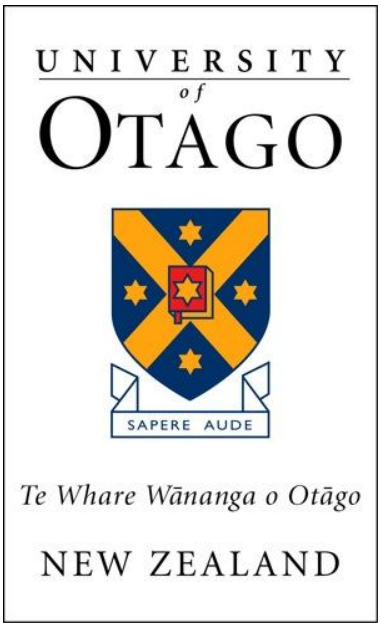
The effect of incremental lower lip advancement on intraoral pressures



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Abstract

Objectives: The aim of this study was to investigate the response of the lower lip musculature to incremental advancement, both during swallowing and at rest.

Material and Methods: Intraoral lip pressures were measured using four miniature pressure sensors in ten participants (2 males, 8 females; 20-39 years) who were free of relevant malocclusion. Custom-made acrylic trays were used, with the sensors located to record pressures at the midline and canine on both the labial and lingual surfaces. EMG sensors recorded muscle activity of the orbicularis oris and mentalis muscle at the lower midline. The pressure sensors were calibrated using a pressure chamber and the recorded pressure and EMG signals were analog-to-digital converted at 1kHz, and stored for off-line analyses. For each participant, the lower lip was advanced incrementally by inserting trays with different labial thicknesses (0.5, 2.5 and 4.5mm). Resting lip pressures were assessed three times over a 30-second window with teeth in light contact and apart. Each participant was also asked to complete three on-command saliva swallows at one-minute intervals for each tray. Data were analysed using a mixed linear model, combined with visual analysis of each individual swallow profile.

Results: Resting lip pressure generated at the midline increased as the lower lip was advanced ($p<0.001$, $F=14.7$). There was no statistically significant difference in EMG activity when the lip was advanced from 0.5mm to 2.5mm, but activity increased significantly between 2.5mm and 4.5mm of advancement ($p<0.001$). For the saliva swallow task, peak

pressure generated at the canine labial site increased as the lower lip was advanced ($p<0.05$), while no change in peak pressure was seen at the other three sites ($p>0.05$). Each individual's swallow profile was maintained during both the intra- and inter-tray swallows. For pressure, EMG and swallow activity, there was a highly significant tray/subject interaction (pressure $p<0.001$, $F=24.3$; EMG $p<0.001$, $F=26.5$; swallow $p<0.001$).

Conclusion: Lip pressure generated at the midline increased as the lower lip was advanced, while EMG activity increased only after the lip was advanced further than 2.5mm. This suggests that the initial pressure increase on the lower incisors was from the inherent viscoelastic properties of the lower lip, while the pressure increase between 2.5 and 4.5mm advancement was due to increased muscle activity as the subject attempted to maintain oral seal. These findings support the proposal that each individual has a signature swallow which is maintained when the anterior oral seal is challenged. It also suggests that each individual responds to lower lip advancement in a different yet subject-specific manner. The individual pressure response to incremental lip advancement needs to be further investigated in future research to understand how this affects the long-term stability of the lower labial segment.

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1 Introduction

To achieve long-term stability in orthodontics, it is considered important to place the teeth in a position that is in balance with the surrounding soft tissues. This recommendation is based on the so-called "equilibrium theory", which states that the teeth occupy a zone of stable equilibrium between the opposing muscular forces exerted by the tongue on one side, and the lips and cheeks on the other (Weinstein *et al.*, 1963; Proffit, 1978). It has been proposed that the ability of the soft tissues to adapt to changes in tooth position is limited, hence, it is the soft tissues that determine the physiological boundaries of dental compensation (Ackerman and Proffit, 1997). Unfortunately, a lack of understanding still surrounds the reaction of the soft tissues to labial tooth displacement.

The primary objective of this research project is to expand on the current knowledge of lower lip response to advancement. This study will investigate baseline pressures at four sites on the lower arch, with EMG activity of the mentalis and orbicularis oris muscles measured concurrently at the lower midline. Oral pressure and EMG activity will be recorded both at rest and during function, and will monitor how muscle behaviour changes as the lower lip is advanced forward. As the lower lip is advanced, it also becomes more difficult for subjects to maintain anterior oral seal. This study will investigate how swallowing behaviour changes when the oral seal is challenged.

2 Literature Review

2.1 Instrumentation used for oral pressure measurement

2.1.1 The strain gauge based design

In many of the early studies investigating oral pressure, measurement techniques were based on a strain gauge device. The gauge consisted of a foil wire bonded to a flexible backing, and once it was firmly attached to a structure, stressing or bending it up to its elastic limit caused a temporary elongation of the wire. This, in turn, produced a change in resistance in the wire, which could then be recorded (Lindeman and Moore, 1990).

2.1.2 The hydraulic system of pressure measurement

One of the difficulties with the strain gauge design was its size, which may interfere with the function being studied, leading to measurement errors (Proffit, 1975a). In an attempt to overcome this, a hydraulic system was devised to measure oral pressure (Thüer *et al.*, 1985) (Figure 2-1). Oral pressure was measured using an open cannula embedded in a small custom-made acrylic shield which was bonded to the teeth. The cannula was connected via a thin tube to an extra-oral pressure measuring system consisting of water, compressed air, a pressure transducer and a flow-limiting valve. A constant stream of water (2ml/min) flowed through the end of the cannula, and when the lip or tongue covered this stream of water, resistance was offered. The amount of resistance, which was measured with a pressure transducer connected to a manometer, reflected the pressure from the lip or tongue.

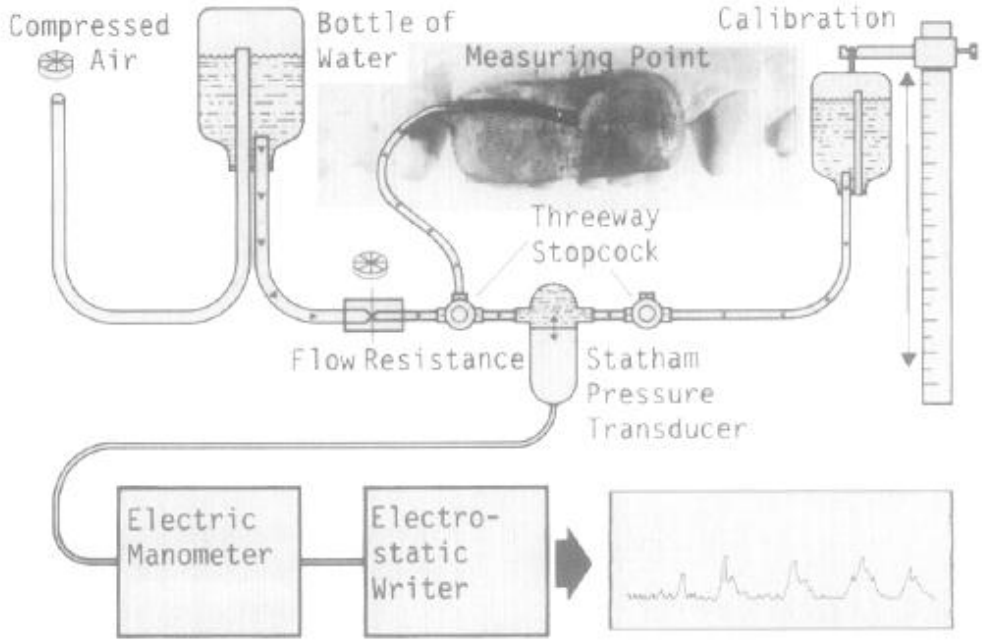


Figure 2-1: Water-based oral pressure measurement system (Thüer *et al.*, 1985)

Initially, the authors used the above system to investigate the pressure from the lip in a group of 27 children using this device while at rest, swallowing and during chewing on two separate occasions (Thüer *et al.*, 1985). Unfortunately, the intra-individual variation found between sessions was almost as great as the inter-individual variation. The authors concluded that this finding was likely due to the large differences in functional responses among subjects, rather than due to any recording difficulties, although this seems unlikely.

2.1.3 Diaphragm pressure transducers

In recent years, the use of diaphragm pressure transducers has become more common. This device incorporates the same basic principle as the strain gauge, but is more complex in its mechanism of action. It is designed as a sealed, self-contained unit that contains four semi-conductive strain gauges bonded to a thin, circular diaphragm (Shellhart *et al.,* 1996).

In an attempt to define the "gold standard" technique for oral pressure measurement, a number of studies have compared the pressure transducer

to the strain gauge design (Shellhart *et al.*, 1996; Lindeman and Moore, 1990). These studies will be discussed in more detail below.

Size

In an attempt to improve the reliability of oral pressure measurement, Gould and Picton (1962) studied the role of sensor thickness. It was proposed that increasing the thickness of the sensor might encroach on the soft tissue space, leading to higher muscular pressures being generated. Consequently, these pressures would no longer be a true representation of baseline at rest pressure. A strain gauge unit was placed in seven patients with a pre-existing interdental space. To investigate this theory, the authors measured baseline pressure adjacent to the tooth surface (0mm), and then moved the sensor labially in 1mm increments. When the sensor was 1-2mm from the surface of the tooth, the pressure readings were similar to the baseline readings. However, the pressure recorded increased markedly in the majority of the subjects once the sensor was 3mm from the tooth surface. The authors concluded that the recording surface of the pressure sensor should be 2mm or less from the tooth surface to ensure accuracy of measurement.

The strain gauge is much thicker in cross-section than the pressure transducer, and must be mounted on a carrier with space behind it to allow the beam to deflect (Shellhart *et al.*, 1996; Lindeman and Moore, 1990). Consequently, the strain gauge design is bulkier and maintaining the sensor surface within the recommended distance from the tooth surface can be problematic.

Thermal drift

The pressure transducer is contained within a sealed unit that is thermally compensated during manufacturing. The strain gauge is an uncompensated system, hence it is more sensitive to changes in temperature of the ambient environment. This is especially important when measuring tasks such as swallowing or speaking, as the sensor is frequently exposed to the ambient oral temperature, leading to a higher likelihood of thermal related errors in

measurement when a strain gauge system is used (Lindeman and Moore, 1990).

Direction of pressure measurement

Another important feature of the diaphragm pressure transducer is that it is designed to measure pressure exerted by a gas or fluid, and is able to measure forces generated from more than one direction. In contrast, one strain gauge is designed to measure force, and can only record force exerted in one direction (Lindeman and Moore, 1990). This is a major issue when measuring pressures from the oral musculature, as pressure is continually exerted in multiple directions. Consequently, the use of the strain gauge imposes restrictions on the accuracy of pressure measurement (Shellhart *et al.*, 1996).

In the mid 90s, a study of 22 subjects aged 20-30 years with Class I occlusion was carried out to compare the strain gauge with the pressure transducer (Shellhart *et al.*, 1996). Each subject had lower labial pressure measured at the midline and right canine with both a strain gauge and a pressure transducer. The pressure transducers consistently recorded smaller errors of measurement than the strain gauge design (although the standard deviation for both groups was still large). The labial pressures and standard deviations are listed in Table 2-1.

	Location	
Transducer type	Lower midline	Lower right canine
Diaphragm pressure transducer	7.5 ± 6.9	4.6 ± 3.9
Strain gauge	20.0 ± 15.1	11.1 ± 12.3

Table 2-1: Resting pressure values for both types of transducers in g/cm^2 ± standard deviation (Shellhart *et al.*, 1996)

The resting labial pressures for the strain gauge design were approximately twice the value of those for the pressure transducer. The authors concluded that the main reason for this was the difference in sensor thickness. The sensing surface of the strain gauge was approximately 2.6mm away from the tooth surface, while the pressure transducer was only 1.3mm from the tooth surface (Shellhart *et al.*, 1996). For this reason, caution must be exercised when comparing results of studies that have used different measuring techniques.

2.2 The history of oral pressure measurement

2.2.1 The equilibrium theory

In 1873, Tomes asserted that opposing forces from the lips and cheeks on one side and the tongue on the other, determined the position of the teeth. This became known as the equilibrium theory and was a widely accepted paradigm by the dental profession at the time, though it was based mainly on clinical experience and observation rather than scientific evidence (Jacobs, 1969). It was not until the 1950s that significant clinical research was undertaken to investigate this theory.

Many of the early studies on the equilibrium theory focused on the generation of maximum pressure by the oral musculature. Winders (1956) used a strain gauge to measure buccal pressure at the upper right first molar and lower left first molar, and lingual pressure at both lower first molars. Pressure was measured during swallowing, speaking a sentence and maximum pressure. In all instances, the tongue generated three to four times the pressure generated by the cheek musculature.

In his initial investigations, Kydd (1956) also employed a strain gauge design to measure lateral forces on dentures. However, due to the bulk of this system, it was subsequently abandoned when investigating dentate subjects. In a follow-up study, lip and tongue pressure was recorded in 30 dental students using a manometer. Maximal tongue pressure was almost twice that of the maximal lip pressure (Kydd, 1957).

In 1963, Weinstein *et al.,* completed an experiment on oral pressure in an attempt to further clarify the equilibrium theory. A second premolar pontic with a strain gauge transducer attached was placed in an existing extraction space. The pontic was displaced 2mm labially, which caused an appreciable increase in the pressure from the buccal musculature, accompanied by a decrease in pressure from the tongue.

A similar experiment was then repeated with eight subjects who were scheduled for first premolar extractions for orthodontic purposes. A 2mm gold onlay extension was added to the buccal or lingual surface of the tooth, and the subjects were monitored over an eight-week period. During this time small amounts of tooth movement were observed. Weinstein *et al.,* concluded that forces exerted on the crown of the tooth by the surrounding musculature were capable of moving teeth. It was hypothesised that if the position of a tooth impinges on the soft tissue space, the oral musculature will generate a force to move the tooth back into a position of equilibrium.

Another theory suggested was that the teeth have multiple positions of stability, with each stable position having minimum potential energy. Weinstein *et al.* (1963) asserted that the position of stable equilibrium of any static body is determined by the state of potential energy of the system (consisting of the static body and its environment). If more than one such minimum energy state exists, then the tooth will be stable in any of them. A frequently observed example of this phenomenon is where the teeth are in molar crossbite, where there are four possible stable buccolingual positions (Figure 2-2) (Weinstein *et al.*, 1963).

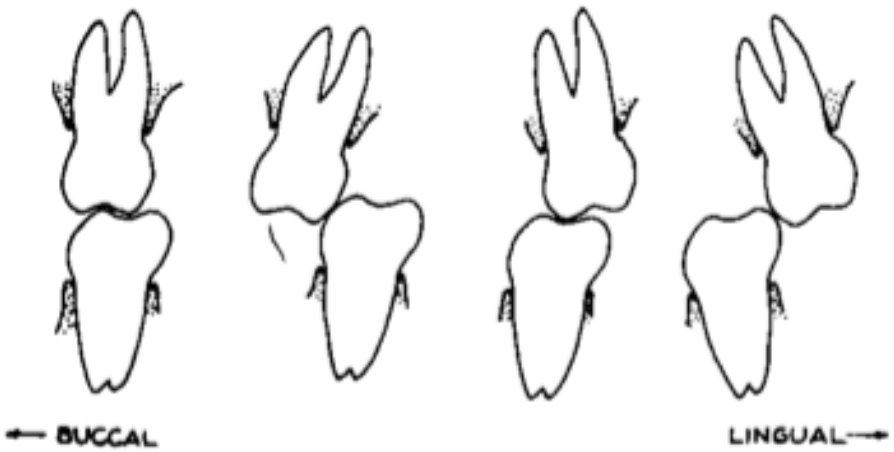


Figure 2-2: Four possible stable positions of minimum energy for the molar buccolingual relationship (Weinstein *et al.*, 1963).

In 1964, Proffit and co-workers reported findings from the first of a number of studies investigating lip and tongue pressure. A strain gauge design was used to record lip and tongue pressure in a group of 25 young adult males (22-32 years) at rest and during swallowing on the upper centrals and upper first molars. Care was taken to ensure the recommendations on sensor thickness were followed. Negligible resting lip pressure was recorded in all but two subjects. Most individuals demonstrated light (<20g/cm^2) lip pressure on swallowing, however three subjects showed heavy (50-150g/cm^2) pressure. In general, lower resting lip pressures were found than had previously been reported, which Proffit concluded was due to the decreased distance of the strain gauge transducer from the tooth surface.

Subsequently, Proffit went on to study oral pressure among Australian Aborigines (Proffit, 1975a; Proffit *et al.*, 1975b), whose dental arches were much larger than individuals of European descent. It was initially thought that the Aboriginal group would show either increased tongue pressure or decreased lip pressure at rest and that this would explain the increased arch width seen in this subject group. However, at rest, the Aboriginal subjects showed decreased resting tongue pressures when compared with a North American control group, while lip pressure was comparable.

Swallowing pressures among the Aboriginal group were also decreased compared with the controls. It was concluded that there was an inverse relationship between arch dimensions and tongue pressure, and that heavy tongue pressure and/or decreased labial pressure was not the reason for the increased arch size (Proffit *et al.*, 1975b).

In 1978, Proffit published a landmark paper on the equilibrium theory. He postulated that as the teeth remain in a stable position most of the time in most people, and since tooth movement is observed when additional forces are added to the oral environment (i.e. a poorly fitting partial denture or a contracting scar after an injury), the teeth are in an equilibrium that can be disrupted. However, as stated above, investigators have not found a state of balance between the two muscular systems, with the tongue consistently exerting more force during function and at rest (Figure 2-3).

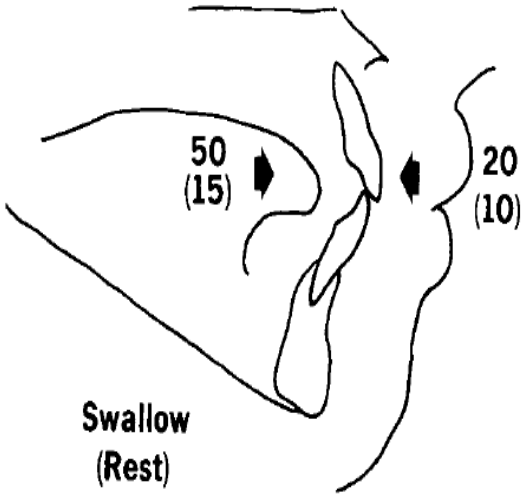


Figure 2-3: Diagrammatic representation of tongue and lip pressures during swallowing and at rest. Tongue pressure is greater than lip pressure in both instances (Proffit, 1978).

