducer and the use of the strain-gauge transducer covered with EVA sheets. This is surprising in that it eliminates discomfort, and a resulting unused spare force-generating capacity in the jaw closing muscles, from being a significant factor that would have contributed to the large differences in MVBFs recorded using the different transducers in the previous study (Chapter 4) and the present study. This also arguably brings the difference between the strain-gauge transducer and the pressure transducer in terms of three-dimensional capabilities, as discussed earlier and also in Chapter 4, to the top of the list of the possible explanations for the large differences in MVBFs recorded using the different transducers, especially after also eliminating the other possible factor (thickness of transducer) in the previous study (Chapter 5).

As suggested previously, the higher maximum potential bite force predicted for the pressure transducer may be linked to the three-dimensional nature of bite force which is composed of both horizontal and vertical components (Koolstra et al., 1988; van Eijden, 1991; Osborn and Mao, 1993; Mericske-Stern, 1998a). It is likely there would have been a difference between the strain-gauge transducer and the pressure transducer in terms of their capacities to detect three-dimensional forces. It might be argued that the maximum potential bite forces predicted for the strain-gauge transducer represent the maximum potential vertical bite forces, while the maximum potential bite forces predicted for the flexible, and seemingly multidirectional, pressure transducer possibly represent the maximum potential total bite forces (vector sum of the vertical and the horizontal components).

6.4.4 Low Percentage Spare Capacities in Subjects with High MVBFs

General trends towards negative correlations were found between the MVBFs (n = 8) and the percentage spare capacities with the use of both the strain-gauge transducer covered with EVA sheets (fig. 6.7a) and the pressure transducer (fig 6.7b). The trend towards a negative correlation was found to be statistically significant with the pressure transducer but not with the strain-gauge transducer covered with EVA sheets. The lack of significance with the strain-gauge transducer is possibly due to the small n value rather than a “true” lack of effect.

These findings are in agreement with previous findings by Lyons et al. (1996) who also found that in general, the subjects who had higher MVBFs were the ones who had lower spare capacities and vice versa.

6.4.5 The Possibility of Full Voluntary Activation of the Jaw Closing Muscles using either of the two transducers

All the subjects except one (n = 8; subject 3; Table 3) did not achieve their maximum potential bite forces on the strain-gauge transducer covered with EVA sheets. This is again in agreement with previous findings by Lyons et al (1996) who also found that the majority of the subjects in their study did not achieve their maximum potential bite forces on a strain-gauge transducer with acrylic indices. On the other hand, half of the subjects (n = 8; subjects 1, 3, 5 and 7; Table 3) recorded MVBFs on the pressure transducer that resembled their maximum potential bite forces (only 0 – 3% percentage spare capacity) as predicted by the technique of twitch interpolation. Taking also into account the scarcity of tendon organs and their associated tendon-organ inhibition in the jaw closing muscles (see Matthews, 1975), these findings support the theory that some individuals are able to achieve full voluntary activation of their jaw closing muscles (i.e. no spare capacity), providing that they have confidence in the bite force transducer [see visual analogue scale responses (Chapter 4)] and that there is no fear of any possible injury to their teeth.

6.4.6 Future Experiments

Having eliminated both the transducer thickness and the amount of discomfort and its associated unused spare force-generating capacity in the jaw closing muscles, there remained two broad categories of explanation for the differing MVBFs on the two different types of bite force transducer: a) a biological in that for some reason there is a higher activation of the jaw closing muscles when maximally biting on the pressure transducer (which can be investigated by means of EMG recordings from the muscles) and; b) a technical in that there is a difference in the way the two different transducers measure the generated force (e.g. whether the measured force is a partial or a total force).

To that end, it was planned in the next study to investigate again the MVBFs, with the use of both the strain-gauge transducer covered with EVA sheets and the pressure transducer, with simultaneous EMG recording from the jaw closing muscles.

Chapter 7: An Investigation of Maximum Voluntary Bite Forces and Electromyographic Activities of Jaw Closing Muscles When Biting on Two Different Force Transducers

7.1 Introduction

As revealed in Chapter 6, the amount of discomfort and its associated unused spare force-generating capacity in the jaw closing muscles was surprisingly not found to be a significant factor that would have contributed to the large differences in maximum voluntary bite forces (MVBFs) recorded using the different transducers in the previous studies (Chapters 4 and 6).

After also previously eliminating the transducer thickness factor (Chapter 5), there remained two broad categories of explanation for the large differences between the MVBFs recorded on the two different transducers (the strain-gauge transducer covered with EVA sheets and the pressure transducer): (a) that the differences relate to the way in which the transducers measure the generated forces [e.g. the difference between the strain-gauge transducer and the pressure transducer in terms of three-dimensional capabilities (see Chapter 4)]; (b) that for some reason, there is a greater activation of the jaw closing muscles when biting on the pressure transducer than when biting on the strain-gauge transducer. However, it should be noted that these categories of explanation are not mutually exclusive and evidence supporting each category cannot preclude the other. Indeed each of these two categories might, at least in part, explain the other e.g. if the pressure transducer encourages a more multidirectional bite, then that could partly explain the greater activation of the closing muscles on this transducer.

As discussed in Chapter 4, the strain-gauge transducer and the pressure transducer are different in terms of three dimensional capabilities in that the strain-gauge transducer is capable only of measuring the vertical component of bite force while the pressure transducer is possibly capable of measuring the total bite force or at least something closer to it. However, as also discussed in Chapter 4, it is hard to conclude that the difference between the strain-gauge transducer and the pressure transducer in terms of three-dimensional capabilities would fully explain the large differences in the MVBFs recorded using the different transducers, as there is not enough information on what proportion of the total bite force can be accounted for by each of the different components of bite force (the horizontal and the vertical components).

As mentioned in Chapter 1, a proportional relationship has been shown to exist between the EMG and the muscle force (bite force) in the jaw closing muscles (Pruim et al., 1978; Tortopidis et al., 1998a; Bakke, 2006). This relationship was found to be linear in some studies (e.g. Bakke et al., 1989; Ferrario et al., 2004b), but was found to be non-linear in others (e.g. Haraldson et al., 1985; Stiles and Pham, 1991). In general, there is an agreement that the EMG of the jaw closing muscles increases linearly with bite force at submaximal contraction levels but starts to deviate from linearity as bite force increases towards the MVBF (Tortopidis et al., 1998a).

Thus, it may be concluded that although an EMG cannot directly measure the muscle force output, it is still a good indicator to evaluate and compare different levels of muscular efforts (Perry and Bekey, 1981), i.e. higher EMG activities will be associated with higher muscular efforts and force outputs, and vice versa.

Accordingly, it could be assumed that the higher MVBFs recorded on the pressure transducer than on the strain-gauge transducer (as found in Chapters 4 and 6), would also be associated with higher EMG activities in the jaw closing muscles if the explanation is a biological one (extra activation of the muscle) as opposed to a technical one (e.g. directional sensitivity of the transducers). Thus, the aim of the present study was to investigate the force output of jaw closing muscles using EMG recordings from these muscles and the two bite force transducers used in the previous studies (Chapters 4 and 6), namely the strain-gauge transducer covered with EVA sheets and the pressure transducer. It was hypothesised that higher MVBFs would again be recorded on the pressure transducer, and that these might be associated with higher EMG activities in the jaw closing muscles.

7.2 Materials and Methods

The study took place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. It required around one hour for each subject in a single visit.

7.2.1 Subjects

Six male subjects were recruited. Their ages ranged from 31 to 36 years (mean = 33 years).

7.2.2 MVBF Measurements

Each subject was asked to bite as hard as possible three times on the two different types of bite force transducer while the transducer was placed between the anterior teeth from canine to canine. The highest bite force recorded was considered as the MVBF for each type of transducer. The two different types of bite force transducer were: (a) a strain-gauge transducer covered with EVA sheets; (b) a pressure transducer-based system.

The order in which the two different transducers were used was randomized to avoid time-related effects, and the subjects were required to rest for five minutes before changing to a different transducer. Before the use of each transducer, subjects were asked to undertake trial sub-maximal clenches in order to become familiar with the procedure. All the measurements were done while the subjects were seated upright in a dental chair. The two different transducers and the EVA sheets were disinfected before the experiments by immersing them for 2 minutes in a disinfectant solution (made with Actichlor™ Chlorine Releasing Disinfectant Tablets, Ecolab Limited, Leeds, UK).

7.2.3 The Bite Force Transducers

7.2.3a The strain-gauge transducer covered with EVA sheets

A detailed description of the strain-gauge transducer covered with EVA sheets was given in Chapter 3 (section 3.2.3b; page 66).

7.2.3b The pressure transducer

A detailed description of the pressure transducer was given in Chapter 2 (section 2.3.2; page 43). Borders were marked on the tubing so that all the subjects bit within these borders during the experiment. This minimised the possibility that any inter-subject variations in the bite force signal output would be related to changes in the location of the teeth along the tube.

7.2.4 Calibration

7.2.4a Calibration of the strain-gauge transducer

The strain-gauge transducer was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.1; page 45). On all the experimental occasions, a linear relationship was found between the applied loads and the response of the instrument. Linear regression was used to calculate the best-fit line and the resulting equation was then applied to convert voltage changes associated with biting to forces in Newtons (see Fig. 2.4).

7.2.4b Calibration of the pressure transducer

The pressure transducer was calibrated on each day of experimentation. A detailed description of the calibration method was given in Chapter 2 (section 2.4.2; page 47). On all the experimental occasions, a non-linear but consistent relationship was found between the applied loads and the response of the instrument. The best-fit curve generated by second order polynomial regression was calculated and the resulting equation was then applied to convert voltage changes associated with biting to forces in Newtons (see Fig. 2.10).

7.2.5 EMG Recording and Processing

EMGs were recorded bilaterally from the masseter and the anterior temporalis muscles. For this purpose, disposable self-adhesive surface electrodes (Product No. 720 00-S/25, Ambu® Neuroline 720, Ambu Ltd, Cambridgeshire, UK), dimensions (45 × 22 mm), skin contact size (30 × 22 mm), were used. Two electrodes were placed (i.e. in a bipolar configuration) on the skin overlying the bellies of each of the four muscles (i.e. two on each side). For each muscle, the centres of the two electrodes were 24 mm apart. The location of the electrodes was determined by palpation while the subjects were biting two or three times in the intercuspal position. An additional electrode was placed on the left ear lobe and served as the common (reference) electrode (Fig. 7.1). The skin was prepared before applying the electrodes, by thorough cleaning with alcohol wipes in order to increase the adherence of the electrodes and reduce the impedance of the skin (and thus of the recording circuit).

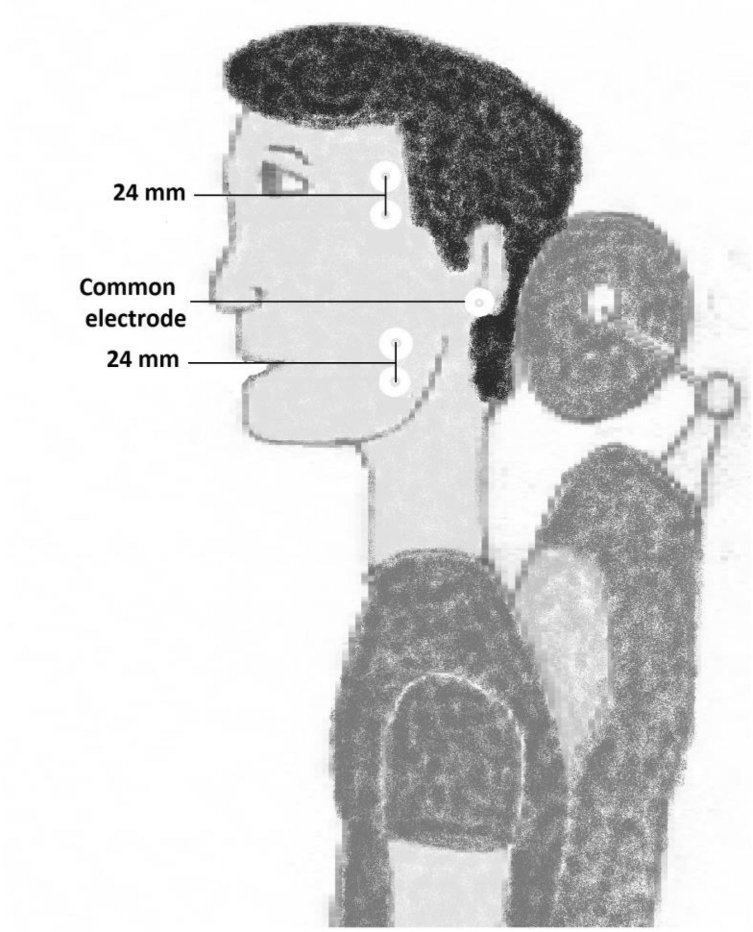

Figure 7.1: Electrodes set-up for EMG recording.