Proffit concluded that tooth position could not be explained purely as a position of balance between tongue and lip pressures, and suggested that other forces must be involved in maintaining equilibrium, such as forces from the dental occlusion and the periodontal ligament (Table 2-2).

Primary factors in equilibrium	
Intrinsic forces	From the tongue and lips
Extrinsic forces	Habits, orthodontic appliances
Forces	From the dental occlusion
Forces	From the periodontal ligament

Table 2-2: Examples of forces involved in maintaining dental equilibrium (Proffit, 1978)

As stated in Table 2-2, extrinsic forces are one of the primary factors that determine tooth position. It has been suggested that extrinsic forces on the teeth are capable of causing tooth movement when the duration is more than six hours per day (Proffit *et al.*, 2006). It is likely the high strength, short acting forces, such as those generated during speaking or swallowing, play only a minor role in establishing dental equilibrium, as the total duration of these forces is in the order of minutes per day (Proffit, 1978). Long acting forces, such as pressure from the lips and tongue at rest, seem to be more important in determining the position of the teeth (Proffit *et al.*, 2006).

2.2.2 The role of the soft tissues in orthodontic stability

Prior to the 1960s it was assumed that the muscles did not adapt to changes in the contour of the dental arch, and that this lack of adaptation accounted for relapse after orthodontic treatment (McNulty *et al.*, 1968). It was argued that when teeth were moved orthodontically to a new position, they impinged on the soft tissue space and became subject to an unbalanced set of forces from the lip or tongue. The muscles then generated forces which moved the teeth back towards their original

position (Jacobs, 1969), which was seen clinically as orthodontic relapse. To further understand this concept, it is essential that orthodontists understand the behaviour of the surrounding oral musculature in response to lower incisor movement.

In an attempt to do this, a number of studies have been completed over the years. McNulty *et al.* (1968) measured lip pressure changes in the maxillary central incisor region with normally contoured and protrusive partial dentures. When the protrusive denture was initially inserted, an instant increase in lip pressure was recorded. However, after a week of wearing the protrusive denture, the lip pressure forces had decreased in all patients, and frequently were equal to the pressures measured at baseline. It was concluded that the musculature was able to adapt to the new incisor position over time, and that the stability of the post-treatment result may be related to whether an individual's musculature accommodates to the new tooth position.

Soo and Moore (1991) investigated the response of the lower lip to a mandibular lip bumper appliance over an eight-month period. The authors found that the pressure generated at the midline was increased after one month, but that this decreased to near or below pre-treatment levels at the end of the eight months. Like McNulty *et al.*, the authors believed this indicated the lip musculature has the ability to adapt to a new position.

To further examine this concept, a series of experiments investigating the response of the lower lip musculature to advancement was completed in the mid-90s (Moawad *et al.,* 1996; Shellhart *et al.*, 1996). It was hypothesised that by simulating lower incisor advancement using acrylic stents, changes in lip pressure could be recorded. Initially, it was proposed that expanding the dental arch anteriorly would lead to an increase in pressure on the teeth from the lips, and that unless tongue pressure increased to balance this, or lip pressure eventually decreased, these forces could eventually cause changes in the position of the teeth (Moawad *et al.*, 1996).

In the initial study (Moawad *et al.,* 1996), 22 subjects (mean age 23.3 years) with Class I occlusion were selected, and baseline pressures were measured at the lower midline and lower right canine with a thin, plastic stent in place. A stent that simulated 2.5mm labial expansion was then inserted, and pressures were re-measured at the same sites. Each participant wore the expanded stent full-time for one week, and then returned to have pressure measured at the same sites with the expanded stent in place.

The mean pressures recorded are outlined in Table 2-3. It can be seen that their lip pressure increased significantly when the expanded stent was first placed. After a week, the lip pressure had decreased at the midline, so that it was no longer significantly different from the baseline reading. There was no such decrease for the canine, suggesting that there may be an adaptation response that differs according to location.

	Baseline pressure	Initial extended	1 week extended
Midline pressure	7.5 ± 6.9	13.7 ± 6.9	9.6 ± 6.2
Canine pressure	4.6 ± 4.4	9.4 ± 8.3	9.7 ± 6.6

Table 2-3: Lip pressure values (g/cm^2) at baseline; at initial with 2.5mm lower lip advancement; and at one week with 2.5mm lower lip advancement (Moawad *et al.*, 1996).

The same authors then carried out a further study to investigate the adaptation response over a six-month period (Shellhart *et al.*, 1997). A stent simulating 2.5mm labial expansion was placed and again, the lip pressure increased initially. Each participant then wore the expanded stent full-time for six months. Again, the midline pressure adapted more quickly than the canine pressure, but the pressure at both locations returned to pre-expansion pressures within the first month. It was suggested that the

reason for the different timing of adaptation may be due to differences in the anatomy of the musculature. The muscular anatomy at the midline is relatively simple, with only the orbicularis oris and mentalis muscles involved. In contrast, pressure on the canine comes from the modiolus, where the fibres of a number of muscles intersect (Norton, 2007). It is thought that the increased muscle complexity in the canine area may lead to a delay in muscle adaptation (Shellhart *et al.*, 1997).

2.2.3 The role of oral musculature in the development of malocclusion

The role of the soft tissues in the development of malocclusion is another area that has warranted much investigation over the years. Gould and Picton completed one of the earlier investigations in the late 1960s. Participants with Class I occlusion (controls from a previous study) were compared with subjects with Class II division 1 (Class II/1), Class II division 2 (Class II/2) and Class III malocclusions. Pressure on the upper and lower first molars, first premolars and central incisors was measured. More pressure was found on the lower central incisors than the upper centrals in all subject groups. The highest pressures were recorded at the upper premolar site which was considered to be due to the position and action of the modiolus muscle (Gould and Picton, 1968).

In an attempt to determine the relationship between lip strength and lip pressure, 84 children with varying types of malocclusion were recruited (Thüer and Ingervall, 1986). Lip strength was assessed using a pommeter which consisted of a mouthpiece connected to a dynamometer that recorded traction force in grams (Figure 2-4). Participants were asked to hold the mouthpiece between their lips and resist the pull of the dynamometer, giving a reading for the maximum possible pressure generated by the lips. Electromyographic (EMG) activity of the lips was also measured.



Figure 2-4: Use of a pommeter to record maximum lip strength (Thüer and Ingervall, 1986)

Pressures on the upper and lower central incisors were measured using the hydraulic system described above in Figure 2-4 (Thüer and Ingervall, 1986). Lip strength tended to increase with age, and be lower in children with a large overjet, proclined incisors, or an Angle Class II jaw relationship, although this may have been due to measurement difficulties. It was noted that children with Class II jaw relationships or increased overjet had to protrude their lower jaw forward, thus creating an unstable occlusal position, which did not allow them to generate the same amount of lip pressure as a Class I individual. Upper lip pressure was found to be the lowest among children with a Class II/2 incisal relationship with a mean resting upper lip pressure of -1.4 g/cm^2. Lower lip pressure was greatest in the Class II/2 group and least in the Class II/1 group. No correlation was found between lip strength and lip pressure. The authors concluded that there were two possible explanations for the lack of correlation between the two variables. Firstly, the two may truly be independent of each other. Or, secondly, both variables have large biologic intra-individual variation, which would greatly reduce the likelihood of demonstrating an association

between the two. It should also be noted that both the lip strength and lip pressure recordings had large experimental errors.

In 2002, Lapatki and co-workers continued the investigation into lip pressures among Class II/2 individuals. Lip pressure on both the upper and lower centrals was measured at the gingival margin and the incisal edge in Class I and Class II/2 subjects (Figure 2-5). This allowed a pressure differential between the two sites to be measured in both groups. EMG activity of the upper and lower lips was also recorded.

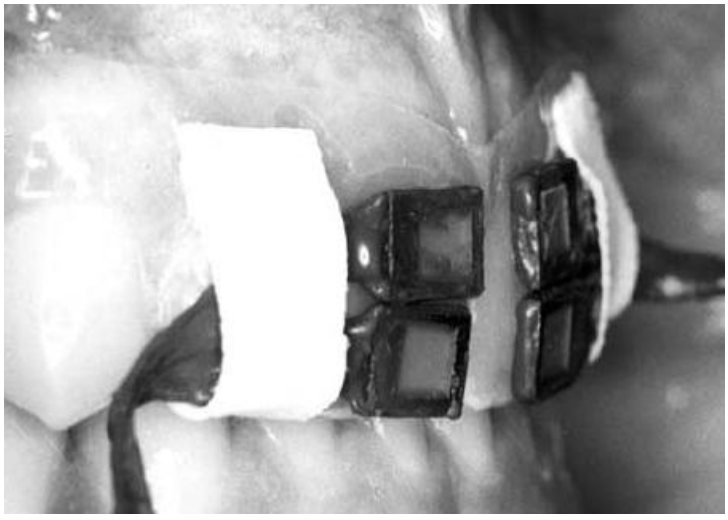


Figure 2-5: Position of pressure transducers on central incisors to detect the pressure differential between sites (Lapatki *et al.*, 2002).

In Class II/2 individuals the pressure at the gingival margin was negative, while the pressure at the incisal edge was positive. This finding agrees with above (Thüer and Ingervall, 1986), where negative resting pressure on the incisors was also found. However, in the earlier study, pressure was only measured at the gingival margin, so the pressure gradient demonstrated by Lapatki and co-workers (2002) was not detected. The pressure gradient was reversed in Class I participants (positive at the gingival margin and negative at the incisal edge). This study seems to indicate that it is the pressure redistribution seen in Class II/2, with more pressure from the lower lip on the incisal edges, which causes the central incisors to retrocline. No difference in EMG activity was seen between the two groups,

hence it was concluded that the retroclined upper central incisors in Class II/2 individuals is due to differences in pressure rather than differences in the resting muscle tone of the circumoral musculature (Lapatki *et al.,* 2002).

Di Fazio and co-workers (2011) used a force sensing resistor device (Figure 2-6) to evaluate pressure on the maxillary central incisors in Class I and Class II skeletal subjects. They demonstrated pressures higher than previously reported, with a mean recording of 24.59 ± 2.55 g/cm^2. No significant differences were found in pressure between Class I and Class II individuals; however, no separation was made between Class II/1 and Class II/2 individuals in the Class II group which may have influenced the results seen.



Figure 2-6: Example of force sensing resistor device used to record resting labial pressure at the upper midline (Di Fazio *et al.*, 2011).

2.3 Electromyography (EMG) activity of the oral musculature

2.3.1 Lip competency

In an individual with competent lips, the lips are held in contact without clinically distinguishable muscular activity of the lips (Yamaguchi *et al.*, 2000). In contrast, an individual with lip incompetence requires distinguishable activity of the lower lip and unusual movement of the tongue to close the lips (Gustafsson and Ahlgren, 1975). A diagnosis of lip competency may be made on the basis on clinical on EMG findings. The

former is based on the lips being in contact in rest position with no apparent lip strain. However, visual estimation of circumoral muscular activity may be less reliable as very slight contraction of the lip musculature can be difficult to detect. For this reason, a diagnosis of lip incompetency may also be made on the basis of circumoral muscle EMG activity at rest (Yamaguchi *et al.*, 2000).

Burstone (1967) found that patients with shorter lips, increased vertical dimension or large anteroposterior dental discrepancies had increased interlabial gaps which required significantly more effort from the lips, particularly the lower lip, to achieve oral seal. More recently a number of EMG studies have investigated the importance of each of these factors in lip incompetency.

Simpson (1976) recorded EMG activity of the mentalis and suprahyoid muscles in patients with Class II/1 malocclusion and clinically incompetent lips. Subjects with a large ANB and/or large overjet had increased EMG activity in both muscle groups, while no correlation with increased vertical height was found. It was concluded that the upper lip played a passive role in these patients, and maintenance of anterior oral seal was dependent on the mentalis muscle pushing the lower lip up and forward, while the tongue was brought forward by the suprahyoid group of muscles. This agrees with the findings of Marx (1965) who found greater mentalis muscle activity in subjects with an ANB greater than 4°, when compared with a control group with an ANB of 2-4°.

Gustaffson and Ahlgren (1975) found that vertical relations of the jaws and anterior face height also had a decisive influence on lip posture and perioral muscle activity. An increased lower anterior face height was associated with increased mentalis EMG activity. The authors concluded that orthodontic treatment in subjects with incompetent lips should focus on influencing vertical and horizontal skeletal patterns in an attempt to improve lip competency.

Yamaguchi *et al.* (2000) completed a similar study comparing subjects with positive overjet and overbite to a group who had a skeletal open bite. Interestingly, EMG activity of the mentalis muscle was more indicative of lip sealing than EMG activity of the upper and lower lips, indicating that EMG of the mentalis muscle with lips together may offer an objective criterion for assessing lip competency.

2.3.2 EMG activity in mandibular rest position

The mandibular rest position (MRP) has been defined as the position "in which the mandible is involuntarily suspended by the reciprocal coordination of the muscles of mastication and the depressor muscles, with the teeth separated" (Ballard, 1955). The nature of masticatory muscle activity found in MRP has been well studied over the years, with the objective to define whether clinical methods of determining MRP coincide with minimal electrical activity in the muscles of mastication.

Jaraback (1957) induced MRP phoenetically in both dentate and edentulous subjects, and found that MRP corresponded with electrical silence in both the mandibular elevator and depressor muscles. Participants were then asked to slowly close and open their jaws, and the masseter and temporal muscles remained electrically silent until occlusal contact was made. This finding suggested that the mandibular elevator muscles were electrically inactive over a range of vertical dimensions, rather than at just one position. Similar studies by Hickey *et al.* (1961) and Feldman *et al.* (1987) concurred with these findings.

In 1981, Manns *et al.* further investigated EMG activity in postural muscles at varying vertical dimensions. It was found that on increased jaw opening, masseter and temporalis activity first declined to a point where minimal EMG activity was reached, which was followed by increased muscle activity as the jaw was opened wider. The anterior temporalis muscle showed minimal activity over a wide range of vertical dimensions, where the masseter muscle showed minimal activity over a much narrower range. In

both muscles, minimal activity was found to correspond to a face height which was significantly greater than at clinical rest position.

Michelotti *et al.* (1997) recorded EMG activity in the masseter and anterior temporalis muscles in a group of 40 subjects. Each subject had a lateral cephalogram taken and a low angle group of eight subjects (mandibular plane angle ≤20 degrees), and a high angle group of eight subjects (mandibular plane angle ≥28 degrees) were selected. The remaining subjects were used as a control group. EMG activity was measured at varying vertical dimensions, and it was found that EMG activity tended to decrease until the jaw was opened 3-4mm, at which point the EMG activity increased (Figure 2-7). The average difference between electromyographic rest position and clinical rest position was 6.3 ± 2.5mm (range 0.3 to 10.3mm). Interestingly, clinical rest position was significantly greater in the low angle group (2 ± 1.3mm) than the high angle group (0.8 ± 0.8mm), whereas no statistically significant difference was seen in electromyographic rest position between the two groups. These findings suggest that the MRP and the position of minimal muscle activity as determined by EMG do not seem to coincide (Watkinson, 1987).

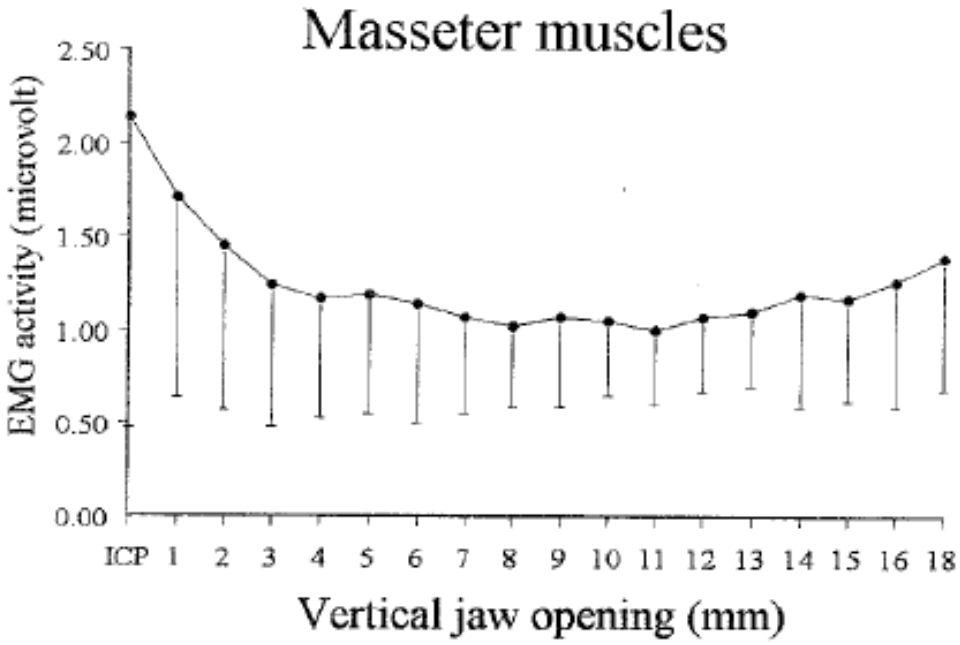


Figure 2-7: Mean values and standard deviations of masseter EMG activity in 40 subjects. There was a considerable decrease in EMG activity over the first 3-4mm of opening, after which the decrease leveled out before gradually increasing again (Michelotti *et al.*, 1997).

2.3.3 Circumoral EMG activity

The effect of different skeletal and dental relationships on circumoral EMG activity has been extensively investigated. Marx (1965) assessed the orbicularis oris and mentalis muscle activity in Class I, Class II/1, Class II/2 and Class III individuals. He reported that 78% subjects had circumoral EMG activity while in habitual rest position. There was no difference in activity between Class I and Class II/1 subjects, although Class II/2 subjects had decreased EMG activity of the lower orbicularis oris muscle. Ahlgren *et al.* (1973) and Lowe *et al.* (1983) have also found no difference in circumoral EMG activity between Class I and Class II/1 individuals.

In the mid-80s, Lowe and co-workers studied circumoral muscle activity in subjects with different occlusions. In an initial study, orbicularis oris activity was measured in Class II/1 subjects. A constant baseline EMG activity of the lower orbicularis oris muscle was recorded in mandibular

rest position. This was then compared with EMG activity with the teeth in maximum intercuspation. No statistically significant difference in EMG activity was seen between the two jaw positions (Lowe *et al.,* 1983).