The EMG signals were amplified using first a differential input pre-amplifier (NL 834, Digitimer, Letchworth Garden City, UK) and then an isolator amplifier (NL 820, Digitimer, Letchworth Garden City, UK). The signals were then band pass filtered (20 Hz – 1 KHz) using Neurolog filters (NL 125, Digitimer, Letchworth Garden City, UK). This was done in order to eliminate frequencies which were unlikely to originate in the muscles under the electrodes.

The EMG signals were then sent to a computer following analogue-to-digital conversion using a 1401 Plus data acquisition interface (1401 Plus, Cambridge Electronic Design Limited, Cambridge, UK). Subsequent EMG data processing and analyses were performed using the Signal software (Signal 2.16, Cambridge Electronic Design Limited, Cambridge, UK) and involved full wave rectification (FWR), averaging, and digital filtering (smoothing). The digital filtering eliminated frequencies outside the range DC – 5 Hz. This low pass 5 Hz cut-off point is within the range used in some previous EMG / bite force studies (e.g. Slagter et al., 1993; van der Glas et al., 2000; van der Bilt et al., 2008). The EMG signals were always sampled at a rate of 2000 Hz and recorded for 1.5 (noise recording) or 10 (bite force recording) second periods.

7.2.6 Experimental Protocols

As mentioned earlier, the study required around one hour for each subject in a single visit. It was performed in the following stages:

a- EMG recording was set-up as described in the previous section (7.2.5).

b- A "Noise" recording was performed for three 1.5 second periods. The subjects were instructed to relax and not to speak or move the jaw during the noise recording.

c- Bite force was recorded three times on each of the two transducers as described in the previous section (7.2.2).

d- With each bite force recording, the EMG recording was started a few seconds before the subject bit, and continued for a few seconds after the subject completed their bite. The total EMG recording period was 10 seconds (Fig. 7.2).

After determining the MVBF for each transducer (the highest of the three bite force recordings), the corresponding EMG signals were rectified (FWR) and digitally filtered (Fig. 7.2). The noise signals were rectified (FWR), averaged, and digitally filtered. The EMG signals were then exported into Excel software for further analysis (see next section).

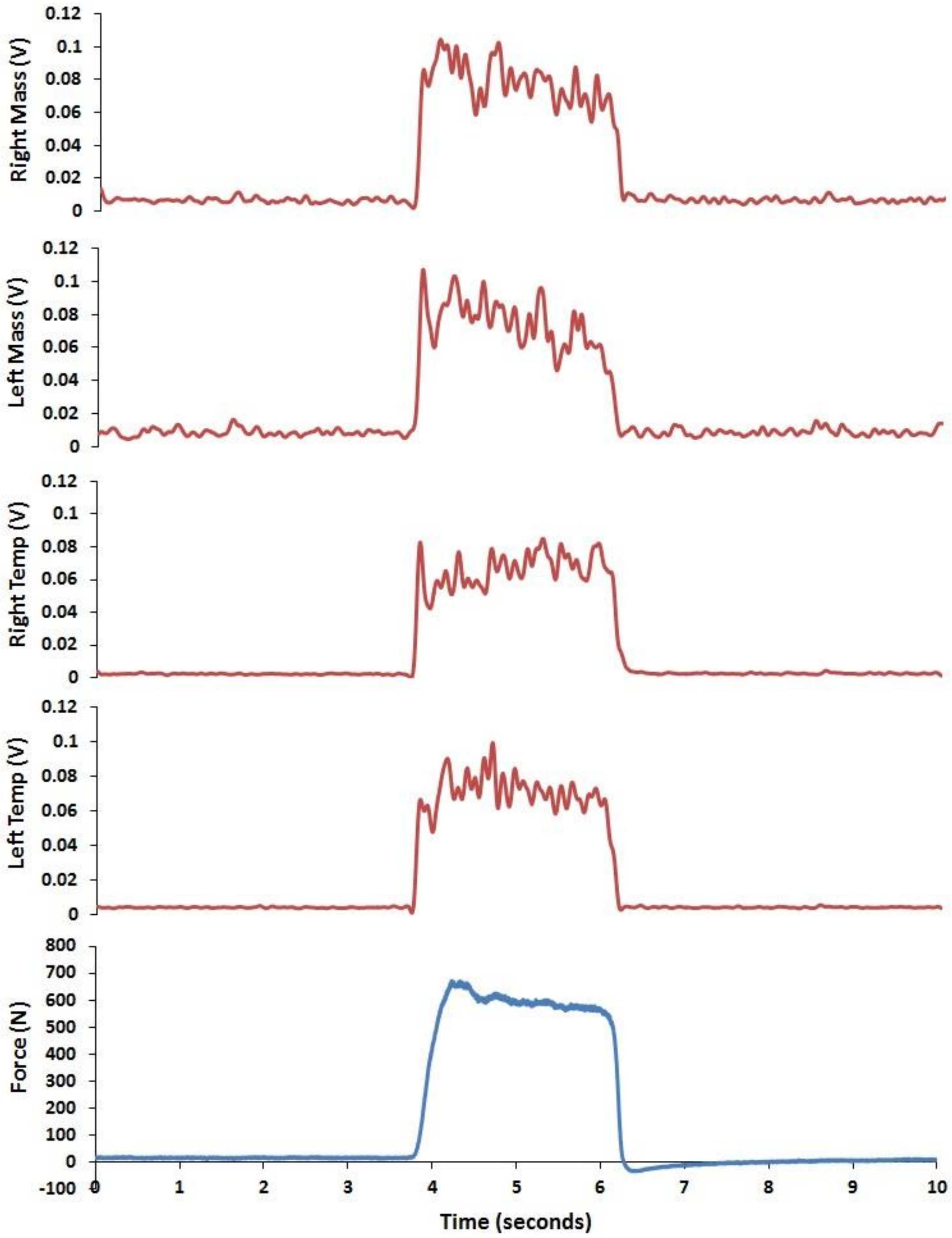

Figure 7.2: Example of MVBF / EMG recordings after the processing (FWR and digital filtering) of the raw EMG signals and before noise subtraction. Note that there are four EMG recordings from: the right masseter muscle (R Mass), the left masseter muscle (L Mass), the right anterior temporalis muscle (R Temp), and the left anterior temporalis muscle (L Temp). The MVBF was recorded on the pressure transducer.

7.2.7 Data and Statistical Analyses

Microsoft® Excel® 2010 software was used to calculate the total EMG values associated with the MVBFs on the two transducers in each subject. The total EMG value represented the sum of the peak EMG values recorded from the four muscles (right masseter, left masseter, right anterior temporalis, and left anterior temporalis) after subtraction of the mean "noise" value for each muscle.

The “percentage increase in MVBF” was the difference (in Newtons) between the MVBF recorded on the pressure transducer and the MVBF recorded on the strain-gauge transducer covered with EVA sheets, expressed as a percentage of the MVBF recorded on the strain-gauge transducer covered with EVA sheets. The “percentage difference in EMG” was the difference (in Voltage) between the EMG associated with MVBF on the pressure transducer and the EMG associated with MVBF on the strain-gauge transducer covered with EVA sheets, expressed as a percentage of the EMG associated with MVBF on the strain-gauge transducer covered with EVA sheets. A positive sign (+) was used to indicate a higher EMG associated with the pressure transducer. A negative sign (-) was used to indicate a higher EMG associated with the strain-gauge transducer.

IBM® SPSS® 21 statistical analysis software was used in this study. Paired t tests were applied to examine whether there were any significant differences between: (a) the MVBFs recorded on the two different types of bite force transducer; (b) the total EMG values associated with MVBFs on the two different types of bite force transducer; (c) the percentage differences in EMGs of the bilateral masseter muscles and the percentage differences in EMGs of the bilateral temporalis muscles. One sample t tests were applied to examine whether each of the following were significantly different from zero: (a) the percentage increases in MVBFs; (b) the percentage differences in total EMGs. Spearman’s rank correlation test was used to assess the relationship between the percentage increases in MVBFs and the percentage differences in total EMGs. A P value < 0.05 was considered statistically significant.

7.3 Results

7.3.1 MVBFs

All six subjects recorded higher MVBFs on the pressure transducer than on the strain-gauge transducer covered with EVA sheets (Fig. 7.3). The mean MVBFs (± S.D.) on the two transducers were: the strain-gauge transducer covered with EVA sheets, 254 ± 83 N; and the pressure transducer, 577 ± 259 N. A paired t test showed this difference between the MVBF results for the two different types of bite force transducer to be significant (P = 0.017).

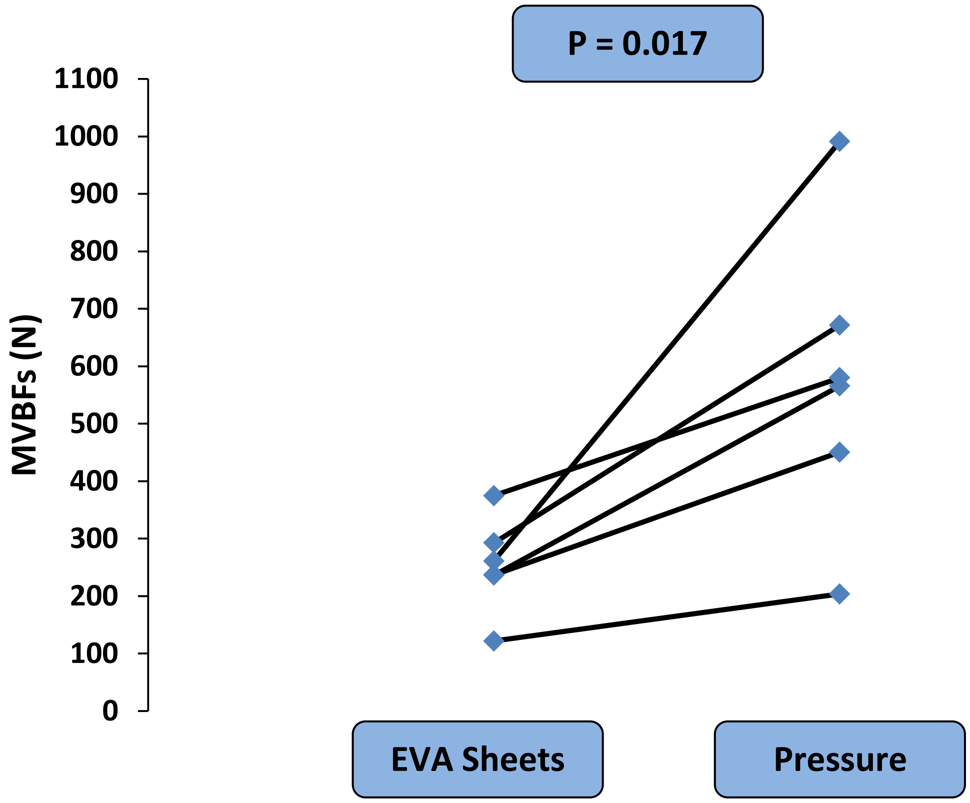

Figure 7.3: Scatter plot showing the MVBFs (N) obtained with the two different types of bite force transducer by each subject. The data for individual subjects are linked by the lines between symbols. P value for a paired t test is also shown.

As defined earlier, the “percentage increase in MVBF” was the difference (in Newtons) between the MVBF recorded on the pressure transducer and the MVBF recorded on the strain-gauge transducer covered with EVA sheets, expressed as a percentage of the MVBF recorded on the strain-gauge transducer covered with EVA sheets. The mean percentage increase in MVBF (± S.D.) was 127% ± 82%. A one sample t test showed that the percentage increases in MVBFs were significantly different from zero (P = 0.013).

7.3.2 EMG Activities of the Jaw Closing Muscles

In all six subjects, higher total EMG values were found to be associated with the MVBFs on the pressure transducer than with the MVBFs on the strain-gauge transducer covered with EVA sheets (Fig. 7.4). The mean total EMG values (± S.D.) associated with the two transducers were: the strain-gauge transducer covered with EVA sheets, 0.19 ± 0.10 V; and the pressure transducer, 0.24 ± 0.12 V. A paired t test showed this difference between the total EMG results for the two different types of bite force transducer to be significant (P = 0.014).

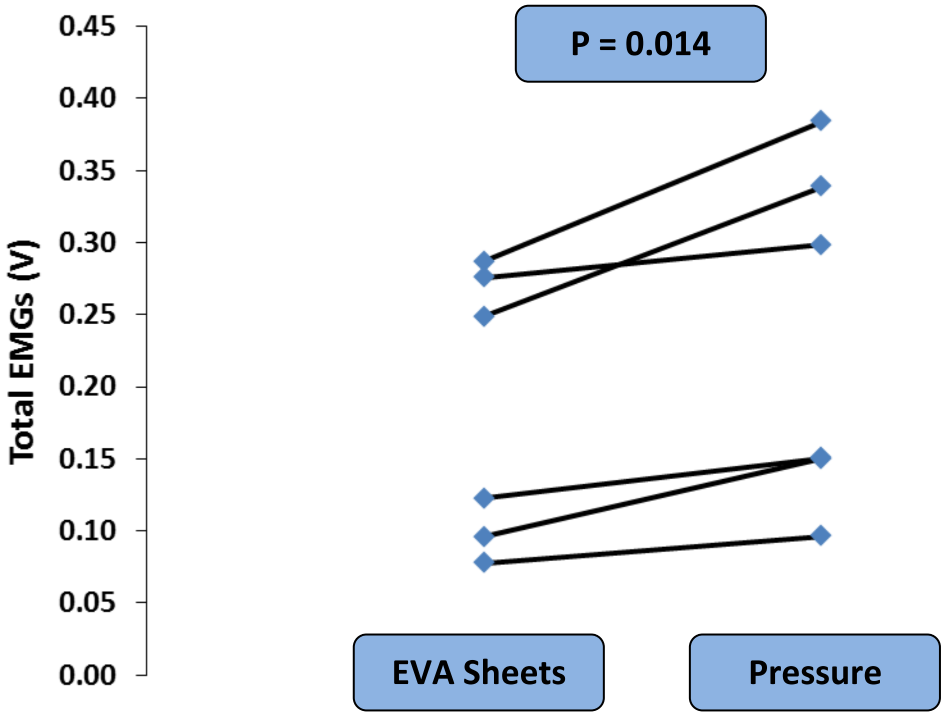

Figure 7.4: Scatter plot showing the total EMGs (V) associated with the MVBFs on the two different types of bite force transducer in each subject. The data for individual subjects are linked by the lines between symbols. The P value for paired t test is also shown.

As defined earlier, the “percentage difference in EMG” was the difference (in Voltage) between the EMG associated with MVBF on the pressure transducer and the EMG associated with MVBF on the strain-gauge transducer covered with EVA sheets, expressed as a percentage of the EMG associated with MVBF on the strain-gauge transducer covered with EVA sheets. The mean percentage difference in total EMGs (± S.D.) was +30% ± 16%. A one sample t test showed that the percentage differences in total EMGs were significantly different from zero ($P = 0.0059$).

In five subjects, higher EMGs in both the bilateral masseter muscles and the bilateral temporalis muscles were found to be associated with the MVBFs on the pressure transducer than with the MVBFs on the strain-gauge transducer covered with EVA sheets. In the other subject, higher EMGs in the bilateral masseter muscles were also found to be associated with the MVBFs on the pressure transducer, but the EMGs in the temporalis muscles were lower for the MVBFs on the pressure transducer (Fig. 7.5).

The mean percentage difference in EMGs (between the pressure transducer and the strain-gauge transducer covered with EVA sheets; see section 7.2.7 for definition) of the bilateral masseter muscles (± S.D.) was +34% ± 18%. The mean percentage difference in EMGs (between the pressure transducer and the strain-gauge transducer covered with EVA sheets; see section 7.2.7 for definition) of the bilateral temporalis muscles (± S.D.) was +25% ± 16%. A paired t test showed no significant difference between the percentage differences in EMGs of the bilateral masseter muscles and the percentage differences in EMGs of the bilateral temporalis (P = 0.20; Fig. 7.5).

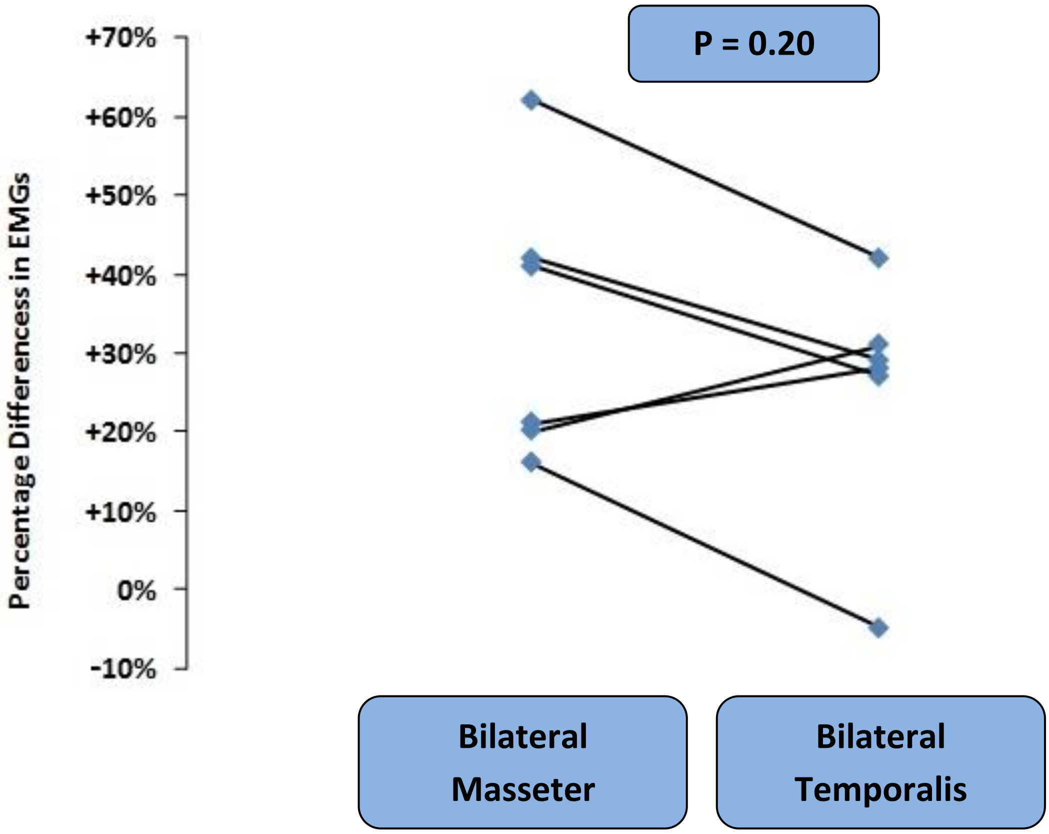

Figure 7.5: Scatter plot showing the percentage differences in EMGs of the bilateral masseter muscles and the bilateral temporalis muscles in the six subjects. The data for individual subjects are linked by the lines between symbols. P value for paired t test is also shown.

7.3.3 The Relationship between the “Percentage Differences in Total EMGs” and the “Percentage Increases in MVBFs”

A high and significant (Spearman’s Rho (rs) = 0.94; P = 0.0048) positive correlation was found between the percentage differences in total EMGs and the percentage increases in MVBFs (Fig. 7.6).

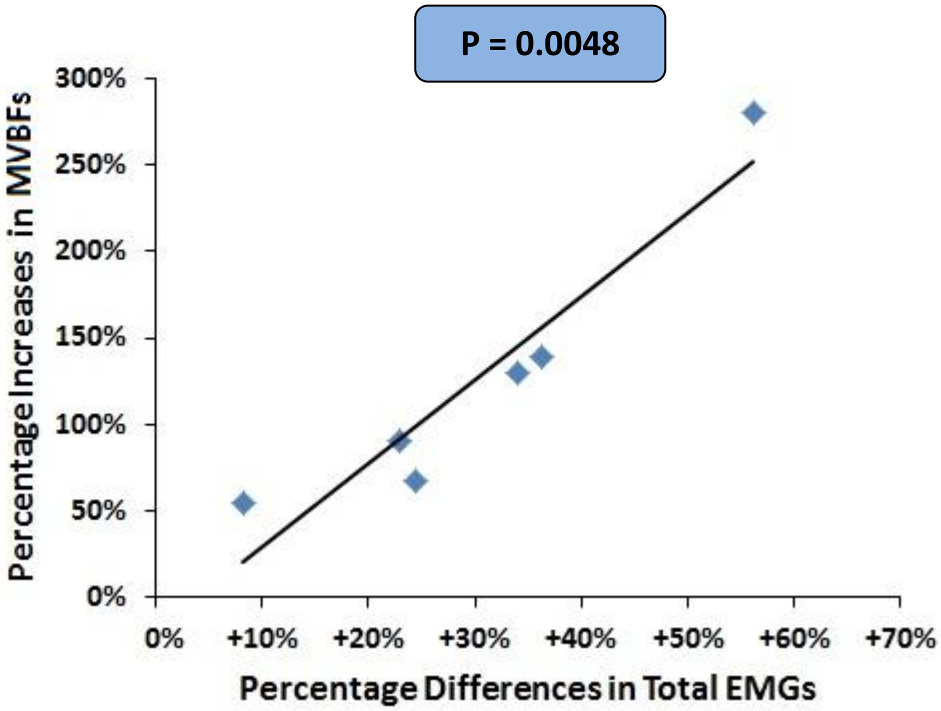

Figure 7.6: Scatter plot showing the relationship between the percentage differences in total EMGs and the percentage increases in MVBFs. P value for Spearman’s rank correlation is also shown.

7.4 Discussion

7.4.1 General

As discussed earlier and also in Chapter 1, EMG is a physiological measure which is known to be proportionally related to muscle force production (see Inman et al., 1952; Bigland-Ritchie, 1981; Basmajian and DeLuca, 1985). The relationship between muscle force production and EMG might be linear or non-linear, and this depends on many factors such as muscle fibre composition [slow twitch (type I) or fast twitch (type II); uniform or mixed], muscle fibre distribution (even or uneven), and muscle force generating mechanisms (motor unit recruitment / firing rate; Woods and Bigland Ritchie, 1983). These factors might vary from one muscle to another in the human body (Lawrence and De Luca, 1983). Thus, linear EMG / force relationships were found for some muscles e.g. quadriceps (e.g. Stokes and Dalton, 1990) and the first dorsal interosseous muscle (e.g. Woods and Bigland Ritchie, 1983), whereas non-linear EMG / force relationships were found for others e.g. extensor carpi radialis (e.g. Metral and Cassar, 1981) and biceps brachii (e.g. Lawrence and De Luca, 1983). Moreover, linear and non-linear EMG / force relationships were reported by different groups of workers in the same investigated muscles e.g. the biceps brachii muscle (e.g. Lawrence and De Luca, 1983; Dalton and Stokes, 1991). This has been attributed mainly to some variations in electrode configuration and EMG signal acquisition and processing (Disselhorst-Klug et al., 2009).

As also discussed earlier, a proportional relationship, as for the other muscles in the human body, has been shown to exist between bite force and the EMG activities of jaw closing muscles (Pruim et al., 1978; Tortopidis et al., 1998a; Bakke, 2006). However, the changes in the EMG activities of the jaw closing muscle cannot accurately reflect the changes in the bite force as the relationship between the bite force and the EMG activities was found, again as for the other muscles in some studies, to be non-linear especially at the higher force levels (see Perry and Bekey, 1981; Haraldson et al., 1985; Stiles and Pham, 1991; Tortopidis et al., 1998a). Thus, the EMG activities of the jaw closing muscles can be used to indicate (but not to directly measure) the varying levels of bite force.

As in the studies described in the earlier chapters of this thesis (Chapters 4 and 6), significantly higher MVBFs were recorded on the pressure transducer than on the strain-gauge transducer covered with EVA sheets.

7.4.2 Higher EMGs Associated with MVBFs on the Pressure Transducer

Significantly higher total EMG activities in the jaw closing muscles were found to be associated with the MVBFs recorded on the pressure transducer than with the MVBFs recorded on the strain-gauge transducer covered with EVA sheets. These findings suggest that there is a higher activation of these jaw closing muscles while maximally biting on the pressure transducer. These findings therefore suggest that the explanation for the differences between the MVBFs recorded on the two different transducers were, to a significant extent, of biological origin (extra activation of the muscles while maximal biting on the pressure transducer). However, as discussed earlier, this and the alternative explanation that the difference is due to technical considerations such as the directional sensitivities of the transducers are not mutually exclusive and one need not preclude the other.