In a further study involving Class I, Class II/1 and Class II/2 subjects, much greater orbicularis oris activity of the lower lip was seen in the Class II/2 individuals at rest, in maximum intercuspation and during jaw opening (Lowe and Takada, 1984). The authors concluded that this provides evidence of the importance of jaw posture as a possible determinant of tooth position. This is in contrast to other authors who have reported either similar (Lapatki *et al.*, 2002) or decreased (Marx, 1965) EMG activity of the lower lip in Class II/2 individuals compared with Class I controls.

Lip incompetency also affects the amount of circumoral EMG activity seen. Tosello *et al.* (1998, 1999) investigated individuals with clinically competent and incompetent lips. Only the incompetent subjects showed orbicularis oris and mentalis EMG activity in MRP, while subjects with competent lips had no EMG activity in these muscles at rest. The incompetent lips group also had more muscle activity during swallowing, with the lower orbicularis oris muscle showing the most EMG activity. A number of other authors have also found increased circumoral EMG activity in subjects with incompetent lips (Gustaffson and Ahlgren, 1975; Ahlgren *et al.*, 1973; Yamaguchi *et al.,* 2000).

The role of circumoral muscle activity in determining incisor inclination is controversial. Marx (1965) found that proclined incisors (both upper and lower) led to increased amounts of orbicularis oris and mentalis muscle activity. However, he concluded that resting posture did not affect the position of the incisors, but that the muscle activity seen is secondary to the position of the incisors. In contrast, Simpson (1976), Janson and Ingervall (1982) and Lapatki *et al.* (2002) found no relationship between incisor inclination and EMG activity of the lips.

2.4 Swallowing

Swallowing is normally associated with light closure of the teeth and contact of the lips without marked lip contraction. During swallowing, the floor of the mouth is raised and the tongue is compressed against the anterior palate in order to clear the mouth of saliva (Peng *et al.*, 2004).

In neonates, the tongue lies in a more forward position at rest, and when feeding, the tongue is placed against the lower lip. The tongue forms a furrow that allows the milk to flow posteriorly (Proffit *et al.*, 2006). The maturation to an adult swallow occurs at around age six for most children, and by age nine only 25-30% of the population swallow with a tongue thrust (Fletcher *et al.*, 1961). Sometimes, this infantile tongue to lip activity may progress into adulthood with active contraction of the tongue and lips against each other, with associated lowering of the mandible to accommodate this behaviour (Freer and Ho, 2009). It has been noted that a transitional "tongue thrust" type swallow persists into adulthood in 10-15% of the population (Proffit *et al.*, 2006).

2.4.1 Labial pressure generated during swallowing

Early studies investigating oral pressure generated during swallowing found no noticeable rise in labial pressure in subjects where the anterior teeth could be brought into occlusion (Winders, 1958). The only instance where the labial musculature was contracted during swallowing was when an anterior open bite was apparent and the lips were contracted to gain anterior oral seal. In each of these cases, a tongue thrust swallow was also seen.

Later studies by Kydd *et al.* (1963), Gould and Picton (1964), Proffit *et al.* (1964) and Luffingham (1969) all disagreed with this finding, recording a distinct rise in labial pressure on swallowing. As discussed above, Proffit *et al.* (1964) found light labial pressure on swallowing in most subjects ($<20 g/cm^2$), although one individual generated a relatively heavy pressure of $150 g/cm^2$. Lingual pressure was also investigated and asymmetric

tongue pressure during swallowing was the rule during an individual swallow, with most subjects generating heavier pressure on the left side.

In 1969, Proffit *et al.* researched swallowing behaviour in children. Pressure was measured lingual to the central incisors and opposite the deciduous second molars on the hard palate in children five to eight years of age. Again, asymmetric swallowing behaviour was seen in all individuals, with most children having more pressure on the left than on the right.

A group of 18 adolescent Australian Aborigines were investigated in a later study (Proffit *et al.*, 1975b), and as part of the investigation pressures generated during saliva and water swallowing were compared. A rise from resting lip pressure on swallowing was noted in all subjects, and lip and tongue activity during swallowing lasted for approximately the same amount of time. As noted above, smaller tongue pressures were generated than in a comparable sample of North American males, so it was concluded that heavy tongue pressures were not the reason for the expanded dental arches seen in the Australian Aborigine sample group.

2.4.2 The role of swallowing in the development of malocclusion

The forces produced by the oral musculature during swallowing are complex and controversy surrounds the effect that these forces has on the development of malocclusion. An example of this is the tongue thrust swallow. As stated earlier, in normal swallowing, the tip of the tongue rests at the anterior palate and contraction of the perioral musculature is usually minimal while the posterior teeth close into momentary contact. In a tongue thrust swallow however, the tongue comes forward to contact the lower lip, there is increased perioral muscle contraction and an absence of tooth contact (Proffit et al., 2006).

The possible deleterious effects of the tongue thrust swallow were well reported during the 1950s and 1960s. Winders (1958) found that all the subjects with an anterior open bite also demonstrated a tongue thrust swallow. He argued that the tongue thrust swallow was a primary cause of

anterior open bite. It was concluded that, this was a retained infantile swallow reflex in which the tongue thrust did not allow the anterior teeth to erupt, and that the tongue thrust swallow was the cause not the result of an anterior open bite. He found no evidence for increased labial pressure on swallowing or of a tongue thrust swallow in the subjects with Class II dental relationships in the presence of adequate overbite.

Kydd *et al.* (1963) investigated lip and tongue pressure on the maxillary central incisors on two patient groups. One group contained anterior open bite patients who had maintained good overbite one year into retention (control group), while the other group had had relapse of the open bite (relapse group). The relapse group exhibited twice as much mean tongue pressure as the controls during swallowing and had only 65% as much labial pressure. It was also found that the relapse group also applied lip and tongue pressure on swallowing for longer than the control group, with the lip always applying pressure first. It was suggested that these differences in swallow behaviours might play a role in relapse of an anterior open bite following orthodontic treatment.

Gould and Picton (1968) studied the amount of labial pressure generated in subjects of different occlusions. The pressure on both the upper and lower centrals was greater in the swallow in the Class II/1 group than either of the other groups. This is in contrast to the findings of Winders (1958) who found no correlation between swallowing pressure and anteroposterior position of the teeth. The heavier pressure generated by the Class II/1 group was thought to be because of varying degrees of lip competence in this patient group. This meant that there was often forward movement of the mandible and adaptive movement of the lips to achieve oral seal. Luffingham (1969) carried out a similar study and again found increased labial swallowing pressure in subjects with increased overjet.

Thüer and Ingervall (1986) completed a study investigating at rest and swallowing pressure in children with different malocclusions. Although they found significantly higher pressures in children with an increased

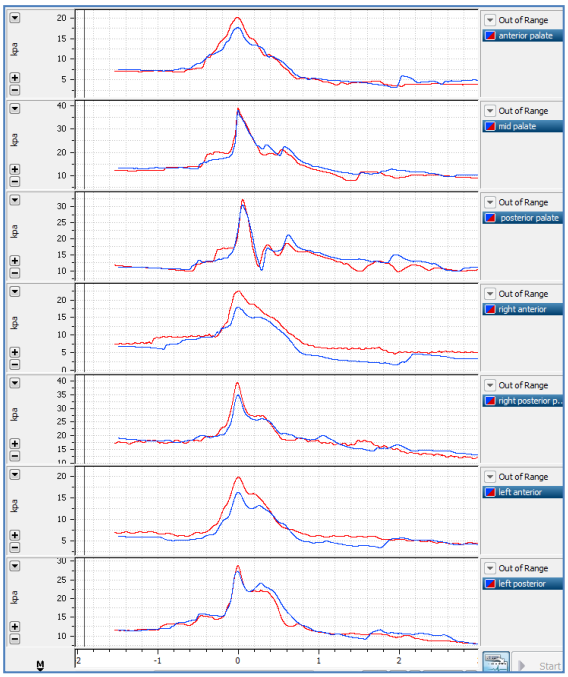
overjet at rest, no statistically significant difference was seen between the groups in labial pressure on swallowing. Di Fazio (2011) also found no difference in labial pressure generated during swallowing in Class I and Class II occlusions.

In subjects with an anterior open bite or an increased overjet it is more difficult to maintain anterior oral seal while swallowing, and a tongue thrust swallow is a physiological adaptation that prevents fluids escaping. It seems most likely that a tongue thrust swallow appears as either a transitional phase between infantile and a mature adult swallow (Proffit, 1972) or in the presence of an increased overjet or anterior open bite where the behaviour is an adaptation to the space between the teeth (Proffit *et al.*, 2006). It is estimated that we swallow approximately 600 times per day (Lear *et al.*, 1965), which, if each swallow lasts for approximately one second, only amounts to pressure on the teeth from swallowing for approximately 10 minutes a day. In light of the equilibrium theory, it seems unlikely that a tongue thrust swallow is the cause of malocclusion, but rather, that it is an adaptive response that allows anterior oral seal to be maintained (Proffit *et al.,* 2006).

2.4.3 Individual swallow pattern

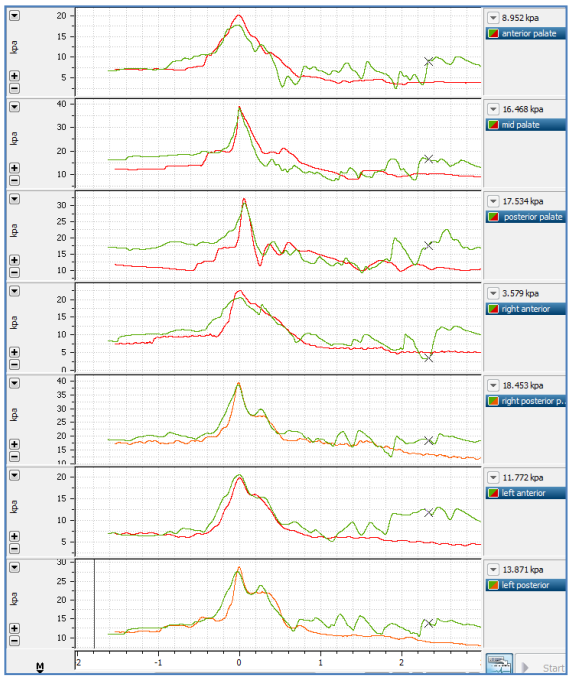
Although there is considerable evidence of inter-individual variation on swallowing (Shaker *et al.,* 1988; Proffit *et al.*, 1969), research investigating intra-subject variation has found that each person has a remarkably reproducible swallow profile (Kennedy *et al.,* 2010; Proffit *et al.* 1969; Peng *et al.,* 2007). Kennedy and co-workers (2010) found that individuals had similar swallow profiles which were highly reproducible over five consecutive days. Each swallow was similar in the peak pressure generated, timing of swallow and polarity of the swallow event. Proffit *et al.* (1969) also found this when they investigated swallow behaviour in children aged five to eight years. The pattern of swallow was consistent for each child, and an individual pattern was so distinctive, that the authors were able to identify each child from their swallow pattern alone. Farland

(2011) investigated the effect of changes in bolus viscosity in a group of young, healthy subjects on the timing and pattern of swallow generated across the palate. He also found this unique individuality of swallow was evident, not only in timing and polarity of the swallow, but also in how these factors changed with alterations in bolus consistency (Figure 2-8).



Water = Blue Mizone® =Red

Figure 2-8: Pressure profile overlay comparisons of seven sensor channels on the hard palate during one swallow for one participant. The graph outlines the difference between water and Mizone®. Note the similarities in pressure profiles with changes in bolus taste (Farland, 2011).



Mizone® =Red Honey = Green

Figure 2-9: Pressure profile overlay comparisons of seven sensor channels on the hard palate during one swallow for one participant. The graph outlines the difference between water and honey. Note the similarities in pressure profiles with changes in bolus viscosity (Farland, 2011).

3 Methodology

3.1 Purpose of this study

The so-called equilibrium theory suggests that orthodontic treatment should not compromise muscular balance and that, excessive labial displacement of incisors is unlikely to be stable if it interferes with this equivalence. However, many orthodontic patients are treated by advancing the arches labially, with long-term stability reported in many cases (Houston and Edler, 1990). One area that has had minimal investigation however, is the short term response of the lip musculature responds to incremental advancement. The present study will focus on the effect of tongue and lip pressures in patients with incremental advancement of the lower lip both at rest and during functional activities. Electromyographic (EMG) data will also be recorded during these tasks in an effort to evaluate the response of lip muscle activity to this incremental advancement.

3.2 Principal research questions

1. What is the effect of incremental lower lip displacement on lip pressure?
2. Is there a difference in lip pressure generated at the canine compared with the midline?
3. Does EMG activity change as the lower lip is advanced?
4. Does mandibular rest position (teeth together or teeth apart) affect lip muscle activity?
5. Is more pressure generated by the lower lip when anterior oral seal is challenged?
6. How does advancing the lower lip during swallowing affect the amount of work done by the tongue and the time taken to swallow?

3.3 Research hypotheses

1. That the lower lip pressure increases in a linear fashion as it is incrementally displaced.
2. That more labial pressure would be generated at the canine than at the midline.
3. That EMG activity in the lower lip will increase linearly as the lower lip is advanced.
4. That mandibular rest position will not affect the amount of EMG muscle activity.
5. That more lip pressure will be needed to achieve an oral seal for swallowing with incremental labial advancement.
6. That the work done by the tongue and the time taken to swallow will also increase as the lower lip is advanced.

3.4 Ethical approval

The study protocol fully complied with the principle of the Helsinki Declaration and was approved by the University of Otago Ethics Committee. All participants were paid NZ$100 for taking part in the study.

3.5 Study design

3.5.1 Sample

A convenience sample was used where participants were recruited via an advertisement on Faculty of Dentistry notice boards and on a student job website. Ten participants were recruited in total, with eight females and two males.

3.5.2 Inclusion criteria

A number of authors have found no sex difference in oral pressure or EMG activity of the lower lip between subjects (Thüer and Ingrevall, 1986; McNulty *et al.*, 1968; Gould and Picton, 1964; Ingervall and Janson, 1981); therefore, it was decided not to analyse the participants on the basis of sex.

Participants were healthy, with no history of dysphagia or neurological disorders, and were willing to participate in the study. All subjects were over the age of 18 years, and were of caucasoid ethnicity.

3.5.3 Exclusion criteria

Participants with an overjet greater than 4mm or less than 2mm, or an overbite less than 10% or greater than 80% were excluded. The absence of more than two teeth (with the exception of third molars) were also criteria for exclusion from the project.

3.5.4 Initial clinical examination of subject group

Initially, a questionnaire and clinical examination was completed to ensure that the participants met the selection criteria for the experiment. A profile photograph was taken to verify the vertical relationship of the jaws and to record soft tissue profile (Figure 3-1). One subject (subject 7) had a dolichofacial jaw relationship, all others participants were mesiofacial. It was also recorded whether the patient was lip competent or -incompetent. Lip incompetency was defined as visible mentalis action required to achieve lip seal (Gustafsson and Ahlgren, 1975). Three of the subjects included had clinically incompetent lips (subjects 3, 4 and 7).



Figure 3-1: Example of profile photograph taken to act as a record of vertical and soft tissue pattern.

A standard clinical orthodontic examination was undertaken to record overjet, overbite and molar classification (Angle, 1907).

3.6 Stent fabrication and design

3.6.1 Pressure transducers

Intra-oral pressure was assessed by means of miniaturised pressure sensors (type 105S, Precision Measurement Company (PMR), Michigan, USA) with stainless steel diaphragms (Figure 3-2). The sensors were small with a low profile (thickness of 0.508mm and a diameter of 2.67mm), and they were used to measure absolute pressure (0-420kPa). The sensors were designed to detect pressure changes from the oral musculature, and to transmit these raw input signals in the form of analogue voltage.

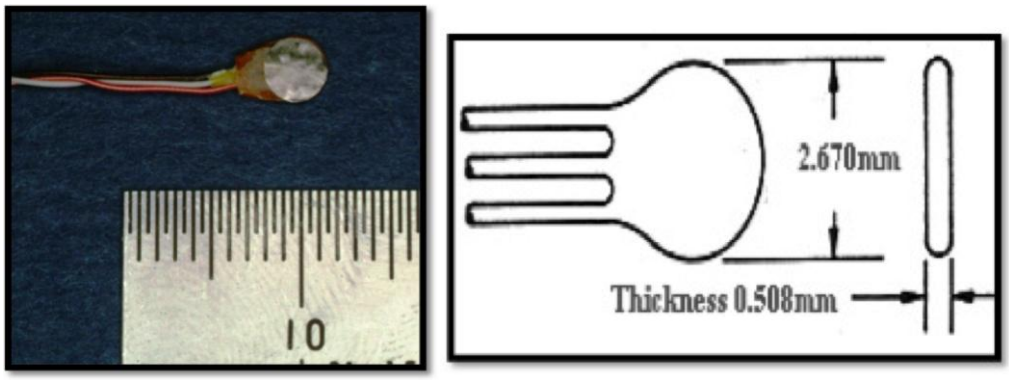


Figure 3-2 - Dimensions of type 105S pressure sensor.

3.6.2 Stent design and sensor location

The sensors were embedded in vacuum formed stents (VFS) (Duran, Scheu Dental, Germany) which provided a thin, relatively rigid platform for the measurement of pressure at four simultaneous locations. They were placed 4mm from the occlusal surface on the labial and lingual surfaces at the midline (between the lower right and left central incisors) and 5mm from the occlusal surface on the labial and lingual surface of the right canine. The slightly increased distance from the occlusal surface on the canine was to compensate for the increased height of the canine crown. This ensured the standardisation of the midline and canine sensor height. Gould and Picton (1962) have shown that the pressures on the right side of the dentition approximate the pressures on the left, so it was considered appropriate to record pressure on one side of the dentition only. As the function of a strain gauge is affected by temperature, a thermocouple adaptor (Isotech ITAII, ADInstruments, NSW, Australia) was also placed on the VFS on the labial surface of the lower left canine to measure intra-oral temperature. The initial sensor and thermocouple location used for the pilot study is shown below (Figure 3-3).