The strong and significant correlation between the percentage increases in MVBFs and the percentage differences in total EMGs (see section 7.2.7 for definitions) confirms the proportional relationship between the bite force and the EMG activities of the jaw closing muscles as reported in many previous studies (e.g. Pruim et al., 1978; Bakke et al., 1989; Stiles and Pham, 1991; Ferrario et al., 2004b).

7.4.3 Relative Contributions of the Masseter and the Temporalis Muscles while Biting on the Two Different Force Transducers

No significant difference was found between the percentage differences in EMGs of the bilateral masseter muscles and the percentage differences in EMGs of the bilateral anterior temporalis muscles when biting on the different transducers. This finding suggests that the relative contributions of the two muscles (masseter and anterior temporalis) in bite force production were not significantly different with the use of the two transducers although higher activities of the two muscles were found with the use of the pressure transducer.

As discussed in Chapter 1, Paphangkorakit and Osborn (1997) found that increasing thickness of a bite force transducer was associated with an increase in MVBF, an increase in the ratio of EMG activity between the anterior temporalis and the masseter (temporalis/masseter), and a change in the bite direction from anteriorly directed to posteriorly directed. In the present study, as mentioned above, there was no significant change in the relative contributions of the two muscles (masseter and anterior temporalis) in bite force production with the use of the two transducers. Thus, it may be argued that the large differences in the MVBFs recorded using the different transducers (see Chapters 4, 6, and 7) were not necessarily related to a change in the transducer thickness (as also confirmed in Chapter 5) or to a change in the bite direction.

7.4.4 Conclusions

It may be concluded from the results of this study that:

a- The higher MVBFs recorded on the pressure transducer than on the strain-gauge transducer (Chapters 4, 6, and 7) were associated with higher activation of the bilateral masseter and anterior temporalis muscles.

b- The differences in MVBFs recorded using the different transducers were, to a significant extent, likely to be of biological origin (extra activation of the jaw closing muscles) although an additional possible technical origin (e.g. related to directional sensitivities of the transducers) cannot be ruled out.

c- The difference in thickness between the two transducers did not lead to a significant change in the relative contributions of the masseter and anterior temporalis muscles in bite force production.

Chapter 8: Discussion

8.1 General

It has been shown previously that bite force is composed of vertical, anterior-posterior and medial-lateral horizontal components (Koolstra et al., 1988; van Eijden, 1991; Osborn and Mao, 1993; Mericske-Stern, 1998a). Thus, in principle, the total bite force should be the vector sum of all these components (Koolstra et al., 1988; van Eijden, 1991; Osborn and Mao, 1993; Mericske-Stern, 1998a). However, it is clear that in most bite force studies, only the vertical component has been measured (e.g. Linderholm and Wennström, 1970; Molin, 1972; Ringqvist, 1973; Helkimo et al., 1975; Pruim et al., 1978; Tortopidis et al., 1998b; van der Bilt et al., 2008). This could be attributed largely to two reasons: (a) the lack of enough information and understanding about the three dimensional nature of bite force; and / or (b) the fact that the vertical component is the main component of bite force and therefore most of the previously-used bite force measuring transducers e.g. the strain-gauge transducer, were knowledgeably designed to be uni-directional and to assess and investigate only this component (Molin, 1972; Fields et al., 1986).

The development of bite force measuring devices with a multidirectional capacity, (e.g. van Eijden, 1991; Paphangkorakit and Osborn, 1997; Mericske-Stern, 1998b), has indeed expanded our knowledge about the three dimensional nature of bite force and how its different components contribute to the total bite force. This consideration urges us to be more careful when comparing the maximum voluntary bite forces (MVBFs) reported in different bite force studies where different devices have been used e.g. the unidirectional strain-gauge transducer and the pressure transducer.

8.2 Possible Explanations for the Differing MVBFs on Different Transducers

In these studies, it was found that the highest MVBF values were recorded on the pressure transducer, followed by the strain-gauge transducer covered with EVA sheets and last of all the strain-gauge transducer with silicone indices or with more commonly-used acrylic indices.

There are several possible explanations for this finding. Before discussing these, it should be pointed out that these explanations can be categorised into those of biological origin where there is a greater activation of the jaw closing muscles when maximally biting on one type of transducer than another, and those of technical origin where the differences relate to the way in which the transducers measure the generated forces, e.g. if the measured force is a partial force or a total force. However, these two categories of explanation are not mutually exclusive. The principal explanations considered in this thesis were:

a- Transducer thickness: a number of studies have reported an optimum range of incisal separation (15 – 20 mm) at which the highest bite forces can be produced (Manns et al., 1979; Mackenna and Türker, 1983). Thus, it was argued that the pressure transducer at 19 mm thick might have provided the optimal amount of incisal separation followed by the strain-gauge transducer covered with EVA sheets at 12 mm thick and last of all, the strain-gauge transducers with only indices, at approximately 8 mm thick. However, varying the transducer thickness between 12 and 18 mm did not lead to significant changes in the MVBFs in the present studies. It is therefore unlikely that this would explain the large differences in MVBFs recorded across the three transducers.

b- Nature of the biting surfaces: another possible explanation for the higher MVBFs on the pressure transducer and the strain-gauge transducer covered with EVA sheets was that the soft and the flexible nature of the tube of the pressure transducer and, to a lesser degree, of the EVA sheets, helped to improve comfort and minimise the fear of damage to the teeth. Also, another explanation for the higher MVBFs on the pressure transducer and the strain-gauge transducer covered with EVA sheets could have been the possible initiation of a significant positive reflex modulation of jaw closing muscle activity or biting forces and / or the delay or prevention of a significant negative reflex modulation of jaw closing muscle activities or biting forces (van der Glas et al., 1985; Paphangkorakit and Osborn, 1998; Serra and Manns, 2013). However, as discussed earlier, this explanation is controversial as some studies have disputed whether there is a significant role for periodontal sensory receptors, and their associated inhibitory or positive reflexes, in the control of bite force (see Hellsing, 1980; Orchardson and Cadden, 1998; Kleinfelder and Ludwig, 2002; Morita et al., 2003). Again, as mentioned above, the soft and the flexible nature of the tube of the pressure transducer might have contributed to improved comfort (or reduced discomfort), reduced fear, and increased confidence (see VAS responses, Chapter 4) when biting on this transducer. To that end, it was suggested that the highest MVBFs on the pressure transducer would possibly be the closest to the true maximum bite forces of which the jaw closing muscles are capable and that lowest spare capacities (see Chapter 6 for definition; also Lyons et al., 1996) would be associated with the MVBFs on the pressure transducer. This hypothesis was tested in the study described in Chapter 6 where the technique of twitch interpolation was employed. It was found that the predicted spare capacities when expressed as percentages, were similar for the pressure transducer and the strain-gauge transducer covered with EVA sheets; this eliminated the explanation that discomfort or some other factor (e.g. fear or lack of confidence) would have left larger spare capacities when biting on the relatively hard strain-gauge transducer covered with EVA sheets than when biting on the pressure transducer.

c- Area of tooth contact: there is a possibility that some flattening of the tube of the pressure transducer would occur as the bite force is increased, which would result in involvement of a larger number of teeth and area of tooth contact with the tube. This would give an advantage to the pressure transducer to allow for higher MVBFs to be recorded than on the strain-gauge transducer (see Bates et al., 1975; Tortopidis et al., 1998b; Bakke, 2006; Duygu Koc et al., 2010).

d- Two- versus three-dimensional sensitivity: as already explained, bite force is composed of both horizontal and vertical components (van Eijden et al., 1988; van Eijden, 1991; Osborn and Mao, 1993). The strain-gauge transducer is uni-directional while it seems likely that the pressure transducer is multi-directional. It follows that the strain-gauge transducer would be capable of measuring only a single component of bite force (approximately vertical; van Eijden et al., 1988; van Eijden, 1991), whereas the pressure transducer may be capable of measuring the total bite force (or something closer to it). Thus, it may be argued that the higher MVBFs on the pressure transducer are total bite forces, whereas the lower MVBFs on the strain-gauge transducer are only for the vertical vectors of bite forces. However, as discussed in Chapters 4 and 7, unless enough information on what proportion of the total bite force can be accounted for by each of its different components becomes available, it is hard to conclude that the large discrepancies in MVBFs recorded on the different transducers (see Chapters 4, 6, and 7) were primarily because they are different in terms of three dimensional capabilities.

As pointed out earlier, the above-mentioned explanations do not exclude each other; indeed they might complement each other, e.g. if the pressure transducer allows the subject to have a range of bite directions rather than being restricted in one direction as the case with the strain-gauge transducer, then that might also enhance activation of the closing muscles on this transducer – perhaps of motor units which contribute to force generation in directions other than vertical. In accordance with this hypothesis and as described in Chapter 7, significantly higher EMGs from two pairs of jaw closing muscles were found to be associated with the MVBFs on the pressure transducer than with the MVBFs on the strain-gauge transducer covered with EVA sheets. These findings suggest that there was a higher activation of the jaw closing muscles while maximally biting on the pressure transducer. Again, it might be argued that the higher activation of the closing muscles on the pressure transducer was at least partly because it allowed for a multi-directional bite i.e. no restriction in one axis.

8.3 Conclusions at the End of the Present Studies

Within the limitations of the studies described in this thesis, it may be concluded that the newly-developed pressure transducer was a more capable bite force transducer than the commonly-used strain-gauge transducer (even when the latter was covered with EVA sheets) in the following respects:

a- Higher MVBFs were obtained with the pressure transducer and these were associated with significantly higher EMG activities from jaw closing muscles.

b- Subjects reported greater confidence in the pressure transducer indicating less discomfort or fear when biting on this transducer.

c- The pressure transducer possibly seemed to have some multi-directional capabilities which might have allowed for total bite forces, or at least larger parts of them, to be recorded than on the uni-directional strain-gauge transducer.

In view of these probable advantages of the pressure transducer over the strain-gauge transducer, one might consider that in future, pressure transducers might be used as a better alternative to commonly-used strain-gauge transducers for bite force studies. This might apply to such studies in general, and specifically to studies which investigate bite force in subjects who might experience a greater degree of discomfort when maximally biting on the hard surfaces of the strain-gauge transducer, thus making an accurate measurement of MVBF a difficult task (e.g. those with impaired chewing efficiency, temporomandibular disorders (TMD), orafacial pain, or who wear dentures).

The main drawback of the pressure transducer is that its calibration procedure might become considerably time consuming if the most ideal methodology for its calibration is to be followed. As discussed in Chapters 2 and 4, the variations in tooth morphologies, arch shapes and sizes, and occlusion forms between different subjects could result in differences in the area of contact between the teeth and the tube. However as explained in Chapter 2, with the pressure transducer used in the present studies, the differences in the areas of contact between the teeth and the tube when used with different sets of casts (which were of average shape and size and without significant malocclusions) were minimal and had little effect on the output. It was therefore considered acceptable to use a control set of casts for the calibration on each day of experimentation in subsequent studies, as our studies were performed only in subjects without significant malocclusions or missing anterior teeth.

However, as the effect of the different tooth morphologies, arch shapes and sizes, and occlusion forms might vary with different resiliencies of tubing of different pressure transducers (being greater if a softer tubing is used as found in some initial observations in our laboratory - see Chapter 2), it is recommended that this effect should always be taken into consideration, especially in studies to be performed in subjects with tooth anomalies and / or significant malocclusions. In these cases, it might be necessary to calibrate the pressure transducer individually for each subject using the subject's own set of casts. Unfortunately, this would be even more time-consuming and even impractical in studies where a large number of subjects have to be recruited.

8.4 Suggested Future Studies

As it was suggested that at least part of the discrepancy in MVBFs between the two different types of transducer could be attributed to differences in the transducers' three-dimensional capabilities, it is important now to gain more detail about the three-dimensional nature of bite force, and in particular, about what proportion of the total bite force can be attributed to each of its different vectors. It would be worthwhile to extend previous work in the late 1980s and 1990s (van Eijden et al., 1988; van Eijden, 1991; Paphangkorakit and Osborn, 1997) which started to address the three-dimensional nature of bite force, given that since that time, few if any investigators have revisited this area of research. It would also be of interest to investigate anew, the relative contributions of the different components of bite force to the total bite force under different measuring situations e.g. different amounts of jaw separations as determined by different thicknesses of bite force transducer.