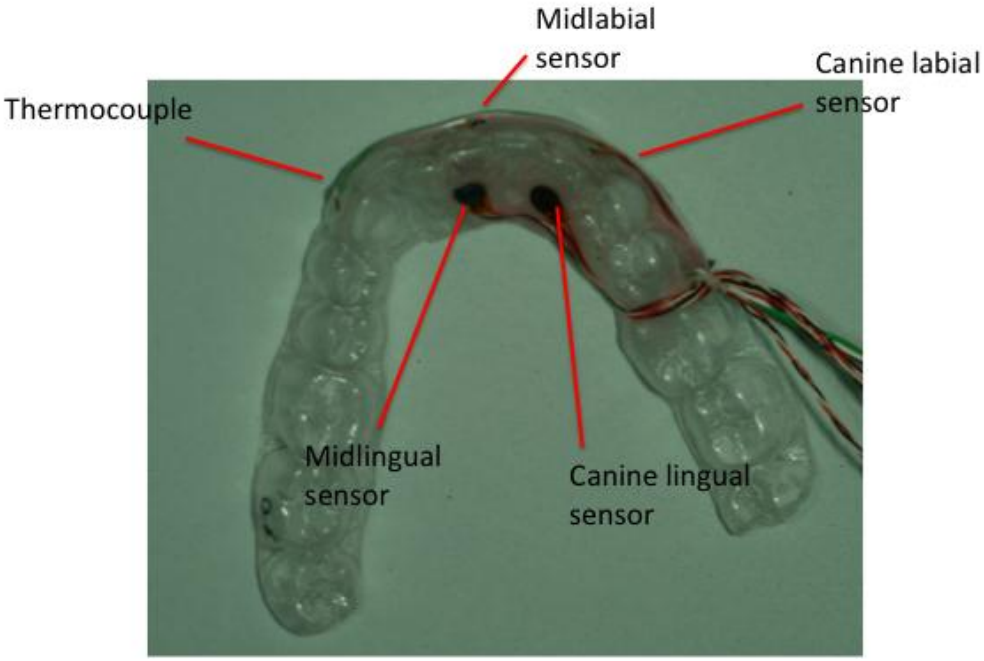


Figure 3-3: Initial sensor and thermocouple location for pilot study.

During the pilot study, the location of the sensors necessitated that the leads from the sensors exited the mouth at the commisure on the right hand side, which compromised the maintenance of an accurate oral seal in this area. This led to difficulties in recording accurate pressure readings on the labial surface of the lower right canine. For this reason the position of the labial canine sensor and the thermocouple had to be swapped. The final sensor location and design is demonstrated in Figure 3-4. Due to technical difficulties, the use of the thermocouple to record temperature was abandoned.

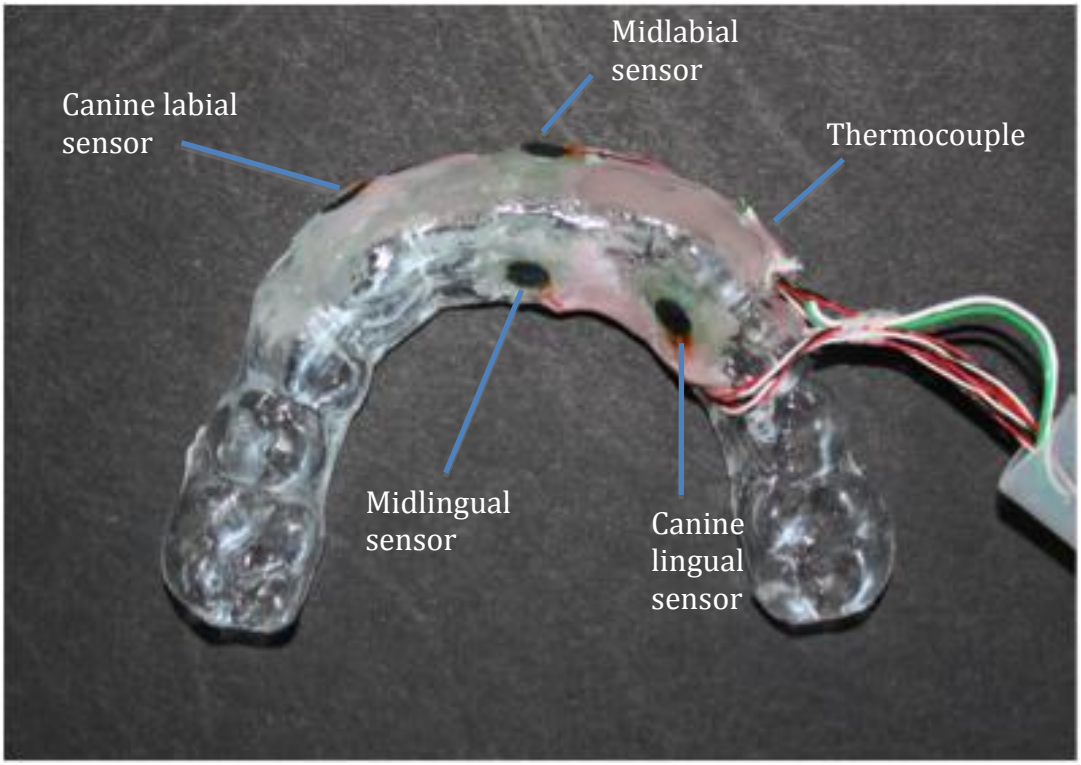


Figure 3-4: Final sensor and thermocouple location.

3.6.3 Stent fabrication and sensor placement

Impressions of the subject's maxillary and mandibular teeth were taken in stock trays using alginate impression material (Kromopan ISO 1563, Class A, type 1, Italy) from which stone casts were poured. Thin, clear, plastic stents (Duran, Scheu Dental, Germany) were constructed on the stone casts, with three stents constructed for each participant. The stent material covered the crowns of the lower teeth, except for the second and third molars. The first stent was constructed with stent material of 0.5mm thickness on all surfaces (Figure 3-5).



Figure 3-5: Baseline VFS which was constructed with 0.5mm thickness stent material on all surfaces.

The second stent had layers of acrylic (Vertex Castapress, Vertex, The Netherlands) added to the labial surface from the lower right to lower left canine to increase its thickness to 2.5mm. The stent material on all the other surfaces remained 0.5mm thick. The third stent had acrylic added to the lower labial surface as above, but to 4.5mm thickness (Figure 3-6).

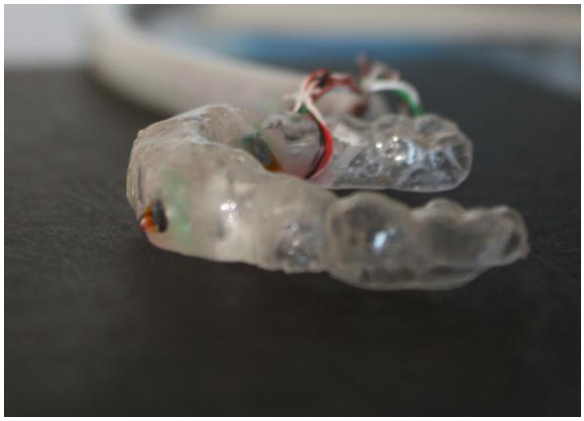


Figure 3-6: 4.5mm VFS with Vertex Castapress acrylic built up on labial surface from the lower left to right canine.

A recessed housing for each sensor and its corresponding wires was placed in each of the sensor locations to ensure standardisation of location and to allow the surface of the sensor to lie flush with the stent surface. However, during the pilot study it was found that having the sensor surface flush with the stent surface made pressure readings difficult. For the following

experiments the well was filled with pink dental wax (Kemdent, UK) so the wax was flush with the stent surface. A layer of 0.3mm casting wax (Bego, Germany) was placed on top of the pink wax to standardise the distance of the sensor from the stent surface. The sensor was then carefully secured using pink dental wax around the edges and along the corresponding wires. A careful inspection was then made to ensure any excess wax was removed from the sensor surface. A digital caliper was used to confirm that the sensor was less than 2mm from the stent surface (Gould and Picton, 1962). Finally, the wires were secured with dental floss to the retention clasp located adjacent to the lower right canine. Once the stent was in the mouth, the wires exited the mouth at the right labial commisure (Figure 3-7) to decrease the interference with lip posture.



Figure 3-7: Example of wires exiting the mouth from the right commissure.

3.7 Electromyography recording

An EMG amplifier (Octal Bioamp, ML138, ADInstruments, NSW, Australia) was used to record muscle activity of the lower lip at the midline. The

recorder had two channel inputs, which were band-pass filtered at 20-1000Hz and band-stop filtered at 40-60Hz. For analysis, the root mean square of the filtered EMG signal was found using the arithmetic function of the LabChart Reader 7.0.2 software (ADInstruments Pty Ltd, NSW, Australia).

At the beginning of each recording session, the facial skin overlying the lower lip was vigorously cleaned with Briemarpak® 70% isopropyl alcohol swabs (Briemar Nominees Pty Ltd, Australia). Male subjects were also shaved if facial hair was observed. This step was essential in removing skin oil and dead skin to improve signal conduction. Two surface pre-gelled self-adhesive EMG electrodes with a 20 x 15mm pad (Alpine Biomed, Denmark) were positioned on the lower lip on either side of the dental midline. An EMG electrode (MLA 1010, ADInstruments Pty Ltd, NSW, Australia) was also placed behind the right ear in the mastoid area to act as a ground electrode (Figure 3-8A and B). The electrodes were connected to the EMG amplifier using MLA 0310 1.8m unshielded lead wires (ADInstruments Pty Ltd, NSW, Australia). Finally, the lower lip sensors were secured using Leukoplast porous tape (1.25cm width) (Smith & Nephew, United Kingdom), while taking care not to secure so tightly that lip mobility was impaired.

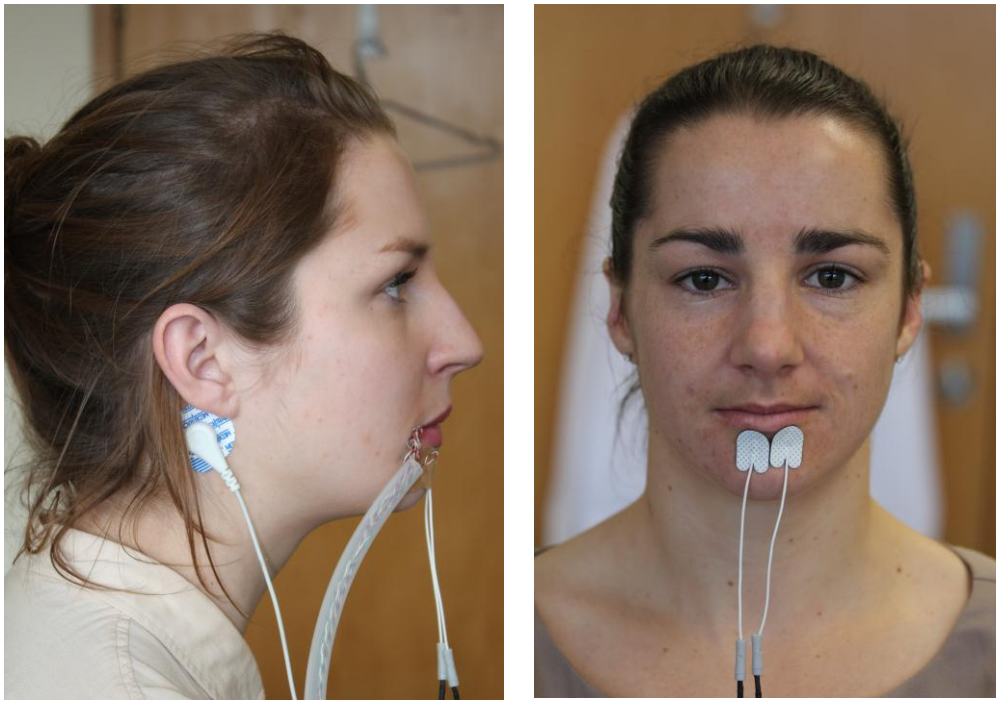


Figure 3-8: A) Location of EMG ground electrode and B) lower lip electrodes positioned to record muscle activity in the orbicularis oris and mentalis muscles.

3.8 Recording set-up and safety

The recording hardware consisted of an analogue to digital converter (PowerLab® 16-30 ML880, ADInstruments, NSW, Australia), and an 8-channel bridge amplifier (PowerLab® Octal bridge amplifier ML228, ADInstruments, NSW, Australia) (Figure 3-9) which was connected to a laptop computer (Toshiba Tecra A11). This hardware amplified the four pressure signals, the temperature signal, and the two EMG signals, which were all digitised at 1kHz. The digitised signals were then transmitted to the computer and displayed on the laptop using the Chart and Scope® software (ADInstruments, Pty Ltd, NSW, Australia).



Figure 3-9: Powerlab® Octal bridge amplifier (ML228) and Powerlab® 16-30 analogue to digital converter (ML880).

The recording equipment was all housed in a "Perspex" (PMMA) case created by Emtech Laboratories, University of Otago for safety reasons (Figure 3-10). To prevent electrocution, two 12-volt gel-cell batteries were used to power the equipment. After each testing procedure, the equipment was connected to the mains to charge the batteries. As a secondary precaution, the housing case was designed to prevent recording while the equipment was connected to the mains.



Figure 3-10: Perspex testing case.

3.9 Calibration

Prior to each recording session, the pressure sensors were calibrated in the following manner. The appliance was connected to the PowerLab and using the Chart software programme, the sensors were zeroed to atmospheric pressure. After zeroing, a specially constructed sealed chamber (Emtech Laboratories, University of Otago) was used to calibrate the pressure sensors. The chamber had sealed cable glands and a pressure gauge, which was connected to a regulated flow of nitrogen gas (Figure 3-11). The appliance was placed in the chamber and the chamber was sealed. Once sealed, the pressure in the chamber was increased using a continuous flow of nitrogen gas through the system. Once a constant pressure of 50kPa was reached, a unit conversion was carried out using the computer to convert millivolts (mV) into kilopascals (kPa) for the channels with input from the pressure sensors. The appliance was then removed from the chamber, and re-zeroed before being inserted in the volunteer's mouth. The calibration process was repeated prior to use of each of the three VFS.



Figure 3-11: Calibration chamber

3.10 Testing protocol

The day before the recording session, each participant was recalled to ensure each of the stents fitted accurately. Approximately eight hours prior to the recording session, nine disposable plastic cups were filled with 10ml of water each and placed in an incubator set to 37°C in preparation for the water swallow task. The recording session was carried out under aseptic conditions in a quiet testing laboratory at the University of Otago, School of Dentistry. The appliance was disinfected using an alcohol solution (70% ethanol) before and after testing sessions.

During the recording session, participants were seated in a comfortable, upright position with their heads unsupported and in the natural head position (NHP) (Figure 3-12). NHP is a standardised and reproducible orientation of the head in space when one is focusing on a distant point at eye level (Cooke and Wei, 1988). This is important as changes in lip pressure have been demonstrated with head posture that is flexed or extended (Hellsing and L'Estrange, 1987). The EMG sensors were attached in their designated locations and the 0.5mm stent was inserted following calibration as described above. Participants were asked to be as relaxed and still as possible during the tasks to minimise movement artefacts in the recordings.

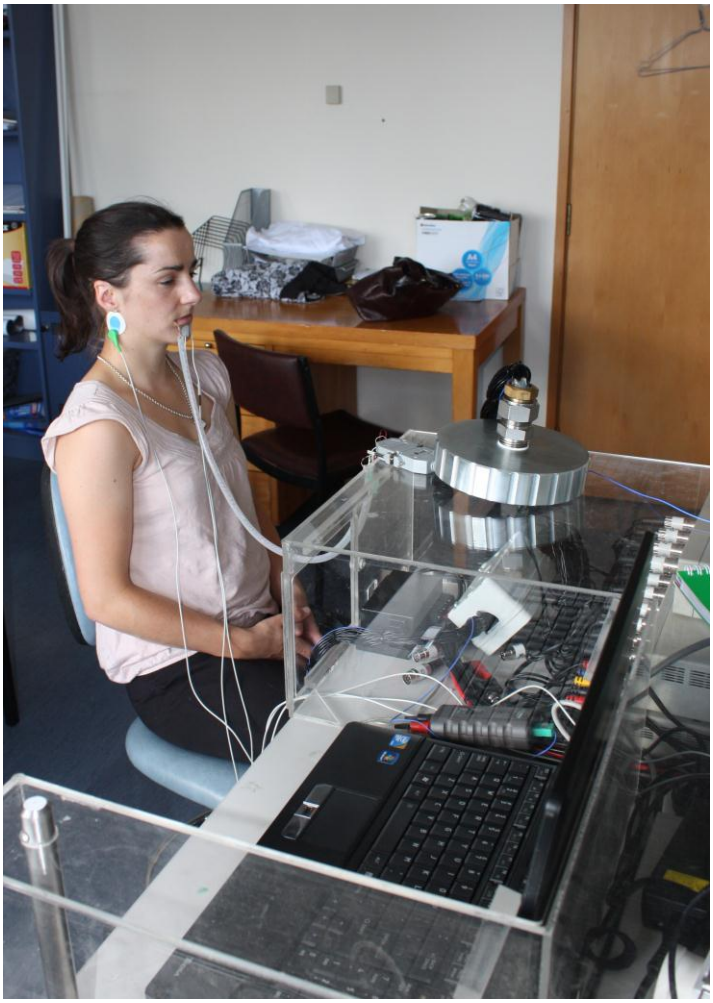


Figure 3-12: Participant in natural head position (NHP) during at rest recordings.

After the stent was placed in the mouth, the pressure trace for each channel was monitored until it stabilised. This usually took three to four minutes. The participants were then asked to perform the task paradigm for the 0.5mm tray, which consisted of sounds, command and water swallows, at rest recordings and maximal lower lip pressure recordings.

3.11 The task paradigm

3.11.1 The "zero" procedure

During the pilot study, difficulty was encountered when zeroing the pressure sensors to atmospheric pressure. This was thought to be due to

the presence of thermal drift. The baseline pressure recorded by the sensor would slowly decrease over time, leading to inaccuracies in the data. To account for this, prior to each task, a research assistant gently pulled the lower lip away from the sensor surface. The volunteer was also asked to place the tip of their tongue at the junction of the hard and soft palate to remove it from the surface of the lingual sensors. A pre-set command was then placed on the data to indicate that this pressure value was atmospheric pressure, which acted as a "zero" marker. The lip was then gently replaced, and the subject was asked to lightly rest their tongue back into its habitual position. The process was completed as quickly as possible to minimise the time the sensors were in contact with the colder external air in an attempt to minimise thermal change in the recordings.

3.11.2 Sound task

Three sounds were chosen to represent the sound task. The b- and p-sound were chosen as examples of bi-labial plosive sounds which typically require action of both lips to enunciate the sound. The f-sound was chosen as an example of a labio-dental fricative sound which requires near contact of the lower lip and the upper incisor teeth (Radford, 2009). Before each task, the research assistant gently performed the "zero" procedure. Each participant was asked to first enunciate a set of 10 p-sounds as clearly as possible. This was then repeated twice more to give a set of three p-sounds, with a "zero" being completed before each p-sound task. The volunteer was then asked to enunciate three sets of 10 f-sounds, followed by three sets of 10 b-sounds.