A number of studies have reported during isometric biting, there can be a co-activation of jaw opening muscles along with the jaw closers (Miles and Wilkinson, 1982; Miles and Madigan, 1983; van Willigen et al., 1993). They found that this co-activation of antagonist muscles was greater when the subjects had a knowledge that a change of resistance would happen between the teeth (Miles and Madigan, 1983). In everyday life such a change in resistance might involve breaking through hard but brittle food. This has been explained as a feed-forward strategy in order to protect, and minimise any possible injury to, the teeth.

If one takes account of this possible co-activation of opening and closing muscles, one may argue that another possible explanation for the lower MVBFs obtained on the strain-gauge transducer could be that there was a greater activation of the jaw opening muscles (notably, the anterior digastric, mylohyoid and geniohyoid), than when biting on the flexible pressure transducer with which subjects were more confident – indeed it might be that there was no co-activation of openers in the latter situation. It would therefore be of interest to investigate a possible role of these muscles in the differences in MVBFs on the two different types of bite force transducer. It would be worthwhile repeating the experiment described in Chapter 7, but with additional EMG recordings from the jaw opening muscles. This might not only help to partly explain the differing MVBFs on the different transducers, but also to further understand the role of these muscles in the control of bite force; an area of research where further investigation is required.

References

ABU ALHAIJA, E. S. J.,AL ZO'UBI, I. A.,AL ROUSAN, M. E. & HAMMAD, M. M. 2010. Maximum occlusal bite forces in Jordanian individuals with different dentofacial vertical skeletal patterns. *European Journal of Orthodontics,* 32**,** 71-77.

ALKAN, A.,KESKINER, I.,ARICI, S. & SATO, S. 2006. The effect of periodontitis on biting abilities. *Journal of Periodontology,* 77**,** 1442-1445.

ANDO, K.,FUWA, Y.,KUROSAWA, M.,KONDO, T. & GOTO, S. 2009. Bite force measurement system using pressure-sensitive sheet and silicone impression material. *Dental Materials Journal,* 28**,** 212-218.

BABU, R. & NAYAR, S. 2007. Occlusion indicators: A review. *Journal of Indian Prosthodontist Society,* 7**,** 170-174.

BAKKE, M. 2006. Bite Force and Occlusion. *Seminars in Orthodontics,* 12**,** 120-126.

BAKKE, M.,HOLM, B.,JENSEN, B. L.,MICHLER, L. & MÖLLER, E. 1990. Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. *Scandinavian Journal of Dental Research,* 98**,** 149-158.

BAKKE, M.,MICHLER, L.,HAN, K. & MÖLLER, E. 1989. Clinical significance of isometric bite force versus electrical activity in temporal and masseter muscles. *Scandinavian Journal of Dental Research,* 97**,** 539-551.

BAKKE, M.,TUXEN, A.,VILMANN, P.,JENSEN, B. R.,VILMANN, A. & TOFT, M. 1992. Ultrasound image of human masseter muscle related to bite force, electromyography, facial morphology, and occlusal factors. *Scandinavian Journal of Dental Research,* 100**,** 164-171.

BANUS, M. G. & ZETLIN, A. M. 1938. The relation of isometric tension to length in skeletal muscle. *Journal of Cellular and Comparative Physiology,* 12**,** 403-420.

BASMAJIAN & DELUCA 1985. *Muscles alive - their function revealed by electromyography,* Baltimore, USA, Williams and Wilkins.

BATES, J. F.,STAFFORD, G. D. & HARRISON, A. 1975. Masticatory function: a review of the literature. (II) Speed of movement of the mandible, rate of chewing and forces developed in chewing. *Journal of Oral Rehabilitation,* 2**,** 349-361.

BAUMGARTNER, R. N.,KOEHLER, K. M.,GALLAGHER, D.,ROMERO, L.,HEYMSFIELD, S. B.,ROSS, R. R.,GARRY, P. J. & LINDEMAN, R. D. 1998. Epidemiology of sarcopenia among the elderly in New Mexico. *American Journal of Epidemiology,* 147**,** 755-763.

BAUMGARTNER, R. N.,WATERS, D. L.,GALLAGHER, D.,MORLEY, J. E. & GARRY, P. J. 1999. Predictors of skeletal muscle mass in elderly men and women. *Mechanisms of Ageing and Development,* 107**,** 123-136.

BIGLAND-RITCHIE, B. 1981. EMG/force relations and fatigue of human voluntary contractions. *Exercise and Sport Sciences Reviews,* 9**,** 75-117.

BOLTON CH, F.,PARKES, A.,THOMPSON, T. R.,CLARK, M. R. & STERNE CH, J. 1989. Recording sound from human skeletal muscle: Technical and physiological aspects. *Muscle and Nerve,* 12**,** 126-134.

BONAKDARCHIAN, M.,ASKARI, N. & ASKARI, M. 2009. Effect of face form on maximal molar bite force with natural dentition. *Archives of Oral Biology,* 54**,** 201-204.

BOUSDRAS, V. A.,CUNNINGHAM, J. L.,FERGUSON-PELL, M.,BAMBER, M. A.,SINDET-PEDERSEN, S.,BLUNN, G. & GOODSHIP, A. E. 2006. A novel approach to bite force measurements in a porcine model in vivo. *International Journal of Oral and Maxillofacial Surgery,* 35**,** 663-667.

BRAUN, S.,BANTLEON, H. P.,HNAT, W. P.,FREUDENTHALER, J. W.,MARCOTTE, M. R. & JOHNSON, B. E. 1995. A study of bite force, part 1: Relationship to various physical characteristics. *The Angle orthodontist,* 65**,** 367-372.

BRAUN, S.,HNAT, W. P.,FREUDENTHALER, J. W.,MARCOTTE, M. R.,HÖNIGLE, K. & JOHNSON, B. E. 1996. A study of maximum bite force during growth and development. *Angle Orthodontist,* 66**,** 261-264.

BRAWLEY, R. E. & SEDWICK, H. J. 1938. Gnathodynamometer. *American Journal of Orthodontics and Oral Surgery,* 24**,** 256-258.

BRODIN, P.,TURKER, K. S. & MILES, T. S. 1993. Mechanoreceptors around the tooth evoke inhibitory and excitatory reflexes in the human masseter muscle. *Journal of Physiology,* 464**,** 711-723.

CALDERON, P. D. S.,KOGAWA, E. M.,LAURIS, J. R. P. & CONTI, P. C. R. 2006. The influence of gender and bruxism on the human maximum bite force. *Journal of Applied Oral Science,* 14**,** 448-453.

CARLSSON, G. E. 1974. Bite force and chewing efficiency. *Frontiers of oral physiology,* 1**,** 265-292.

CHINNI, S. S.,AL-IBRAHIM, A. & FORGIE, A. H. 2014. A simple, safe, reliable and reproducible mechanism for producing experimental bitemarks. *Journal of Forensic Odonto-Stomatology,* 31**,** 22-29.

CUSTODIO, W.,GOMES, S. G.,FAOT, F.,GARCIA, R. C. & DEL BEL CURY, A. A. 2011. Occlusal force, electromyographic activity of masticatory muscles and mandibular flexure of subjects with different facial types. *Journal of applied oral science : revista FOB,* 19**,** 343-349.

DALTON, P. A. & STOKES, M. J. 1991. Acoustic myography reflects force changes during dynamic concentric and eccentric contractions of the human biceps brachii muscle. *European Journal of Applied Physiology and Occupational Physiology,* 63**,** 412-416.

DISSELHORST-KLUG, C.,SCHMITZ-RODE, T. & RAU, G. 2009. Surface electromyography and muscle force: Limits in sEMG-force relationship and new approaches for applications. *Clinical Biomechanics,* 24**,** 225-235.

DUXBURY, A. J.,FRAME, J. W.,ROTHWELL, P. S. & JACKSON, P. D. 1973. An instrument for the measurement of incisive bite force. *Journal of Dentistry,* 1**,** 246-250.

DUYGU KOC,ARIFE DOGAN & BEC, B. 2010. Bite Force and Influential Factors on Bite Force Measurements: A Literature Review. *European Journal of Dentistry,* 4**,** 223-232.

FARELLA, M.,BAKKE, M.,MICHELOTTI, A.,RAPUANO, A. & MARTINA, R. 2003. Masseter thickness, endurance and exercise-induced pain in subjects with different vertical craniofacial morphology. *European Journal of Oral Sciences,* 111**,** 183-188.

FERNANDES, C. P.,GLANTZ, P. O. J.,SVENSSON, S. A. & BERGMARK, A. 2003. A novel sensor for bite force determinations. *Dental Materials,* 19**,** 118-126.

FERRARIO, V. F.,SFORZA, C.,SERRAO, G.,DELLAVIA, C. & TARTAGLIA, G. M. 2004a. Single tooth bite forces in healthy young adults. *Journal of Oral Rehabilitation,* 31**,** 18-22.

FERRARIO, V. F.,SFORZA, C.,ZANOTTI, G. & TARTAGLIA, G. M. 2004b. Maximal bite forces in healthy young adults as predicted by surface electromyography. *Journal of Dentistry,* 32**,** 451-457.

FIELDS, H. W.,PROFFIT, W. R.,CASE, J. C. & VIG, K. W. L. 1986. Variables Affecting Measurements of Vertical Occlusal Force. *Journal of Dental Research,* 65**,** 135-138.

FREEMAN, P. W. & LEMEN, C. A. 2008. Measuring bite force in small mammals with a piezo-resistive sensor. *Journal of Mammalogy,* 89**,** 513-517.

GARNER, L. D. & KOTWAL, N. S. 1973. Correlation study of incisive biting forces with age, sex, and anterior occlusion. *Journal of Dental Research,* 52**,** 698-702.

GIBBS, C. H.,ANUSAVICE, K. J.,YOUNG, H. M.,JONES, J. S. & ESQUIVEL-UPSHAW, J. F. 2002. Maximum clenching force of patients with moderate loss of posterior tooth support: A pilot study. *Journal of Prosthetic Dentistry,* 88**,** 498-502.

GONÇALVES, T. M. S. V.,DE VASCONCELOS, L. M. R.,DA SILVA, W. J.,DEL BEL CURY, A. A. & RODRIGUES GARCIA, R. C. M. 2011. Influence of female hormonal fluctuation on maximum occlusal force. *Brazilian Dental Journal,* 22**,** 497-501.

GONZALEZ, Y.,IWASAKI, L. R.,MCCALL JR, W. D.,OHRBACH, R.,LOZIER, E. & NICKEL, J. C. 2011. Reliability of electromyographic activity vs. bite-force from human masticatory muscles. *European Journal of Oral Sciences,* 119**,** 219-224.

GORDON, A. M.,HUXLEY, A. F. & JULIAN, F. J. 1966. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *The Journal of physiology,* 184**,** 170-192.

HAGBERG, C. 1987. Assessment of bite force: a review. *Journal of craniomandibular disorders : facial & oral pain,* 1**,** 162-169.

HARALDSON, T.,CARLSSON, G. E.,DAHLSTROM, L. & JANSSON, T. 1985. Relationship between myoelectric activity in masticatory muscles and bite force. *Scandinavian Journal of Dental Research,* 93**,** 539-545.

HARALDSON, T.,KARLSSON, U. & CARLSSON, G. E. 1979. Bite force and oral function in complete denture wearers. *Journal of Oral Rehabilitation,* 6**,** 41-48.

HASEGAWA, S.,SEKITA, T. & HAYAKAWA, I. 2003. Effect of denture adhesive on stability of complete dentures and the masticatory function. *Journal of Medical and Dental Sciences,* 50**,** 239-247.

HATCH, J. P.,SHINKAI, R. S. A.,SAKAI, S.,RUGH, J. D. & PAUNOVICH, E. D. 2001. Determinants of masticatory performance in dentate adults. *Archives of Oral Biology,* 46**,** 641-648.

HELKIMO, E.,CARLSSON, G. E. & CARMELI, Y. 1975. Bite force in patients with functional disturbances of the masticatory system. *Journal of Oral Rehabilitation,* 2**,** 397-406.

HELKIMO, E.,CARLSSON, G. E. & HELKIMO, M. 1977. Bite force and state of dentition. *Acta Odontologica Scandinavica,* 35**,** 297-303.

HELLSING, G. 1980. On the regulation of interincisor bite force in man. *Journal of Oral Rehabilitation,* 7**,** 403-411.