3.11.3 Swallowing tasks

Following the sound task, the subject was asked to sit as still as possible and not swallow until asked to. The command for the first swallow was given after one minute of recording. The subject was asked to swallow, the initiation of the swallow being defined as the elevation of the hyoid bone. This event was marked with a pre-set command on the data. The second and third command swallows were completed at one minute intervals in all

subjects except subject 1, where there was only 10 seconds between swallows. As discussed later, this led to this subject being removed from the swallowing analysis. If the first swallow was seen to be a very different pattern to the subsequent swallows, another command swallow was completed. This is why for some subjects there are three sets of swallow data per stent while others have four sets of swallow data. The command swallows were followed by a set of three 10ml water swallows. A measured volume of water was given, as it has previously been found that the force produced during swallowing varied with the quantity of fluid taken (Gould and Picton, 1964). The water was pre-warmed to 37°C to minimise thermal interference with the pressure transducers.

For the water swallows, the participant was instructed to "deliver" the water, then "hold" the water until the sensor trace settled, then finally swallow the water, with the exact point of the swallow marked on the data using a pre-set command. This process helped to limit the number of movement artefacts in the data.

3.11.4 At rest tasks

Participants were then asked to sit in NHP, remaining as still as possible, while the "zero" procedure was carried out. Each participant was asked to sit with their teeth in light contact for 30 seconds. The "zero" procedure and "teeth together task" was then performed twice. Following this, the same procedure was carried out, except the participant was asked to have their teeth slightly apart. The "zero" and "teeth apart" task was also repeated three times.

3.11.5 Maximum pressure task

Finally, each participant was instructed to pull their lower lip back as hard as possible against the lower incisor teeth to record the maximum pressure generated by the lower lip. This task was used to investigate the maximum voluntary contraction (MVC) of the lower lip that each subject was capable

of generating. The MVC was recorded as the peak pressure during either the MVC or sound task.

Following completion of the task paradigm, the 0.5mm stent was removed. The tasks were completed consecutively for the 2.5mm and 4.5mm stents.

3.12 Data analysis

The pressure sensors recorded changes in analogue form which were converted to digital form and transmitted to the attached laptop computer. These signals were then displayed as pressure-time fluctuations on channels 1-4 using the Chart and Scope® software (ADInstruments Pty Ltd, NSW, Australia) (Figure 3-13).

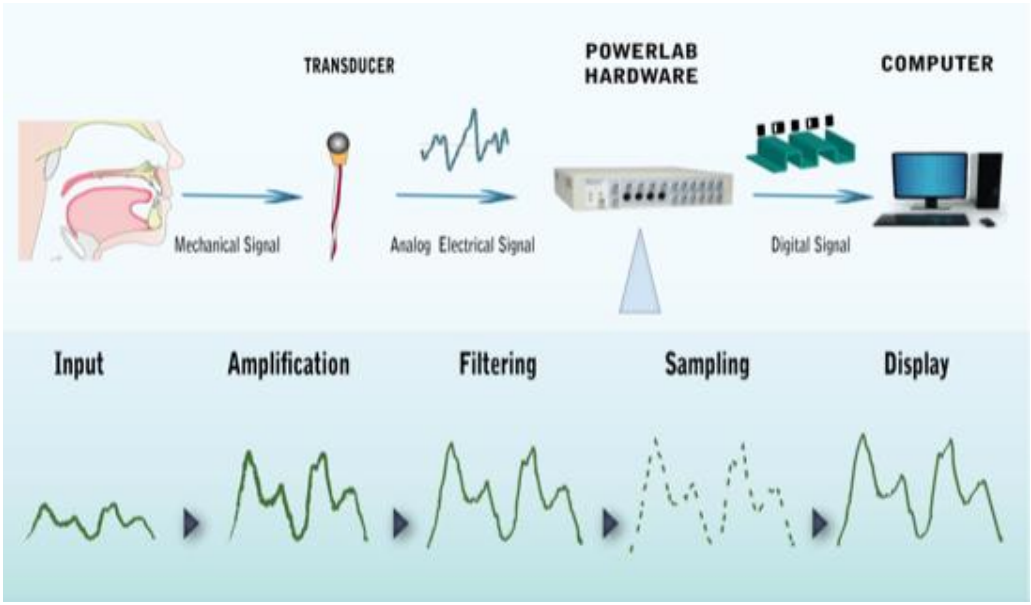


Figure 3-13: Pressure transducer signal conditioning and data recording.

Data were recorded at a rate of 1kHz and then converted from mV to kPa via a calibration relationship. Channel 5 recorded data from the thermocouple and Channel 13 recorded EMG data, both of which remained unchanged from millivolts (Figure 3-14). LabChart Reader 7.0.2 software (ADInstruments Pty Ltd, NSW, Australia) was then used to analyse these pressure signals. Data from each subject were saved and named on the

laptop computer. Each task was then cut from the original file and saved as a separate file to improve ease of analysis.

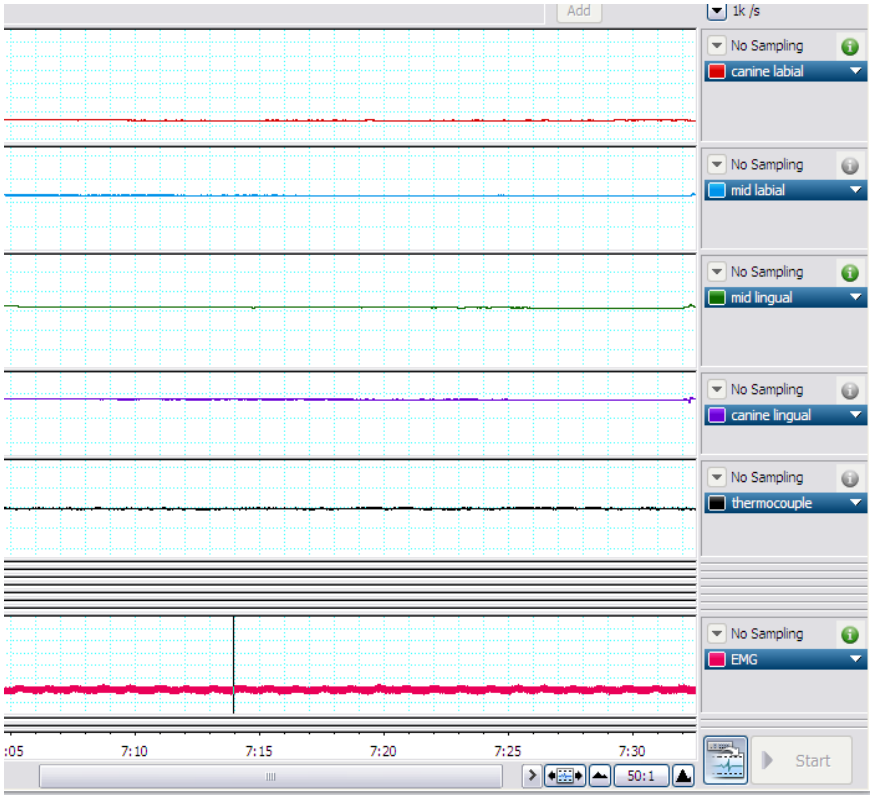


Figure 3-14: Channels 1-4 recorded pressure, channel 5 recorded thermal changes and channel 13 recorded EMG data

3.12.1 "Zero" pressure

To find the "zero" pressure prior to each task, the mean pressure five seconds prior to the zero command was taken on each channel. This was assumed to be the baseline atmospheric pressure. Often the "zero" point for the labial and lingual channels were not the same, as there was a time delay while the subject placed their tongue back in its habitual position. For this reason, the zero pressures on the labial and lingual channels were calculated separately (Figure 3-15A and B) and each was added to a Microsoft Excel spreadsheet under the column "zero" pressure (Figure 3-16).

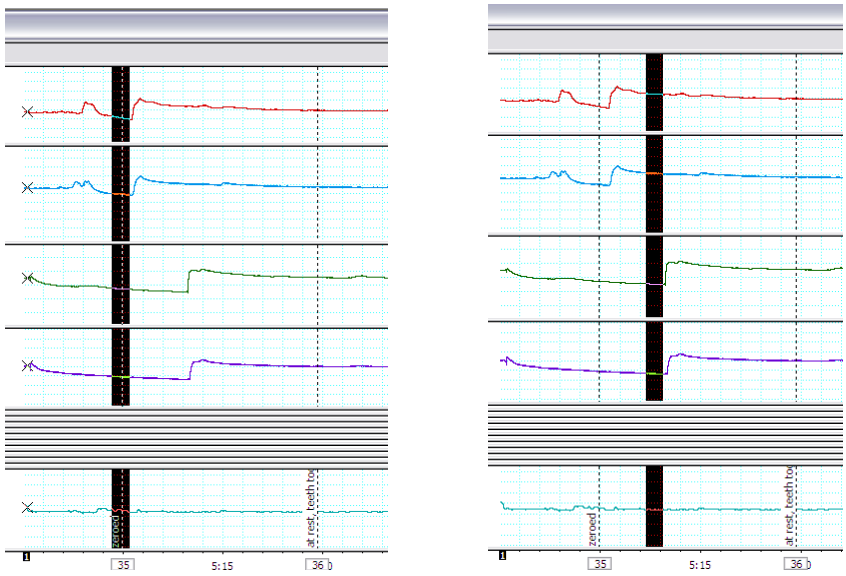


Figure 3-15: A five second window was used to determine mean pressure at "zero" pressure A) "zero" pressure for labial channels B) "zero" pressure for lingual channels

Subject	Sensor	Trial	Tray	Task	zero	lip back	mean pressure (kPa)
1	can lab	1	0.5	TT	0.57	4.32	3.75
1	can lab	2	0.5	TT	0.55	4.52	3.97
1	can lab	3	0.5	TT	0.62	4.33	3.71
1	mid lab	1	0.5	TT	1.9	3.15	1.25
1	mid lab	2	0.5	TT	2.1	3.34	1.24
1	mid lab	3	0.5	TT	2	3.56	1.56
1	mid ling	1	0.5	TT	3.5	4.04	0.54
1	mid ling	2	0.5	TT	3.7	4.64	0.94
1	mid ling	3	0.5	TT	3.8	4.47	0.67
1	can ling	1	0.5	TT	1.55	3.87	2.32
1	can ling	2	0.5	TT	1.5	3.99	2.49
1	can ling	3	0.5	TT	1.66	4.58	2.92
1	can lab	1	2.5	TT	1.6	4.95	3.35
1	can lab	2	2.5	TT	1.83	4.97	3.14
1	can lab	3	2.5	TT	1.9	5.1	3.2
1	mid lab	1	2.5	TT	-3.78	0.46	4.24
1	mid lab	2	2.5	TT	-3.78	0.4	4.18
1	mid lab	3	2.5	TT	-3.7	0.53	4.23

Figure 3-16: Excel spreadsheet used to record "zero" pressure

For each of the tasks the "zero" pressure was recorded on the spreadsheet, then the pressure with the lip and tongue in contact with the sensors was recorded. This pressure was then recorded on the Excel spreadsheet under the column "lip back" (Figure 3-16). The Excel spreadsheet was set-up to automatically perform the equation:

"Lip back" pressure during task – "zero" pressure = mean pressure (kPa)

This determined the actual pressure from the lip or tongue during each task.

3.12.2 At rest tasks

For the "at rest" tasks, the outcome measured was mean pressure from the lip and tongue over a 10 second window for each of the three trays. As each task (teeth apart and teeth together) was repeated three times, there were 198 separate tasks to be analysed. Following the zero command, an accommodation period of 10 seconds was left to allow the pressure data to stabilise. The mean pressure of the 10 second window following this was found using the Datapad function (Figure 3-17).

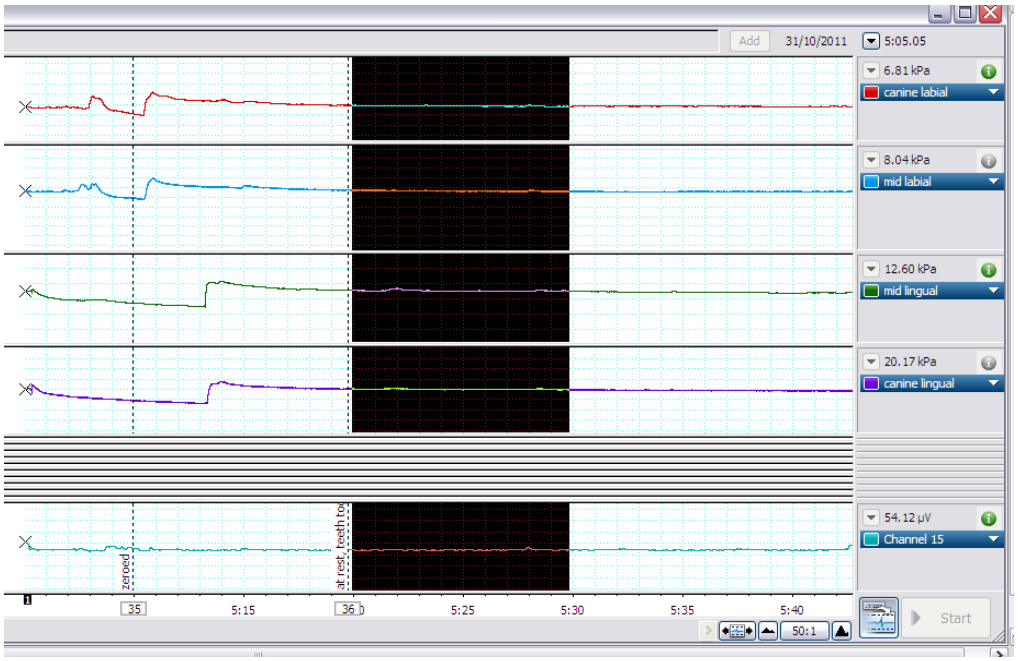


Figure 3-17: 10 second window for measuring mean lip and tongue pressure.

The data were then entered into the Microsoft Excel spreadsheet, which was set up to calculate the mean pressure as discussed above. For the EMG

data a mean μV reading was extracted from the same 10 second window. These data were also added to the spreadsheet for future analysis.

3.12.3 Speaking tasks

Data from each of the three sounds were inspected (p, f and b) with the data from the p-sound task being the most clear. This was the task chosen for subsequent statistical analysis. For the p-sound task each subject was instructed to speak the p-sound as clearly as possible 10 times in a row. This gave a pressure representation on the software of 10 pressure peaks. The first four and last three peaks were discarded, as these peaks were least clear (Figure 3-20). As a group, the subjects tended to take two or three sounds to start a clear rhythm, and would usually tire by the last three or four sounds, thus giving a less clear pressure signal at the beginning and end of the task.

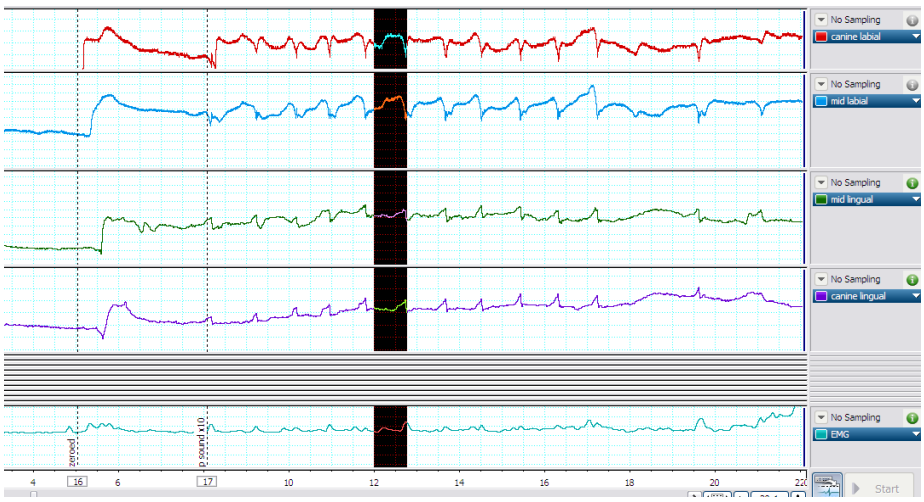


Figure 3-18: Pressure during p-sound task

The maximum pressure for each of the remaining three peaks was found using the Datapad function. These data were then added to the Microsoft Excel spreadsheet which was used to calculate the mean maximum pressure from the three peaks. This was repeated for all three p-sound tasks for each of the three stents, giving 99 sets of p-sound maximum pressure for analysis.

For the EMG data, the maximum pressure from each of the speaking tasks (p, f and b) was found and also added to the spreadsheet.

3.12.4 Maximum pressure task

This task was used to investigate the maximum voluntary contraction (MVC) of the lower lip that each subject was capable of generating. To analyse this, the MVC generated on the EMG channel was found using the Datapad function and added to the Excel spreadsheet along with the maximum pressures from the sounds.

To compensate for the slight differences in EMG sensor positioning between participants, the EMG readings found during the at rest tasks were analysed as a percentage of the maximum pressure found during any of the speaking or MVC tasks for each of the three stents.

3.12.5 Command swallow

For the command swallow task, the absolute pressure data were recorded for all four channels (Figure 3-24). For each swallow, data were extracted using the Peak Analysis component of the software (Figure 3-25). Each channel was individually analysed to find the peak pressure, time to peak and area under the curve. The total time of swallow was found manually using the marker tool. The initiation of the swallow was defined as being at 20% of peak pressure on the ascending slope, with swallow cessation being at 20% of peak pressure on the descending slope (Figure 3-26). All of these data were added to the Microsoft Excel spreadsheet.