HIDAKA, O.,IWASAKI, M.,SAITO, M. & MORIMOTO, T. 1999. Influence of clenching intensity on bite force balance, occlusal contact area, and average bite pressure. *Journal of Dental Research,* 78**,** 1336-1344.

HYLANDER, W. L. 1978. Incisal bite force direction in humans and the functional significance of mammalian mandibular translation. *American Journal of Physical Anthropology,* 48**,** 1-7.

IKEBE, K.,NOKUBI, T.,MORII, K.,KASHIWAGI, J. & FURUYA, M. 2005. Association of bite force with ageing and occlusal support in older adults. *Journal of Dentistry,* 33**,** 131-137.

INGERVALL, B. & MINDER, C. 1997. Correlation between maximum bite force and facial morphology in children. *Angle Orthodontist,* 67**,** 415-424.

INMAN, V. T.,RALSTON, H. J.,DE C.M. SAUNDERS, J. B.,BERTRAM FEINSTEIN, M. B. & WRIGHT JR, E. W. 1952. Relation of human electromyogram to muscular tension. *Electroencephalography and Clinical Neurophysiology,* 4**,** 187-194.

IWASE, M.,OHASHI, M.,TACHIBANA, H.,TOYOSHIMA, T. & NAGUMO, M. 2006. Bite force, occlusal contact area and masticatory efficiency before and after orthognathic surgical correction of mandibular prognathism. *International Journal of Oral and Maxillofacial Surgery,* 35**,** 1102-1107.

KAMEGAI, T.,TATSUKI, T.,NAGANO, H.,MITSUHASHI, H.,KUMETA, J.,TATSUKI, Y. & INABA, D. 2005. A determination of bite force in northern Japanese children. *European Journal of Orthodontics,* 27**,** 53-57.

KAWAZOE, Y.,KOTANI, H. & HAMADA, T. 1979. Relation between integrated electromyographic activity and biting force during voluntary isometric contraction in human masticatory muscles. *Journal of Dental Research,* 58**,** 1440-1449.

KILIARIDIS, S.,KJELLBERG, H.,WENNEBERG, B. & ENGSTRÖM, C. 1993. The relationship between maximal bite force, bite force endurance, and facial morphology during growth. A cross-sectional study. *Acta Odontologica Scandinavica,* 51**,** 323-331.

KLEINFELDER, J. W. & LUDWIG, K. 2002. Maximal bite force in patients with reduced periodontal tissue support with and without splinting. *Journal of Periodontology,* 73**,** 1184-1187.

KOÇ, D.,DOĞAN, A. & BEK, B. 2011. Effect of gender, facial dimensions, body mass index and type of functional occlusion on bite force. *Journal of Applied Oral Science,* 19**,** 274-279.

KOGAWA, E. M.,CALDERON, P. S.,LAURIS, J. R. P.,ARAUJO, C. R. P. & CONTI, P. C. R. 2006. Evaluation of maximal bite force in temporomandibular disorders patients. *Journal of Oral Rehabilitation,* 33**,** 559-565.

KOOLSTRA, J. H.,VAN EIJDEN, T. M. G. J.,WEIJS, W. A. & NAEIJE, M. 1988. A three-dimensional mathematical model of the human masticatory system predicting maximum possible bite forces. *Journal of Biomechanics,* 21**,** 563-576.

LASSILA, V.,HOLMLUND, I. & KOIVUMAA, K. K. 1985. Bite force and its correlations in different denture types. *Acta Odontologica Scandinavica,* 43**,** 127-132.

LAWRENCE, J. H. & DE LUCA, C. J. 1983. Myoelectric signal versus force relationship in different human muscles. *Journal of Applied Physiology Respiratory Environmental and Exercise Physiology,* 54**,** 1653-1659.

LINDAUER, S. J.,GAY, T. & RENDELL, J. 1993. Effect of jaw opening on masticatory muscle EMG-force characteristics. *Journal of Dental Research,* 72**,** 51-55.

LINDERHOLM, H. & WENNSTRÖM, A. 1970. Isometric bite force and its relation to general muscle force and body build. *Acta Odontologica Scandinavica,* 28**,** 679-689.

LINDQVIST, B. & RINGQVIST, M. 1973. Bite force in children with bruxism. *Acta Odontologica Scandinavica,* 31**,** 255-259.

LYONS, M. F. & BAXENDALE, R. H. 1990. A preliminary electromyographic study of bite force and jaw-closing muscle fatigue in human subjects with advanced tooth wear. *Journal of Oral Rehabilitation,* 17**,** 311-318.

LYONS, M. F.,CADDEN, S. W.,BAXENDALE, R. H. & YEMM, R. 1996. Twitch interpolation in the assessment of the maximum force-generating capacity of the jaw-closing muscles in man. *Archives of Oral Biology,* 41**,** 1161-1168.

LYONS, M. F.,SHARKEY, S. W. & LAMEY, P. J. 1992. An evaluation of the T-Scan computerised occlusal analysis system. *The International journal of prosthodontics,* 5**,** 166-172.

MACKENNA, B. R. & TÜRKER, K. S. 1983. Jaw separation and maximum incising force. *The Journal of Prosthetic Dentistry,* 49**,** 726-730.

MANESS, W. L.,BENJAMIN, M.,PODOLOFF, R.,BOBICK, A. & GOLDEN, R. F. 1987. Computerized occlusal analysis: a new technology. *Quintessence international,* 18**,** 287-292.

MANLY, R. S. & VINTON, P. 1951. A survey of the chewing ability of denture wearers. *Journal of Dental Research,* 30**,** 314-321.

MANNS, A.,MIRALLES, R. & PALAZZI, C. 1979. EMG, bite force, and elongation of the masseter muscle under isometric voluntary contractions and variations of vertical dimension. *The Journal of Prosthetic Dentistry,* 42**,** 674-682.

MATSUI, Y.,NEUKAM, F. W.,WICHMANN, M. & OHNO, K. 1996. A Computerized Method for Evaluating Distribution of Occlusal Load on Implant-Supported Fixed Cantilever Prostheses. *International Journal of Oral and Maxillofacial Implants,* 11**,** 67-72.

MATTHEWS, B. 1975. In *Applied Physiology of the Mouth* (Ed. Lavelle C. L. B.), Chap 10, p. 209. Wright, Bristol.

MERICSKE-STERN, R. 1998a. Three-dimensional force measurements with mandibular overdentures connected to implants by ball-shaped retentive anchors. A clinical study. *The International journal of oral & maxillofacial implants,* 13**,** 36-43.

MERICSKE-STERN, R. 1998b. Three-Dimensional Force Measurements with Mandibular Overdentures Connected to Implants by Ball-Shaped Retentive Anchors. A Clinical Study. *International Journal of Oral and Maxillofacial Implants,* 13**,** 36-43.

MERICSKE-STERN, R.,GEERING, A. H.,BURGIN, W. B. & GRAF, H. 1992. Three-dimensional force measurements on mandibular implants supporting overdentures. *The International journal of oral & maxillofacial implants,* 7**,** 185-194.

MERICSKE-STERN, R.,PIOTTI, M. & SIRTES, G. 1996. 3-D in vivo force measurements on mandibular implants supporting overdentures: A comparative study. *Clinical Oral Implants Research,* 7**,** 387-396.

MERTON, P. A. 1954. Voluntary strength and fatigue. *The Journal of physiology,* 123**,** 553-564.

METRAL, S. & CASSAR, G. 1981. Relaionship between force and integrated EMG activity during voluntary isometric anisotonic contraction. *European Journal of Applied Physiology and Occupational Physiology,* 46**,** 185-198.

MILES, T. S. & MADIGAN, M. L. 1983. Programming of antagonist muscle stiffness during masticatory muscle unloading in man. *Archives of Oral Biology,* 28**,** 947-951.

MILES, T. S. & WILKINSON, T. M. 1982. Limitation of jaw movement by antagonist muscle stiffness during unloading of human jaw closing muscles. *Experimental Brain Research,* 46**,** 305-310.

MIYAURA, K.,MORITA, M.,MATSUKA, Y.,YAMASHITA, A. & WATANABE, T. 2000. Rehabilitation of biting abilities in patients with different types of dental prostheses. *Journal of Oral Rehabilitation,* 27**,** 1073-1076.

MOLIN, C. 1972. Vertical isometric muscle forces of the mandible. A comparative study of subjects with and without manifest mandibular pain dysfunction syndrome. *Acta Odontologica Scandinavica,* 30**,** 485-499.

MORITA, M.,NISHI, K.,KIMURA, T.,FUKUSHIMA, M.,WATANABE, T.,YAMASHITA, F.,ZHOU, R.,YANG, J. & XU, X. 2003. Correlation between periodontal status and biting ability in Chinese adult population. *Journal of Oral Rehabilitation,* 30**,** 260-264.

MÜLLER, F.,HEATH, M. R. & OTT, R. 2001. Maximum bite force after the replacement of complete dentures. *Gerodontology,* 18**,** 58-62.

NAKANO K,KAMEGAI T,NAKANO H & Y, S. 1994. A study on the measurement of human biting force - Development of a hydraulic bite pressure apparatus and its application to group oral health examination. *American Journal of Orthodontics & Dentofacial Orthopedics,* 106**,** 667-668.

NEWTON, J. P.,YEMM, R.,ABEL, R. W. & MENHINICK, S. 1993. Changes in human jaw muscles with age and dental state. *Gerodontology,* 10**,** 16-22.

ORCHARDSON, R. & CADDEN, S. W. 1998. Mastication. *In The Scientific Basis of Eating, Frontiers of Oral Biology.* vol. 9, ed. Linden, R.W.A., pp.76-121. Karger, Basel.

ORIZIO, C.,PERINI, R. & VEICSTEINAS, A. 1989. Muscular sound and force relationship during isometric contraction in man. *European Journal of Applied Physiology and Occupational Physiology,* 58**,** 528-533.

ORTU, G. 2002. A new device for measuring mastication force (Gnathodynamometer). *Annals of Anatomy,* 184**,** 393-396.

OSBORN, J. W. & BARAGAR, F. A. 1985. Predicted pattern of human muscle activity during clenching derived from a computer assisted model: Symmetric vertical bite forces. *Journal of Biomechanics,* 18**,** 599-612.

OSBORN, J. W. & MAO, J. 1993. A thin bite-force transducer with three-dimensional capabilities reveals a consistent change in bite-force direction during human jaw-muscle endurance tests. *Archives of Oral Biology,* 38**,** 139-144.

OW, R. K.,CARLSSON, G. E. & JEMT, T. 1989. Biting forces in patients with craniomandibular disorders. *Cranio : the journal of craniomandibular practice,* 7**,** 119-125.

PALINKAS, M.,NASSAR, M. S. P.,CECÍLIO, F. A.,SIÉSSERE, S.,SEMPRINI, M.,MACHADO-DE-SOUSA, J. P.,HALLAK, J. E. C. & REGALO, S. C. H. 2010. Age and gender influence on maximal bite force and masticatory muscles thickness. *Archives of Oral Biology,* 55**,** 797-802.

PAMEIJER, J. H.,GLICKMAN, I. & ROEBER, F. W. 1969. Intraoral occlusal telemetry. 3. Tooth contacts in chewing, swallowing and bruxism. *Journal of Periodontology,* 40**,** 253-258.

PAPHANGKORAKIT, J. & OSBORN, J. W. 1997. Effect of jaw opening on the direction and magnitude of human incisal bite forces. *Journal of Dental Research,* 76**,** 561-567.

PAPHANGKORAKIT, J. & OSBORN, J. W. 1998. Effects on human maximum bite force of biting on a softer or harder object. *Archives of Oral Biology,* 43**,** 833-839.

PATYK, A.,LOTZMANN, U.,SCHERER, C. & KOBES, L. W. 1989. Comparative analytic occlusal study of clinical use of T-scan systems. *Vergleichende okklusionsanalytische Studie zur klinischen Anwendbarkeit des T-Scan Systems.,* 98**,** 752-755.

PEREIRA-CENCI, T.,PEREIRA, L. J.,CENCI, M. S.,BONACHELA, W. C. & DEL BEL CURY, A. A. 2007. Maximal bite force and its association with temporomandibular disorders. *Brazilian Dental Journal,* 18**,** 65-68.

PEREIRA, L. J.,PASTORE, M. G.,BONJARDIM, L. R.,CASTELO, P. M. & GAVIÃO, M. B. D. 2007. Molar bite force and its correlation with signs of temporomandibular dysfunction in mixed and permanent dentition. *Journal of Oral Rehabilitation,* 34**,** 759-766.