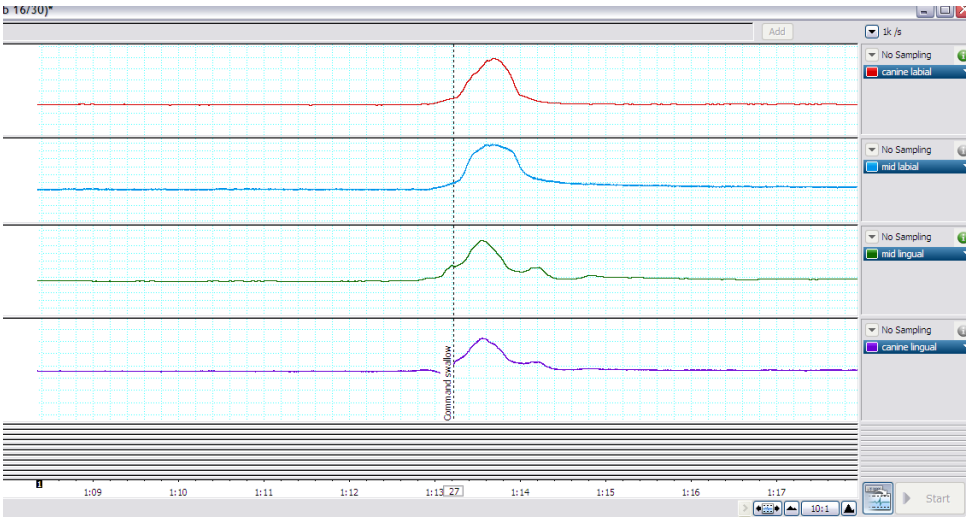


Figure 3-19: Example of a command swallow.

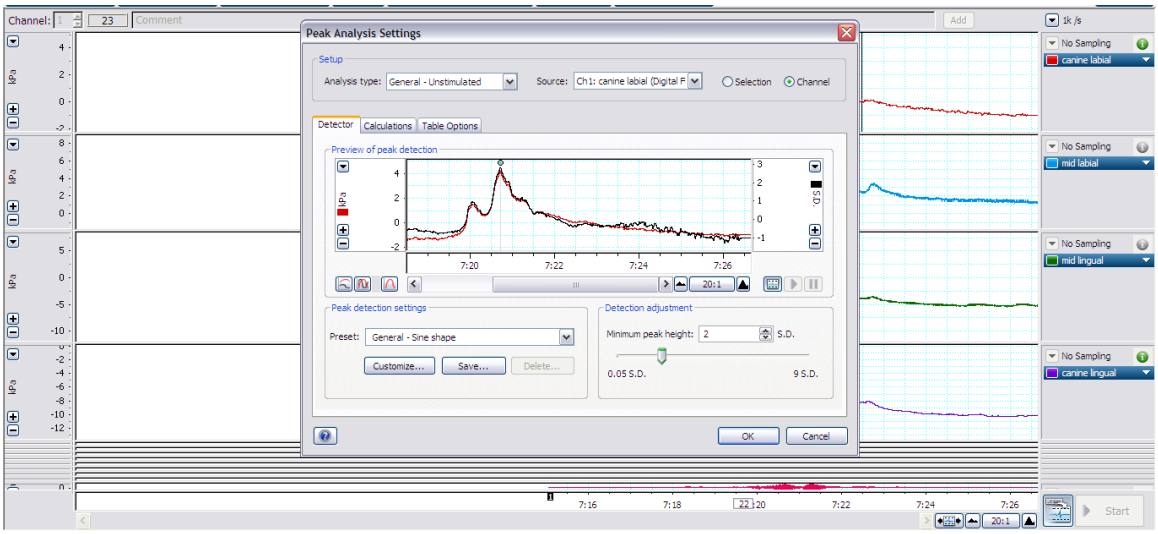


Figure 3-20: Peak analysis function of LabChart software which was used to determine peak pressure, time to peak and area under the curve for each command swallow.

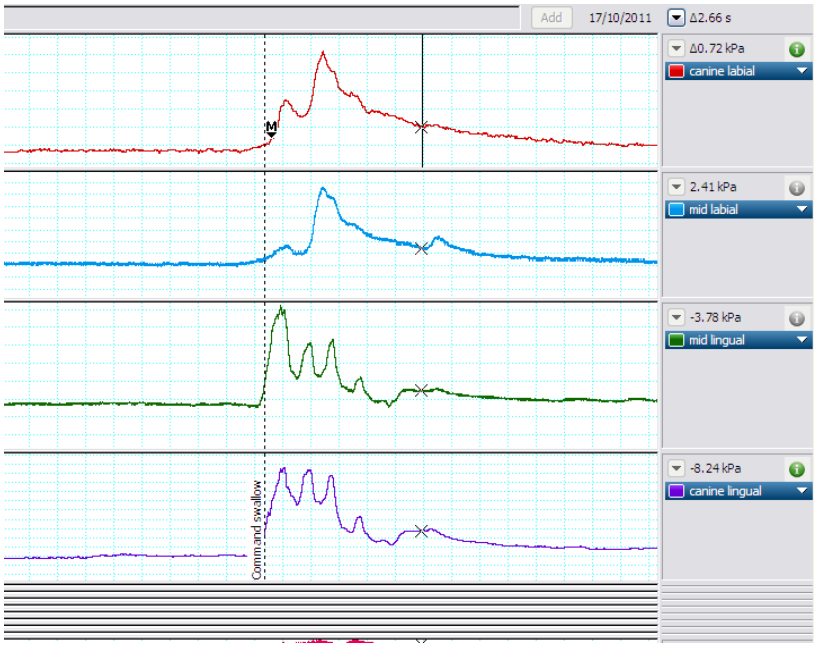


Figure 3-21: LabChart marker (M) used to manually calculate total time of swallow event. The 20% value was calculated for each channel separately due to the different profiles for each channel. The figure above shows the 20% start value fo the canine labial (red) channel.

For some of the subjects, there was minimal pressure activity from the lip (Figure 3-27). To avoid adding inaccuracies to the data, a minimum pressure change of 0.5kPa was required to be defined as lip activity associated with the swallow. Any values less than this were counted as zero activity on the spreadsheet.

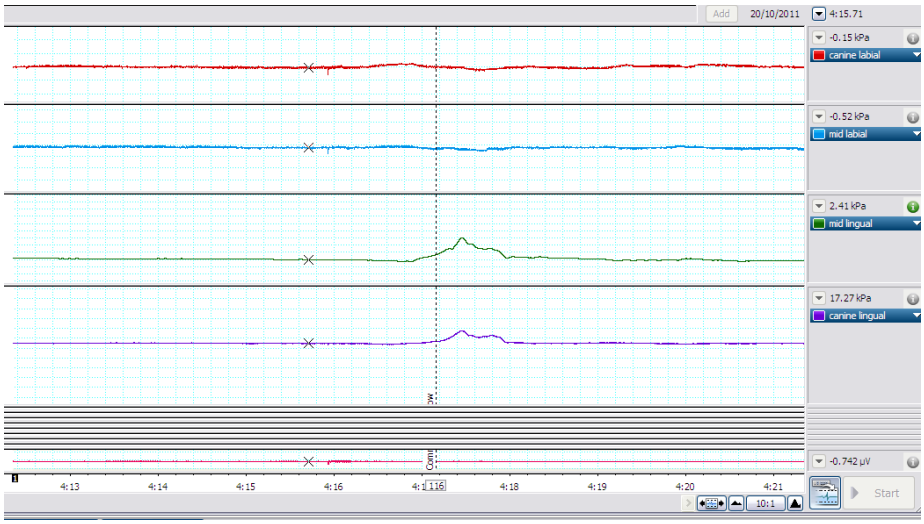


Figure 3-22: Example of a command swallow with no discernable labial pressure change associated with the swallow.

On the lingual pressure channels, there were frequent negative pressures recorded during the swallowing event. When this occurred, the total amplitude of pressure change was recorded using the LabChart marker (Figure 3-28).

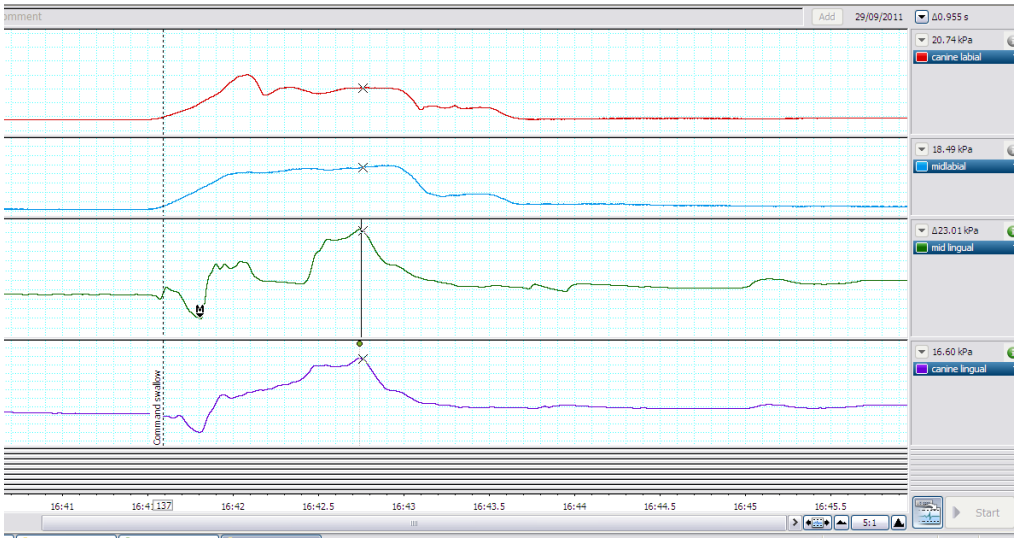


Figure 3-23: Manual marker (M) used to measure total amplitude of swallow.

3.12.6 Swallow overlays

To analyse the individual swallow pattern and how it changed with incremental lower lip advancement, individual charts of each swallow were constructed using the Scope® function of the Labchart® software. For each tray the three swallows were overlaid on top of each other using the set "command swallow" point on the data to overlay the swallows (Figure 3-29). The three swallows were then averaged giving an "average" swallow that represented the three swallows for each stent (Figure 3-30).

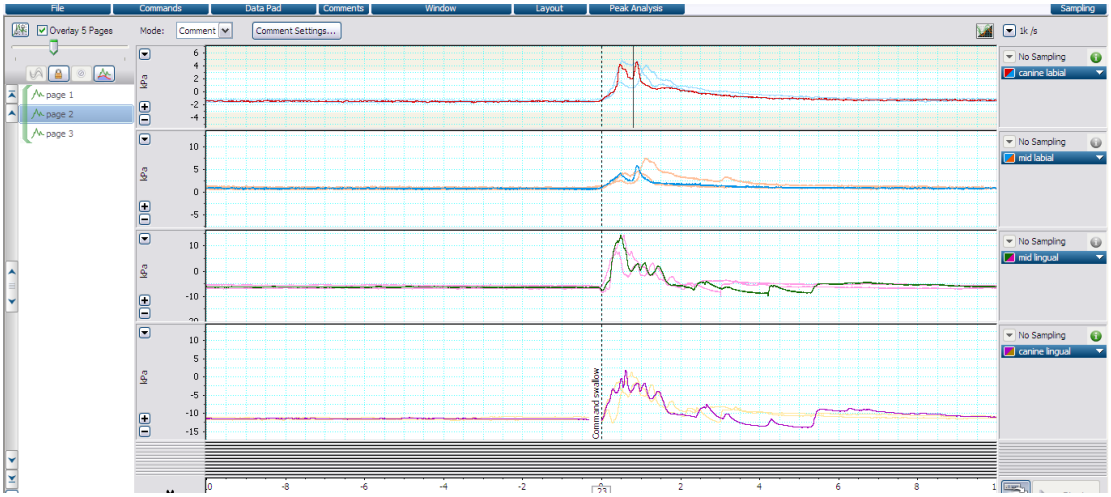


Figure 3-24: Each of the three command swallows overlaid on the same swallow initiation point.

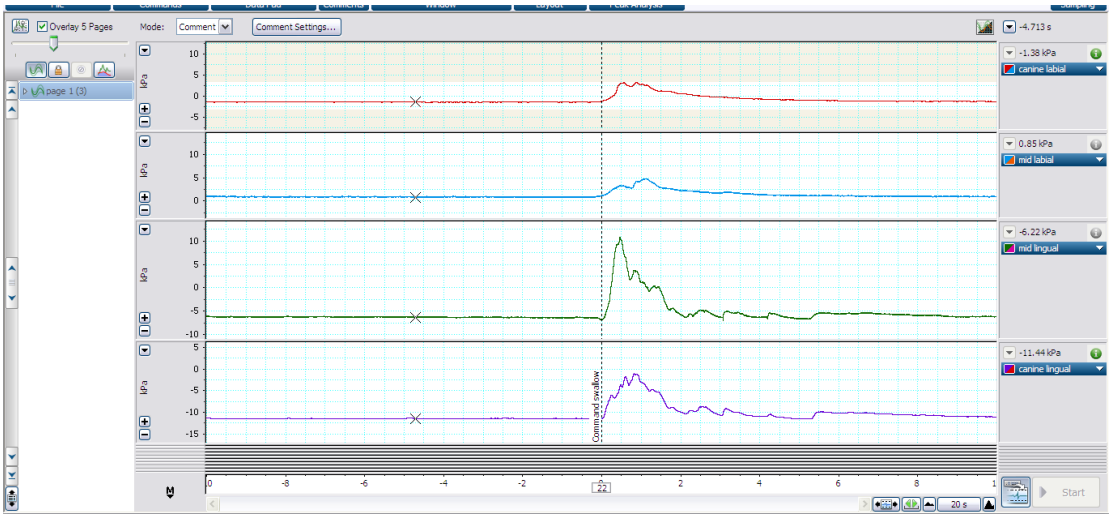


Figure 3-25: The average of the three swallows was constructed to give an overall average swallow for each tray.

Each participant's average swallow for each tray was then overlaid to give a graph which showed how each individual's swallow changed with advancement of the lower lip (Figure 3-31).

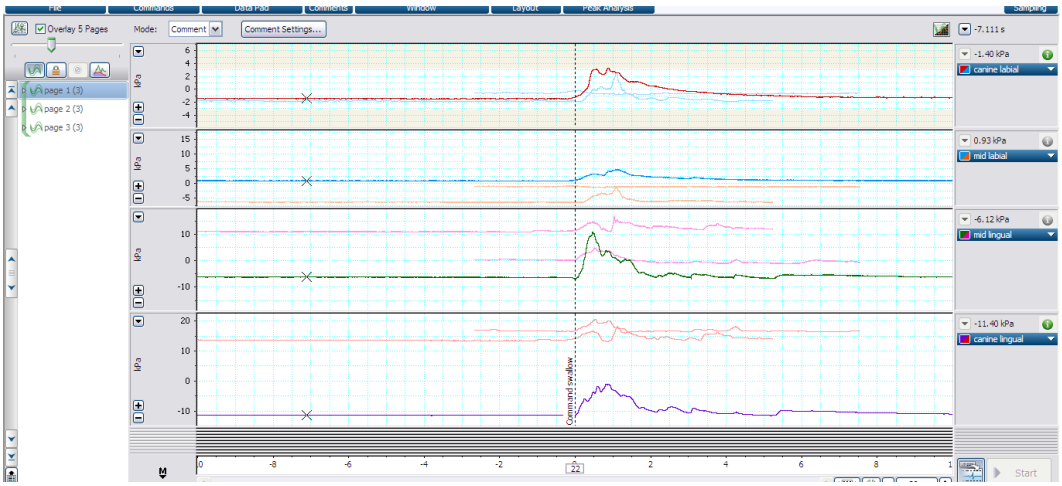


Figure 3-26: Average swallow for each of the three trays overlaid on the swallow initiation point. Note that each average swallow begins at a different baseline pressure, making comparison of swallow patterns between the three stents difficult.

To compensate for each average swallow beginning at a different baseline, the graph was imported into Photoshop® (Adobe Systems Incorporated, United States of America) and aligned so each swallow began from the same baseline point, allowing for direct comparison of the swallows (Figure 3-32). As each graph was on a different baseline pressure, it is not possible to assign absolute values to the pressure measurements. However, the scale used is the same, so visual analysis based on size of pressure peaks is possible.

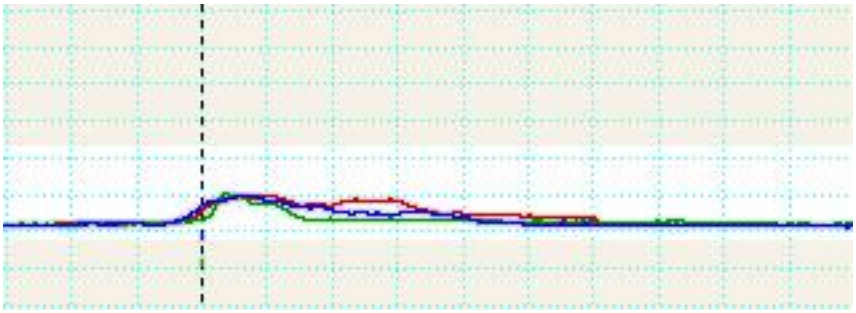


Figure 3-27: Example of adjusted canine labial graph, each line represents the average swallow which is derived from the multiple swallow recorded for each stent. The 0.5mm VFS is shown in red, 2.5mm in blue and 4.5mm in green.

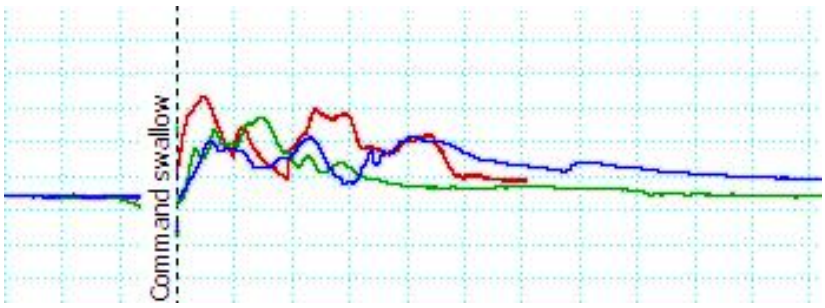


Figure 3-28: Example of adjusted canine lingual swallow graph.

3.13 Statistical analysis

Data were analysed using Statistical Package for the Social Sciences (SPSS) version 20.1 (IBM, United States of America). A linear mixed model was used for analysis, because the term subject was entered into the model as a random effect. An alternative approach would have been to complete a repeated measurement analysis of variance, but this would have produced very similar results. Statistical significance was accepted at $p<0.05$.

3.14 Fourier analysis

A Fourier analysis was completed on the command swallow data in collaboration with the Mathematics Department, University of Otago. Each data file, representing one command swallow, was loaded into MATLAB and saved as a matrix with five columns, and as many rows as there were samples. Each row corresponded to a different time value, recorded in its first entry and the subsequent entries corresponded to the pressures recorded by each of the sensors at that time value.