PEREIRA, L. J.,STEENKS, M. H.,DE WIJER, A.,SPEKSNIJDER, C. M. & VAN DER BILT, A. 2009. Masticatory function in subacute TMD patients before and after treatment. *Journal of Oral Rehabilitation,* 36**,** 391-402.

PERRY, J. & BEKEY, G. A. 1981. EMG-FORCE RELATIONSHIPS IN SKELETAL MUSCLE. *Critical Reviews in Biomedical Engineering,* 7**,** 1-22.

PIZOLATO, R. A.,GAVIÃO, M. B. D.,BERRETIN-FELIX, G.,SAMPAIO, A. C. M. & TRINDADE JR, A. S. 2007. Maximal bite force in young adults with temporomandibular disorders and bruxism. *Brazilian Oral Research,* 21**,** 278-283.

PROFFIT, W. R.,FIELDS, H. W. & NIXON, W. L. 1983. Occlusal forces in normal- and long-face adults. *Journal of Dental Research,* 62**,** 566-570.

PRUIM, G. J.,TEN BOSCH, J. J. & DE JONGH, H. J. 1978. Jaw muscle EMG-activity and static loading of the mandible. *Journal of Biomechanics,* 11**,** 389-395.

RENTES, A. M.,GAVIÃO, M. B. D. & AMARAL, J. R. 2002. Bite force determination in children with primary dentition. *Journal of Oral Rehabilitation,* 29**,** 1174-1180.

RINGQVIST, M. 1973. Isometric bite force and its relation to dimensions of the facial skeleton. *Acta Odontologica Scandinavica,* 31**,** 35-42.

ROWLETT, A. E. 1933. The Gnathodynamometer and Its Use in Dentistry: President's Address. *Proceedings of the Royal Society of Medicine,* 26**,** 463-471.

ŞAHIN, S.,ÇEHRELI, M. C. & YALÇIN, E. 2002. The influence of functional forces on the biomechanics of implant-supported prostheses - A review. *Journal of Dentistry,* 30**,** 271-282.

SAKAGUCHI M,ONO N,TURUTA H,YOSHIIKE J & T, O. 1996. Development of new handy type occlusal force gauge. *Japanese Journal of Medical Electronics and Biological Engineering,* 34**,** 83-92.

SASAKI, K.,HANNAM, A. G. & WOOD, W. W. 1989. Relationships between the size, position, and angulation of human jaw muscles and unilateral first molar bite force. *Journal of Dental Research,* 68**,** 499-503.

SATHYANARAYANA, H. P.,PREMKUMAR, S. & MANJULA, W. S. 2012. Assessment of maximum voluntary bite force in adults with normal occlusion and different types of malocclusions. *Journal of Contemporary Dental Practice,* 13**,** 534-538.

SERRA, C. M. & MANNS, A. E. 2013. Bite force measurements with hard and soft bite surfaces. *Journal of Oral Rehabilitation,* 40**,** 563-568.

SERRAO, G.,SFORZA, C.,DELLAVIA, C.,ANTINORI, M. & FERRARIO, V. F. 2003. Relation between vertical facial morphology and jaw muscle activity in healthy young men. *Prog Orthod,* 4**,** 45-51.

SHINOGAYA, T.,BAKKE, M.,THOMSEN, C. E.,VILMANN, A. & MATSUMOTO, M. 2000. Bite force and occlusal load in healthy young subjects--a methodological study. *The European journal of prosthodontics and restorative dentistry,* 8**,** 11-15.

SHINOGAYA, T.,BAKKE, M.,THOMSEN, C. E.,VILMANN, A.,SODEYAMA, A. & MATSUMOTO, M. 2001. Effects of ethnicity, gender and age on clenching force and load distribution. *Clinical oral investigations,* 5**,** 63-68.

SHINOGAYA, T.,SODEYAMA, A. & MATSUMOTO, M. 1999. Bite force and occlusal load distribution in normal complete dentitions of young adults. *The European journal of prosthodontics and restorative dentistry,* 7**,** 65-70.

SIMONE GUIMARÃES FARIAS GOMES,WILLIAM CUSTODIO,FERNANDA FAOTIII,ALTAIR ANTONINHA DEL BEL CURY & GARCIAII, R. C. M. R. 2011. Chewing side, bite force symmetry, and occlusal contact area of subjects with different facial vertical patterns. *Brazilian Oral Research,* 25.

SLAGTER, A. P.,BOSMAN, F.,VAN DER GLAS, H. W. & VAN DER BILT, A. 1993. Human jaw-elevator muscle activity and food comminution in the dentate and edentulous state. *Archives of Oral Biology,* 38**,** 195-205.

SONNESEN, L. & BAKKE, M. 2005. Molar bite force in relation to occlusion, craniofacial dimensions, and head posture in pre-orthodontic children. *European Journal of Orthodontics,* 27**,** 58-63.

SONNESEN, L.,BAKKE, M. & SOLOW, B. 2001. Bite force in pre-orthodontic children with unilateral crossbite. *European Journal of Orthodontics,* 23**,** 741-749.

STILES, R. & PHAM, D. Year. Acoustic- and surface electro-myography of human jaw elevator muscles. *In*, 1991 Orlando, FL, USA. Publ by IEEE, 946-947.

STOKES, M. J. & DALTON, P. A. 1990. Acoustic myographic activity increases linearly up to maximal voluntary isometric force in the human quadriceps muscle. *Journal of the Neurological Sciences,* 101**,** 163-167.

SUZUKI, T.,KUMAGAI, H.,WATANABE, T.,UCHIDA, T. & NAGAO, M. 1997. Evaluation of Complete Denture Occlusal Contacts Using Pressure-Sensitive Sheets. *International Journal of Prosthodontics,* 10**,** 386-391.

THROCKMORTON, G. S.,BUSCHANG, P. H. & ELLIS III, E. 1996. Improvement of maximum occlusal forces after orthognathic surgery. *Journal of Oral and Maxillofacial Surgery,* 54**,** 1080-1086.

TORTOPIDIS, D.,LYONS, M. F. & BAXENDALE, R. H. 1998a. Acoustic myography, electromyography and bite force in the masseter muscle. *Journal of Oral Rehabilitation,* 25**,** 940-945.

TORTOPIDIS, D.,LYONS, M. F. & BAXENDALE, R. H. 1999. Bite force, endurance and masseter muscle fatigue in healthy edentulous subjects and those with TMD. *Journal of Oral Rehabilitation,* 26**,** 321-328.

TORTOPIDIS, D.,LYONS, M. F.,BAXENDALE, R. H. & GILMOUR, W. H. 1998b. The variability of bite force measurement between sessions, in different positions within the dental arch. *Journal of Oral Rehabilitation,* 25**,** 681-686.

TRAWITZKI, L. V. V.,SILVA, J. B.,REGALO, S. C. H. & MELLO-FILHO, F. V. 2011. Effect of class II and class III dentofacial deformities under orthodontic treatment on maximal isometric bite force. *Archives of Oral Biology,* 56**,** 972-976.

TUXEN, A.,BAKKE, M. & PINHOLT, E. M. 1999. Comparative data from young men and women on masseter muscle fibres, function and facial morphology. *Archives of Oral Biology,* 44**,** 509-518.

VAN DER BILT, A.,TEKAMP, A.,VAN DER GLAS, H. & ABBINK, J. 2008. Bite force and electromyograpy during maximum unilateral and bilateral clenching. *European Journal of Oral Sciences,* 116**,** 217-222.

VAN DER GLAS, H. W.,CADDEN, S. W. & VAN DER BILT, A. 2000. Mechanisms underlying the effects of remote noxious stimulation and mental activities on exteroceptive jaw reflexes in man. *Pain,* 84**,** 193-202.

VAN DER GLAS, H. W.,DE LAAT, A. & VAN STEENBERGHE, D. 1985. Oral pressure receptors mediate a series of inhibitory and excitatory periods in the masseteric poststimulus EMG complex following tapping of a tooth in man. *Brain Research,* 337**,** 117-125.

VAN EIJDEN, T. M.,KOOLSTRA, J. H.,BRUGMAN, P. & WEIJS, W. A. 1988. A feedback method to determine the three-dimensional bite-force capabilities of the human masticatory system. *Journal of Dental Research,* 67**,** 450-454.

VAN EIJDEN, T. M. G. J. 1991. Three-dimensional analyses of human bite-force magnitude and moment. *Archives of Oral Biology,* 36**,** 535-539.

VAN SPRONSEN, P. H. 2010. Long-Face Craniofacial Morphology: Cause or Effect of Weak Masticatory Musculature? *Seminars in Orthodontics,* 16**,** 99-117.

VAN WILLIGEN, J. D.,BROEKHUIJSEN, M. L.,MELCHIOR, H. J.,KARKAZIS, H. C.,KOSSIONI, A. & HEATH, M. R. 1993. Digastric muscle response as a function of knowledge of the task to be performed. *Archives of Oral Biology,* 38**,** 113-121.

VARGA, S.,SPALJ, S.,LAPTER VARGA, M.,ANIC MILOSEVIC, S.,MESTROVIC, S. & SLAJ, M. 2011. Maximum voluntary molar bite force in subjects with normal occlusion. *European Journal of Orthodontics,* 33**,** 427-433.

WALTIMO, A.,NYSTRÖM, M. & KÖNÖNEN, M. 1994. Bite force and dentofacial morphology in men with severe dental attrition. *Scandinavian Journal of Dental Research,* 102**,** 92-96.

WESTING, S. H.,SEGER, J. Y. & THORSTENSSON, A. 1990. Effects of electrical stimulation on eccentric and concentric torque-velocity relationships during knee extension in man. *Acta Physiologica Scandinavica,* 140**,** 17-22.

WILLIAM CUSTODIO,SIMONE GUIMARÃES FARIAS GOMES,FERNANDA FAOT,RENATA CUNHA MATHEUS RODRIGUES GARCIA & CURYIII, A. A. D. B. 2011. Occlusal force, electromyographic activity of masticatory muscles and mandibular flexure of subjects with different facial types. *Journal of Applied Oral Science,* 19, 343-349.

WILLIAMS, W. N.,LOW, S. B.,COOPER, W. R. & CORNELL, C. E. 1987. The effect of periodontal bone loss on bite force discrimination. *Journal of Periodontology,* 58**,** 236-239.

WINOCUR, E.,DAVIDOV, I.,GAZIT, E.,BROSH, T. & VARDIMON, A. D. 2007. Centric slide, bite force and muscle tenderness changes over 6 months following fixed orthodontic treatment. *Angle Orthodontist,* 77**,** 254-259.

WOODS, J. J. & BIGLAND RITCHIE, B. 1983. Linear and non-linear surface EMG/force relationships in human muscles. An anatomical/functional argument for the existence of both. *American Journal of Physical Medicine,* 62**,** 287-299.

Appendix 1

Evaluation of Pressure Based Systems for Assessing Bite Forces

Student: Anas Alibrahim

Supervisors: Dr MF Lyons and Professor SW Cadden

Introduction

Measurement of maximum bite force has been used in dental research for various reasons: to understand the underlying mechanics of mastication, to evaluate the physiological characteristics of jaw closing muscles, to study the effect of different physical factors such as sex, age, height, and weight on occlusal forces, and to provide reference values for studies on the biomechanics of prosthetic devices. Furthermore, maximum bite force has been considered by some to be clinically important in the assessment of the performance and therapeutic effects of prosthetic devices, and in the diagnosis and treatment of temporomandibular disorders.

Unfortunately, obtaining a true maximum bite force is difficult for several reasons: Firstly biting on a steel force transducer without a protective covering risks damage to the teeth, and is very uncomfortable. Secondly, maximum bite force may be limited by inputs from sensory receptors within the periodontium. Thirdly, the subject must make a determined effort to bite as hard as possible and this is often limited by a fear of damaging the teeth 1.

Different coverings such as acrylic resin, rubber materials and gutta percha have been used in order to make biting on steel transducers a more comfortable procedure. However, none of these coverings has totally overcome the discomfort associated with biting on the steel 2. In order to overcome these problems, it is planned to develop an alternative bite force measuring device which would utilize a fluid-filled rubber tube connected to a pressure sensor. The performance and practicality of the two devices would be compared.

Aims and objectives

1- To develop an alternative more comfortable bite force measuring device which would utilize a fluid-filled tube connected to a pressure sensor.
2- To compare the newly developed device to the steel transducer and thus investigating its performance and practicality.