3.14.1 Data analysis

In order to further investigate the pressures exerted on the teeth, the experimental noise in the data was first reduced. This was accomplished through Fourier smoothing. The Fourier transform of a function of time $f(t)$ is a representation of $f(t)$ as a function of frequency $g(v)$ where v represents frequency. Informally, the Fourier transform of a function

represents how much of each frequency is present in the original function. Thus, frequencies that correspond to low values on the Fourier transform of *f (t)* contribute less to *f (t)* than frequencies that correspond to high values on the Fourier transform of *f (t)*. The Fast Fourier Transform, or FFT, was used to produce the Fourier transform or frequency spectrum of the time series of pressure at a sensor location in the mouth.

The frequencies of this spectrum with the lowest absolute values can be attributed to random sampling error. Omitting these frequencies will then produce a Fourier transform of a time series similar to the original function, minus the noise corresponding to the omitted frequencies. For this reason, all but the 600 frequencies with the highest absolute values were omitted. This removed most of the sampling error from the data. An inverse FFT was then performed to transform it from frequency space back into amplitude space. This returned a 600-point time series which corresponded to the time series of the original data with lower noise from sampling errors (Table 3-1).

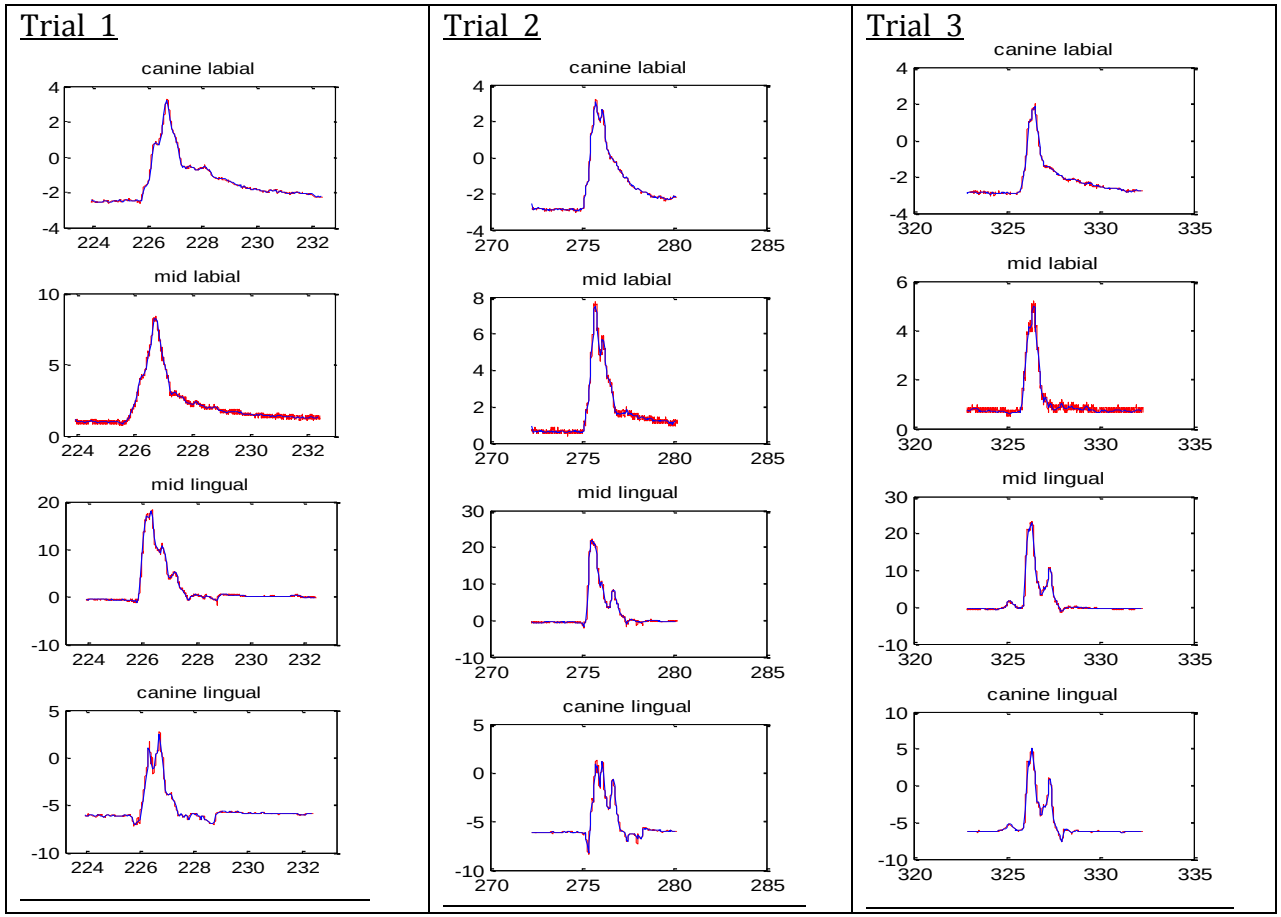


Table 3-1: Graph showing smoothed Fourier transform data for subject 6, 2.5mm tray. The red line represents the Fourier transform data prior to FFT smoothing, the blue line represents the data after smoothing.

The smoothed data for each person was then averaged over several swallows, by adding the smoothed time series from each swallow element by element, then dividing by the number of swallows, to further smooth out errors and inconsistencies. On visual analysis, it was noted that the first swallow was often a different pattern to the swallows that followed. It was thought there may have been an accommodation effect, or this may have been because there was likely more saliva in the mouth as more than 60 seconds had lapsed since the previous swallow. For this reason, the first swallow was omitted from further analysis and only the subsequent two or three swallows were analysed. As discussed above, if the first swallow was noted as being noticeably different on the Labchart software by the researcher, another swallow was completed. This explains the difference in the number of swallows available for analysis for each subject.

The smoothed data were then analysed using Fourier transforms. The Fourier transform of a function represents which frequencies are present in the function, and in what quantity, so two functions can be considered similar if their Fourier transforms are similar. A different colour line was used to identify each individual included in the Fourier analysis (Figure 3-34). It is possible to compare each individual's swallow pattern by plotting the Fourier transforms of the averaged smoothed pressure time series at a particular sensor location, for all subjects, on the same set of axis (Figure 3-35).

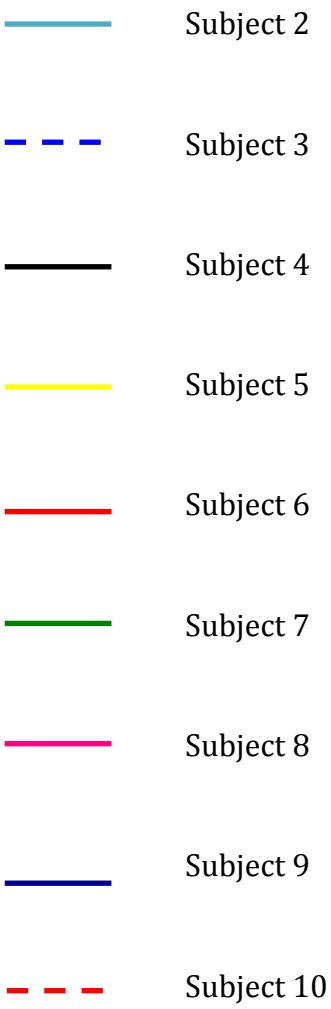


Figure 3-29: Key used to identify subjects included in Fourier analysis

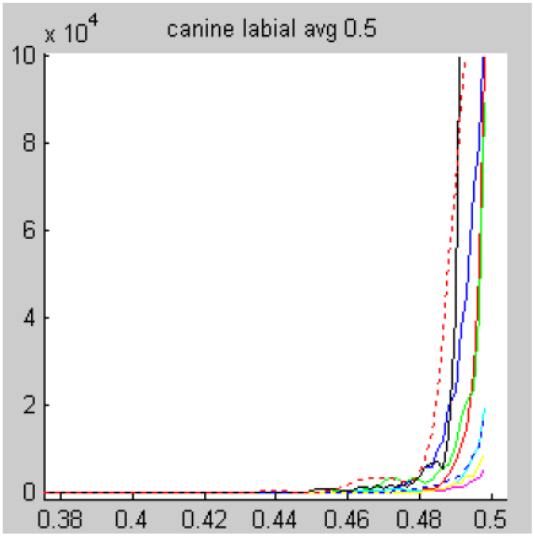


Figure 3-30: Example of smoothed Fourier transform for the canine labial sensor with the 0.5mm tray in place for all nine subjects. Each line represents one subject. The y-axis represents the Fourier co-efficient, the x-axis represents the normalised frequency.

The Fourier transform of any time series is symmetrical around the y-axis, so only the parts of the transforms corresponding to positive frequencies were plotted. Furthermore, only the parts of the transforms that included peaks, which were plotted to make the plots easier to interpret. Plots were made using both a standard scale (Figure 3-35) and a semi-logarithmic base 10 scale for the y-axis (Figure 3-36). The semi-logarithmic base 10 scale was used as it markedly increased the discriminatory power of the plots.

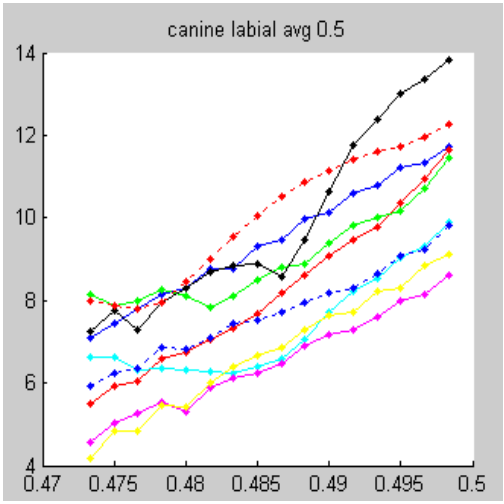


Figure 3-31: Example of smoothed Fourier transform for the canine labial sensor with the 0.5mm tray in place for all nine subjects. The y-axis represents the log of the Fourier co-efficient, the x-axis represents the normalised frequency.

4 Results

Due to the large quantities of data recorded, it was decided to exclude the sound and swallowing tasks from the scope of this thesis.

Static tasks

4.1.1 Oral pressure

The sample mean mid-labial pressure at rest for the 0.5mm tray was 14.6 ± 6.4 g/cm^2, 24.3 ± 8.6 g/cm^2 for the 2.5mm tray and 28.2 ± 8.0 g/cm^2 for the 4.5mm tray (Figure 4-1). This increase in pressure with incremental lip advancement was highly significant ($F=14.7$, $p<0.001$). There was no difference in pressure recorded with the teeth together or apart ($p>0.05$) (Figure 4-2).

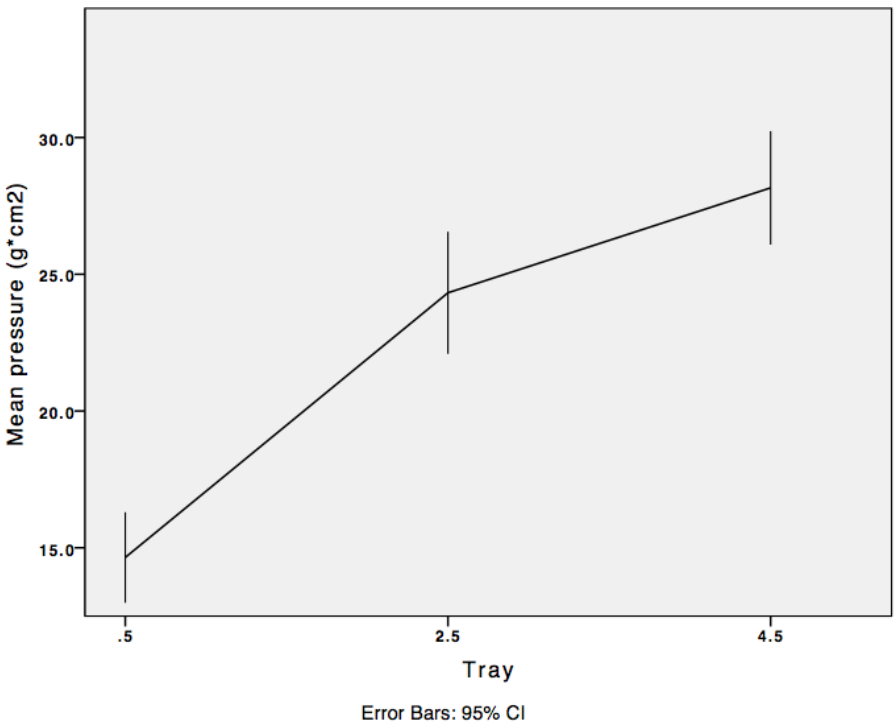


Figure 4-1: Pressure at the mid-labial site increased as the lower lip was incrementally advanced ($p<0.001$) (error bars depict 95% confidence interval).

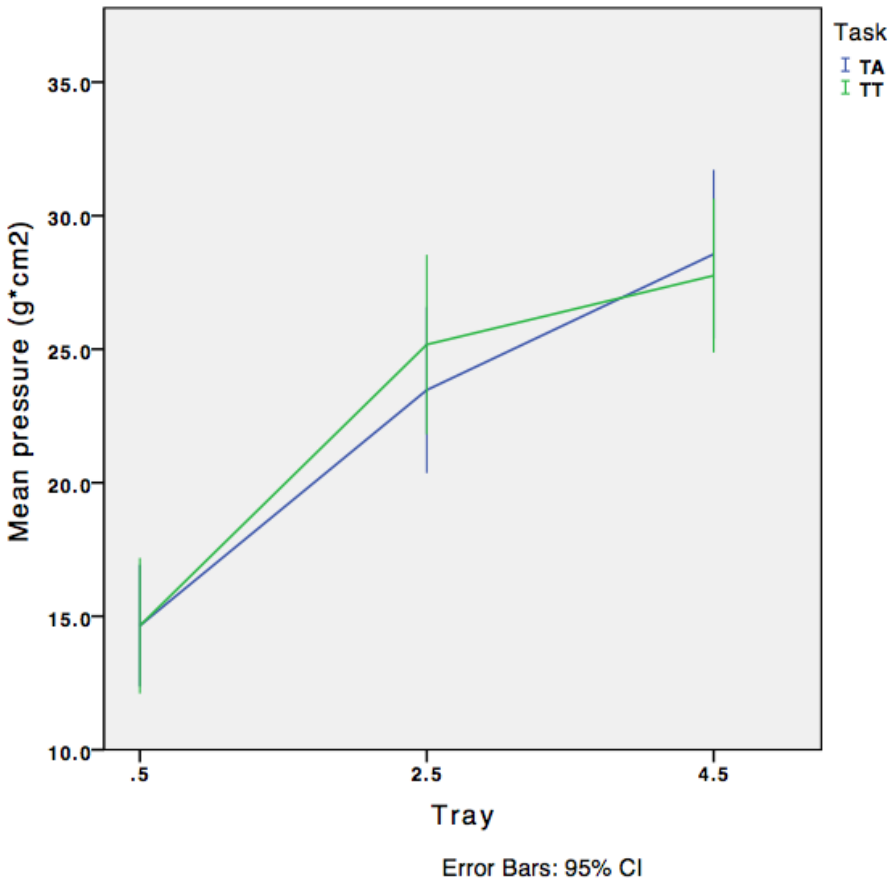


Figure 4-2: The effect of task (TT=teeth together, TA=teeth apart) at the mid-labial site was not clinically significant (p>0.05). Error bars depict the 95% confidence interval.

There was a highly significant tray/subject interaction ($F=24.3$, $p<0.001$), indicating that the response to lower lip advancement varied across participants. To investigate this finding further, individual response profiles were plotted (Figure 4-3). Half of the subjects showed increasing labial pressure at the midline as the lower lip was advanced (subjects 1, 2, 3, 4, and 9), while the other half of the subject group displayed an inverted "v" shape response profile, with pressure decreasing slightly between the 2.5 and 4.5 tray (subjects 5, 6, 7, 8 and 10).

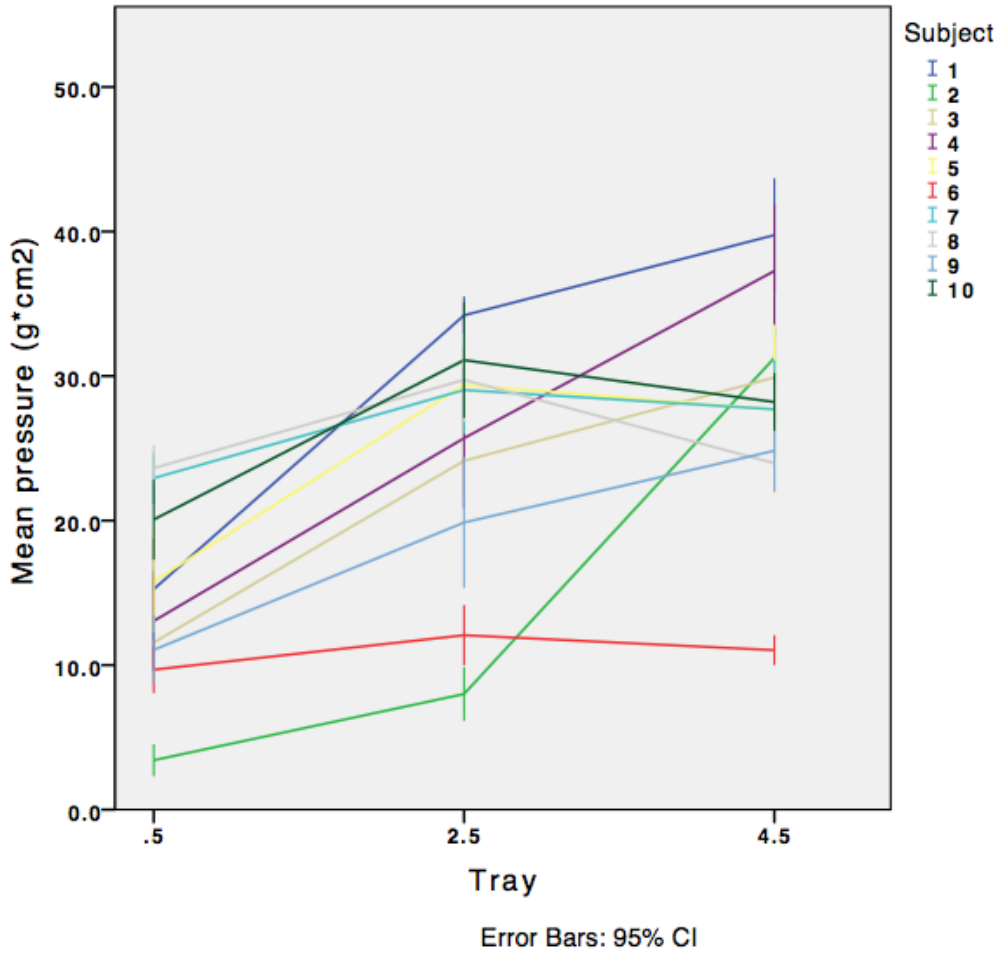


Figure 4-3: The individual pressure changes at the mid-labial site with increasing tray thickness (g/cm²). Error bars show the 95% confidence interval.