Participants

15 postgraduate dental students will be recruited for this study (age 25 to 40). Before taking part in the study, each participant will be asked to read and understand a participant information sheet, and to sign an informed consent form. The participant will have the right to decide to stop being part of the research study at any time without explanation and without penalty.

Design and methods

The study will take place in the Oral Neurophysiology Research Laboratory at Dundee Dental School. It will require around 1 hour, to be completed in one visit, and the participation is voluntary. Each participant will be asked to bite three times on three different approaches for the measurement of bite force which are:

a- The pressure transducer (the newly developed device)
b- The steel transducer while it is covered with an acrylic index (an aid to protect the teeth)
c- The steel transducer while it is covered with Ethyl Vinyl Acetate sheets (a new covering material)

The highest of the three bites will be considered as the maximum bite force for each type of measurement. The order in which the participants will bite on the three different approaches will be randomized and there will be 5 minutes rest period between the different types of measurements.

Simultaneously, surface electromyographic activity (EMG) will be recorded from the right and left masseter and anterior temporal muscles using disposable bipolar surface electrodes.

The participant will also respond by means of a visual analogue scale on which they will be asked how confident they were that they had achieved a maximum force (with anchor points “not confident at all” and “absolutely confident”). Each subject will respond to one VAS for each different type of measurement.

The information which will be collected from participants will not contain any personal details except the gender and age and will be kept in a locked room. The experimental data, which will be gathered from participants, will be in the form of computer files which will be stored in a password-protected computer. The data will be analysed using statistical software (SPSS) and will be kept until after publication and the end of the PhD project.

Risks

There are no known risks from participating in this study.

1- Tortopidis DS, Lyons MF and Baxendale RH. (1999) Bite force, endurance and masseter muscle fatigue in healthy edentulous subjects and those with TMD. Journal of Oral Rehabilitation, 26, 321-328.
2- Lyons MF, Cadden SW, Baxendale RH and Yemm R. (1997) Twitch interpolation in the assessment of the maximum force-generating capacity of the jaw-closing muscles in man. Archives of Oral Biology, 41, 1161-1168.

Appendix 2

Twitch Interpolation Study

Student: Anas Alibrahim

Supervisors: Dr MF Lyons and Professor SW Cadden

Introduction

Measurement of maximum voluntary bite force has been used in dental research for various reasons, including the evaluation of the physiological characteristics of jaw closing muscles and to provide reference values for studies on the biomechanics of prosthetic devices. However, it is notoriously difficult to know if the recorded maximum voluntary bite force is the true maximum of which the muscles are capable. Fear of damaging the teeth and the discomfort associated with biting on the commonly-used steel force transducer are significant problems.

A further consideration relates to feedback from afferent nerves. There is some evidence that inhibitory factors triggered by activation of sensory receptors within the periodontium might exist and may result in a reduction in the activity of the motor nerves which control the jaw closing muscles.

The technique of twitch interpolation has been used in our laboratory as a non-invasive method for the assessment of the potential maximum bite force (1). The principle of twitch interpolation is that electrical stimuli are applied to a muscle at varying states of voluntary contraction. The momentary increase in muscle tension which results from the twitch produced by this stimulus is inversely proportional to the strength of contraction and extrapolation of the regression line should indicate the true maximum force potential of the muscle.

It is now planned to investigate jaw-closing muscle force output using the twitch interpolation technique and a new pressure sensor to record bite force. This new pressure sensor is considerably more comfortable to bite on and may provide more insight into the ability of subjects to voluntarily fully activate their jaw-closing muscles.

Aims and objectives

1- To examine the suitability of a novel pressure transducer and a steel transducer covered with Vinyl sheets to be used with the technique of twitch interpolation.
2- To record the maximum voluntary bite force on the two transducers and the potential maximum bite force as predicted by the technique of twitch interpolation, and thus investigate whether voluntary full activation of jaw closing muscles is possible.

Participants

Eight participants will be recruited for this study (age 24 to 42). All the participants will be from among the students and/or the staff at Dundee dental school. It is planned to contact the subjects personally and provide them with the information sheet, give them enough time to consider the information in the information sheet, and ask them to contact the researcher (Anas Alibrahim) if they are willing to be involved. Before taking part, each participant will be asked to and to sign an informed consent form. The participant will have the right to decide to stop being part of the research study at any time without explanation and without penalty. The researcher (Anas Alibrahim) is not involved in teaching any of the potential participants or in their assessment.

Design and methods

The study will take place in the Clinical Neurophysiology Research Laboratory at Dundee Dental School. It will require two visits, each of one hour duration, and participation is voluntary.

The first visit will involve:

1- Measuring the maximum voluntary bite force using both the steel force transducer covered with Vinyl sheets and the pressure transducer. Each participant will be asked to bite three times on the two bite-force transducers and the highest of the three bites will be considered as the maximum. The order in which the participants will bite on the two transducers will be randomized and there will be a 5 minute rest period between the use of the two different transducers.

2- A stimulus/response relationship for forces produced by the masseter muscle will be established by applying a graded series of transcutaneous electrical stimuli at increasing intensities while the muscle is at rest. A monopolar electrode configuration will be used to apply the transcutaneous stimuli to the masseter muscle. The intensity of 50 mA will not be exceeded as it was found to be uncomfortable for some subjects in a previous study (Lyons et al., 1996).

The second visit:

1- The participant will be asked to perform a series of clenches from just above 0% to 100% of the maximum voluntary bite force with the aid of the visual feedback of the force record. While performing the clenches, and at an unpredictable point of time, a twitch will be elicited by a single 1-ms duration electrical stimulus applied to one masseter muscle.

2- The participant will be asked to perform the clenches in descending order from 100% to 0% of the maximum voluntary bite force and the same electrical stimulus will be applied unpredictably while the participant is performing the clenches.

The information which will be collected from participants will not contain any personal details except the gender and age and will be kept in a locked room. The experimental data will be in the form of computer files which will be stored in a password-protected computer. The data will be analysed using statistical software (SPSS) and will be kept until after publication and the end of the PhD project.

Risks

There are no known risks from participating in this study. However, there might be a possible discomfort experienced with the electrical stimulation procedure.

Study Duration

Estimated start date: 15/04/14

Estimated end date: 15/06/14

1- Lyons MF, Cadden SW, Baxendale RH and Yemm R. (1997) Twitch interpolation in the assessment of the maximum force-generating capacity of the jaw-closing muscles in man. Archives of Oral Biology, 41, 1161-1168.

Appendix 3

Visual Analogue scale (VAS)

How Confident were you that you had achieved a maximum force?

A – The fluid-filled tube:

"not confident at all" ***"absolutely confident"***

B – The two-beam transducer while the plates are covered with acrylic:

"not confident at all" ***"absolutely confident"***

C – The two-beam transducer while the plates are covered with vinyl sheets:

"not confident at all" ***"absolutely confident"***

Extended Summary

Background: Registering a true maximum bite force on the most commonly-used force transducers is problematic. It is often believed that this is related mainly to discomfort and the fear of breaking teeth on the transducers.

Objectives: The overall aim of the project was to compare the suitability of different bite force measuring transducers including ones which were designed to improve subject comfort. The transducers used were a traditional strain-gauge transducer with and without covering with ethylene vinyl acetate (EVA) sheets, and a newly-developed pressure transducer. The following investigations were undertaken: a) comparisons of maximum voluntary bite forces (MVBFs) recorded on the different types and different thicknesses of bite force transducer; b) comparisons of visual analogue scale (VAS) scores of confidence for the different types of bite force transducer; c) comparisons of maximum potential bite forces and spare capacities, as predicted by the technique of twitch interpolation for the different types of bite force transducer; and d) comparisons of total EMGs recorded from two pairs of jaw closing muscles, associated with MVBFs on the different types of bite force transducer.

Methods: Five separate studies were performed in this project. The experiments were carried out on human volunteer subjects (aged 24 to 41 years). They were all dentate with no missing anterior teeth and with no crowns or large composite restorations on these teeth. The following procedures were

used in some or all of the studies: measurement of MVBF, electrical stimulation of the masseter muscle, and EMG recording from the masseter and the anterior temporalis muscles. In all five studies, one or more of the different types of bite force transducer (various forms of strain-gauge transducer and the pressure transducer) was / were used.

Results: The following results were obtained:

First study: Significant differences (ANOVA, P = 0.00014) were found overall between the MVBFs for three different types of strain-gauge transducer namely with silicone indices, with EVA sheets, and with EVA sheets and silicone indices. In addition, there were significant differences between the transducer with silicone indices and the transducer with EVA sheets (165 ± 35 N vs 228 ± 61 N; P = 0.0068), and between the transducer with silicone indices and the transducer with EVA sheets and silicone indices (165 ± 35 N vs 248 ± 66 N; P = 0.0019).

Second study: Significant differences were found between the MVBFs for three different types of bite force transducer: a strain-gauge transducer with acrylic indices, a strain-gauge transducer with EVA sheets, and a pressure transducer (ANOVA and post-hoc tests, P < 0.01). The mean MVBFs (± S.D.) were: strain-gauge transducer with acrylic indices, 163 ± 82 N; strain-gauge transducer with EVA sheets, 239 ± 93 N; and pressure transducer, 359 ± 152 N. Significant differences were found overall between the VAS scores across the three different types of bite force transducer (Friedman test, P = 0.000095). In addition, there were significant differences between the strain-gauge transducer with acrylic indices and the strain-gauge transducer with EVA sheets [median (full range); 14 mm (1.5 - 92 mm) vs 73 mm (38 - 98.5 mm); P = 0.0020], and between the strain-gauge transducer with acrylic indices and the pressure transducer [14 mm (1.5 - 92 mm) vs 95 mm (73.5 - 98 mm); P = 0.0040]. The difference between the scores for the EVA sheets and the pressure transducer narrowly failed to achieve statistical significance (P = 0.051), with a trend for there to be higher scores with the pressure transducer.

Third study: No significant differences were found between the MVBFs for four different thicknesses (12, 14, 16, and 18 mm) of strain-gauge transducers (ANOVA, P > 0.05). In addition, no significant correlation was found between the transducer thickness and the MVBF (Spearman's rank correlation test, P > 0.05).

Fourth study: A significant difference was again found between the MVBFs for the strain-gauge transducer with EVA sheets and the pressure transducer (Paired t test, P = 0.0037). The mean MVBFs (± S.D.) were 277 ± 76 N and 552 ± 243 N for the strain-gauge transducer with EVA sheets and the pressure transducer respectively. In addition, a significant difference was found between the maximum potential bite force predicted by the technique of twitch interpolation for the two different transducers (Paired t test, P = 0.0013). The mean maximum potential bite forces (± S.D.) were 354 ± 67 N and 730 ± 199 N for the strain-gauge transducer with EVA sheets and the pressure transducer respectively. No significant difference was found between the percentage spare capacities for the two different transducers (Paired t test, P = 0.96). The mean percentage spare capacities (± S.D.) were 18% ± 13% and 18% ± 21% for the strain-gauge transducer with EVA sheets and the pressure transducer respectively.

Fifth study: A significant difference was again found between the MVBFs for the strain-gauge transducer with EVA sheets and the pressure transducer (Paired t test, P = 0.017). The mean MVBFs (± S.D.) were 254 ± 83 N and 577 ± 259 N for the strain-gauge transducer covered with EVA sheets and the pressure transducer respectively. A significant difference was found between the total integrated EMGs for the two different transducers (Paired t test, P = 0.014). The mean total EMG values (± S.D.) were 0.19 ± 0.10 V and 0.24 ± 0.12 V for the strain-gauge transducer covered with EVA sheets and the pressure transducer respectively.

Conclusions: Within the limitations of the studies described in this thesis, it may be concluded that: a) the pressure transducer system and to a lesser extent the strain-gauge transducer covered with EVA sheets seemed to overcome the fear associated with biting on the hard surfaces of the strain-gauge transducer alone. This conclusion might be supported by the higher MVBFs on the pressure transducer and the higher VAS scores of confidence; b) the fact that one can argue that the pressure transducer may have some multi-directional capabilities which might have allowed for total bite forces, or at least larger parts of them, to be recorded than on a uni-directional strain-gauge transducer. This latter suggestion in turn is supported by the higher MVBFs on the pressure transducer, the higher maximum potential bite forces predicted for the pressure transducer, and the higher EMGs from jaw closing muscles associated with MVBFs on this transducer.