The mean canine labial at rest reading for the 0.5mm tray was 17.6 ± 6.9 g/cm², which increased to 19.3 ±10.6 g/cm² and 22.3 ± 9.2 g/cm² for the 2.5mm and 4.5mm trays respectively. However, the increasing trend was not statistically significant ($p>0.05$). Again, the effect of having the teeth together or apart was not significant ($p>0.05$).

4.1.2 Pressure difference between labial sites

There was no statistically significant difference between pressure generated at the mid-labial and canine labial site ($p>0.05$).

4.1.3 Electromyography

Post-hoc analysis showed the increase in EMG activity between the 0.5mm and 2.5mm trays was not significant ($p>0.05$); however, the difference between the 0.5mm and 4.5mm, and the 2.5mm and 4.5mm tray were both highly significant ($p<0.001$) (Figure 4-4). There was also a highly significant tray/subject interaction ($F=26.5$, $p<0.001$), indicating that the effect of tray varied across subjects. The effect of task was slightly but significantly different, with less EMG activity in the "teeth together" position compared with the "teeth apart" position ($p<0.05$) (Figure 4-5).

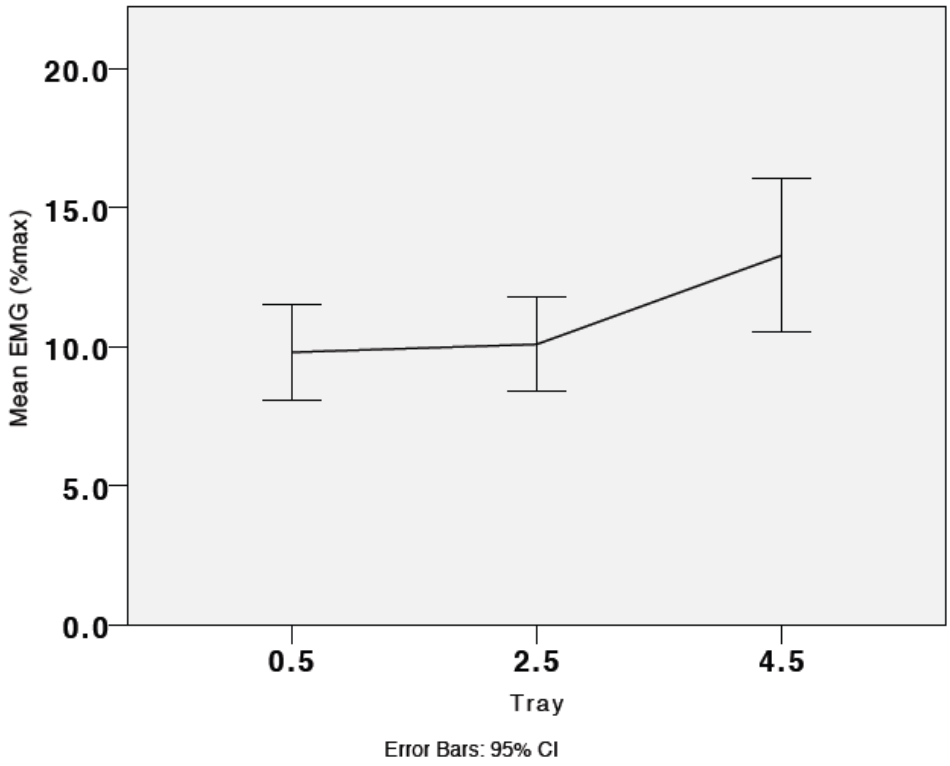


Figure 4-4: The effect of increasing tray thickness on EMG activity (as a % of MVC).

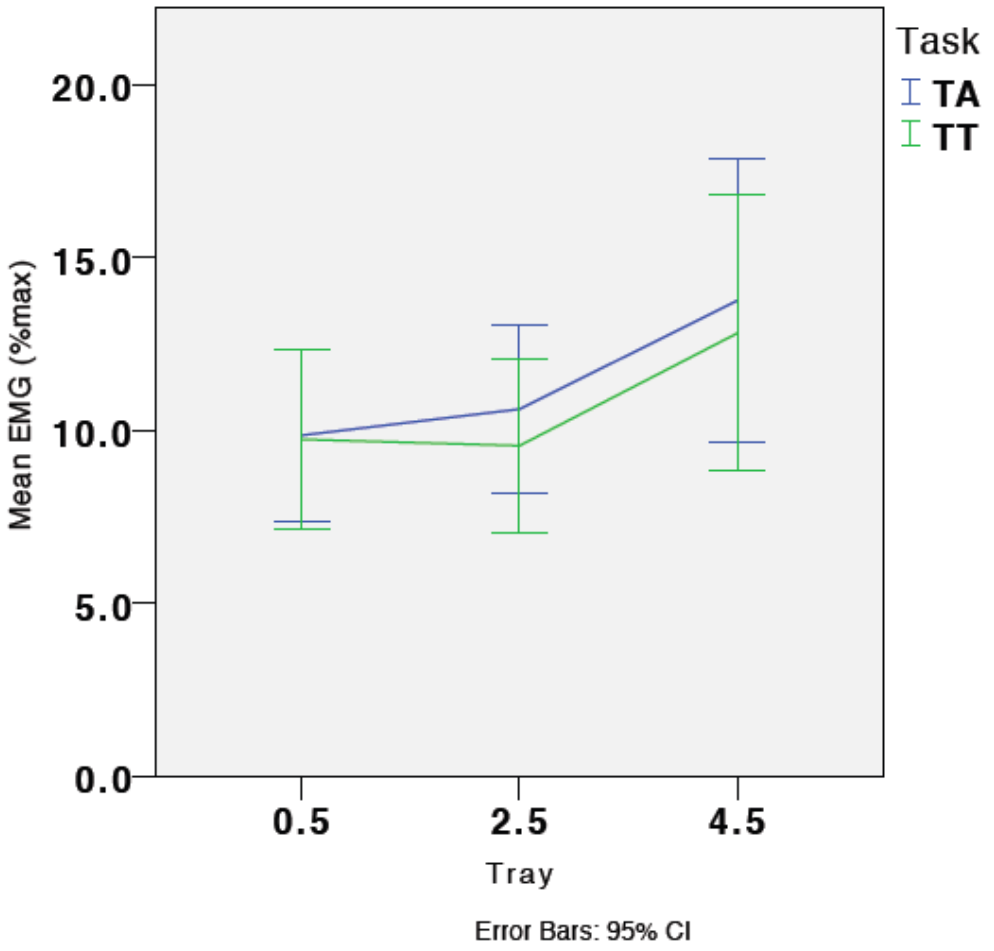


Figure 4-5: The effect of task (TA=teeth apart, TT=teeth together) was significant ($p<0.05$), with less EMG activity when the teeth were in light contact.

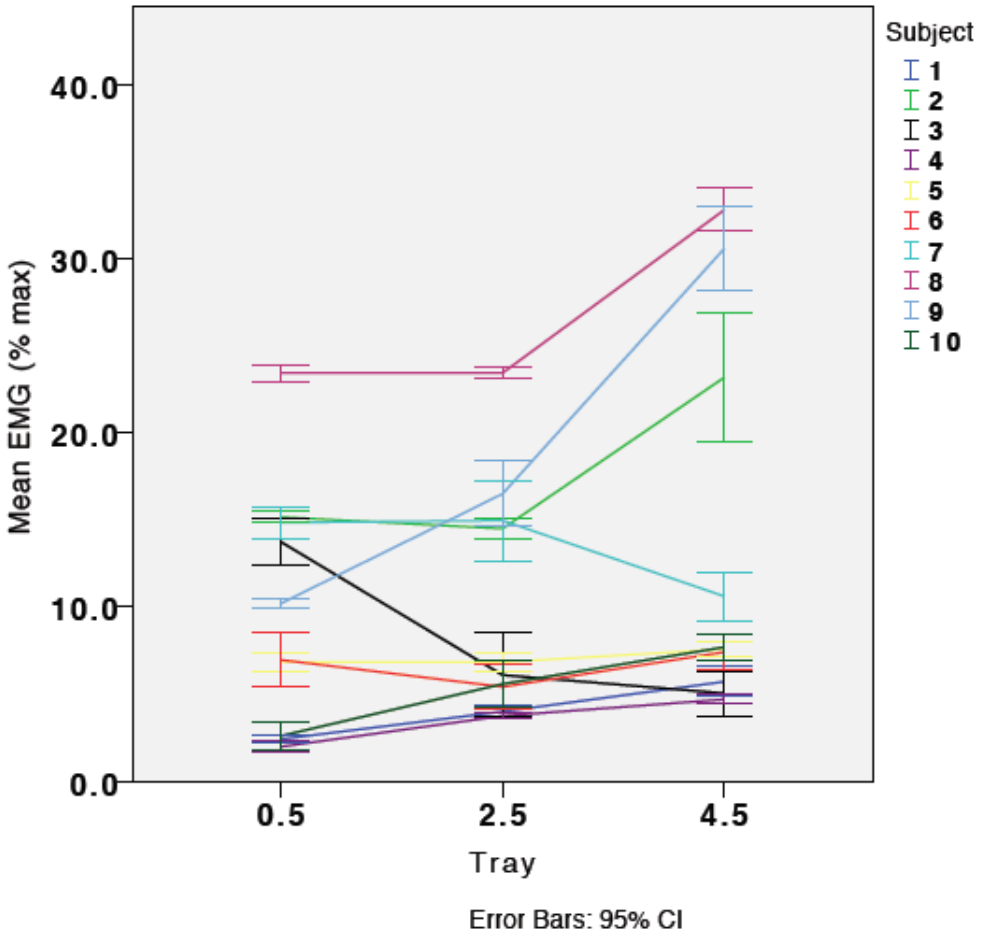


Figure 4-6: Graph showing individual EMG output (as a % of MVC) with incremental lip advancement.

4.2 Swallowing tasks

4.2.1 Lingual pressure

The mean peak pressures for the sample were calculated. For the mid-lingual sensor the mean peak pressures were 13.7 ± 9.1 g/cm^2 for the 0.5mm tray, 12.6 ± 6.3 g/cm^2, for the 2.5mm tray and 14.0 ± 5.8 g/cm^2 for the 4.5mm tray. The mean peak pressures for the canine lingual sensor were 12.2 ± 4.3 g/cm^2, 11.2 ± 5.4 g/cm^2 and 15 ± 7.2 g/cm^2 for the 0.5mm, 2.5mm and 4.5mm trays respectively. There was no effect of incremental lip advancement on peak pressure, time to peak, total time or total area under the curve for either the canine lingual or the mid-lingual sensor

($p>0.05$). For both sites a highly significant tray/subject interaction was seen ($p<0.001$).

4.2.2 Labial pressure

The peak pressures for the mid-labial sensor were 5.9 ± 5.3 g/cm^2 for the 0.5mm tray, 7.0 ± 6.6 g/cm^2 for the 2.5mm tray and 6.9 ± 6.9 g/cm^2 for the 4.5mm tray. There were no statistically significant effects of lower lip advancement on peak pressure, time to peak, total time or area under the curve of the swallow for mid-labial pressure ($p>0.05$).

The peak pressures for the canine labial sensor were 6.2 ± 5.3 g/cm^2 for the 0.5mm tray, 7.8 ± 8.2 g/cm^2 for the 2.5mm tray, and 10.2 ± 10.2 g/cm^2 for the 4.5mm tray. As the lower lip was advanced, the peak pressure generated on the labial surface of the canine increased significantly ($p<0.05$) (Figure 4-7). No statistically significant differences were seen with time to peak, total time or area of the swallow with lower lip advancement ($p>0.05$).

For both sensors, there was a significant tray/subject interaction ($p<0.001$), indicating the labial pressure response varied across individuals.

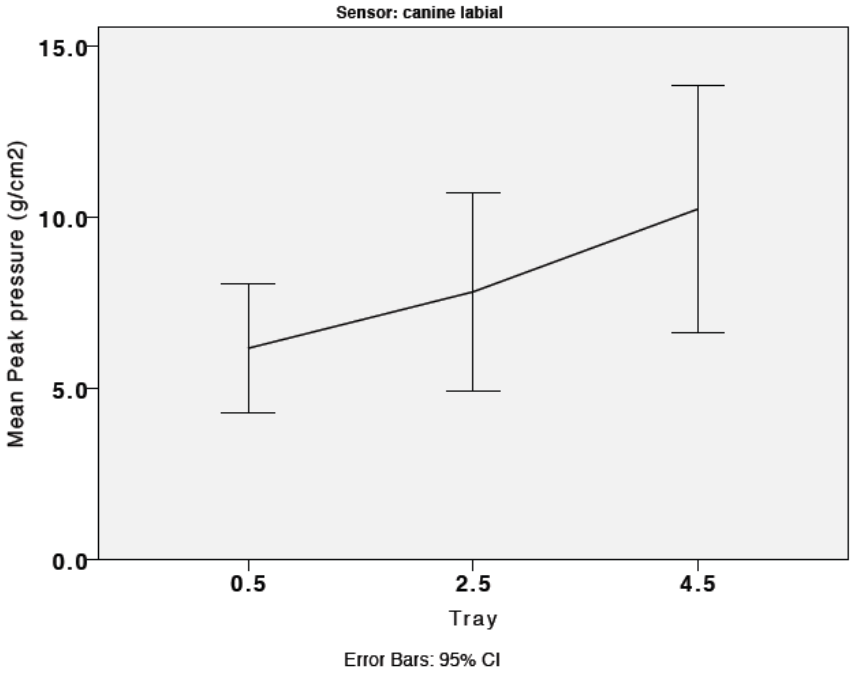


Figure 4-7: Graphical representation of canine labial pressures on saliva swallow as the lower lip was advanced.

4.3 Individual swallow analysis

To investigate the significant tray/subject interaction shown in the above analysis, individual graphs of each person's command swallows were completed. A graph was constructed for each pressure site, with each line representing the average swallow generated from the individual swallow events. As discussed earlier, the first swallow for each participant was removed from analysis, as the initial swallow was consistently different from the other two or three swallow events. Subject 1 was also removed from analysis due to the different time intervals between command swallows.

KEY

0.5 mm tray **2.5mm tray** **4.5mm tray**

For the graphs below, pressure is shown on the y-axis, with time on the x-axis. As each swallow for each tray began at a different baseline pressure and time, it was not possible to define absolute figures for pressure or time;

however, all graphs were generated using the same scale. Visual interpretation of the pressure profiles size allows changes in pressure behaviour to be analysed.

Examples of the individual graphs are shown below.

Subject 4

Subject 4 showed increased labial pressure generation as the lip was incrementally advanced (Figure 4-8, 4-9). The pressure pattern generated was also relatively complex, especially at the canine labial site, and consisted of a number of peaks. Interestingly, subject 4 was one of the lip-incompetent subjects.

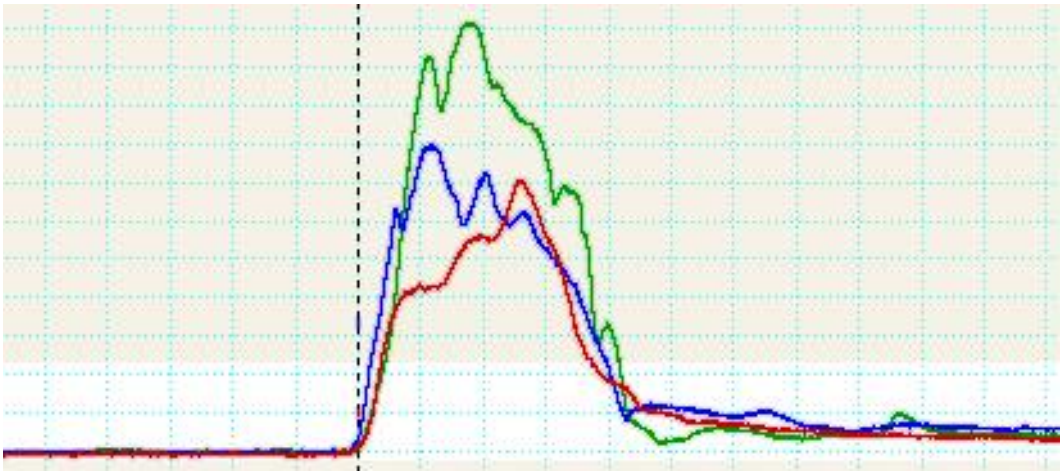


Figure 4-8: Subject 4 canine labial pressure. The pressure profile generated shows multiple pressure peaks for all three trays.

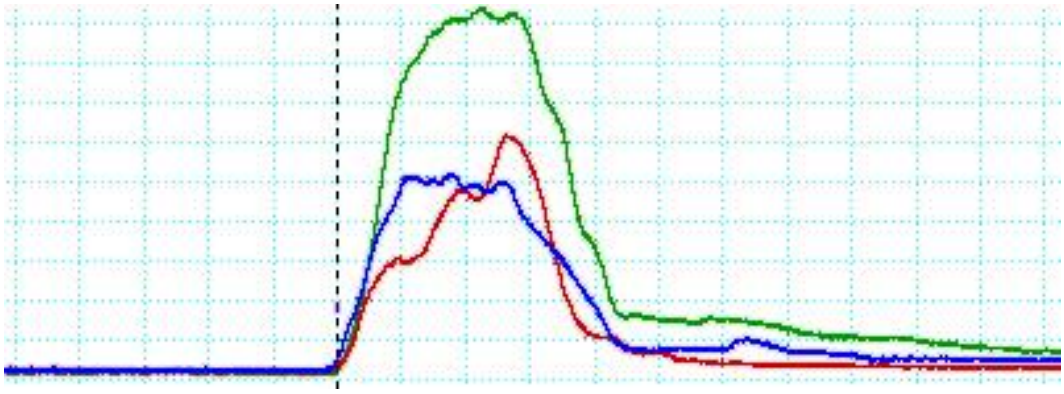


Figure 4-9: Subject 4 mid-labial pressure. As with the canine labial pressure (Figure 4-8), the pressure generated increases from baseline (shown in red) to the 4.5mm tray (shown in green).

The tongue behaviour on swallowing was also relatively complex (Figure 4-10, 4-11). The pattern remains similar, as does the pressure amplitude, as the lower lip is advanced. This subject also generates negative pressure on the lingual surface, which is most clear with the 0.5mm tray.

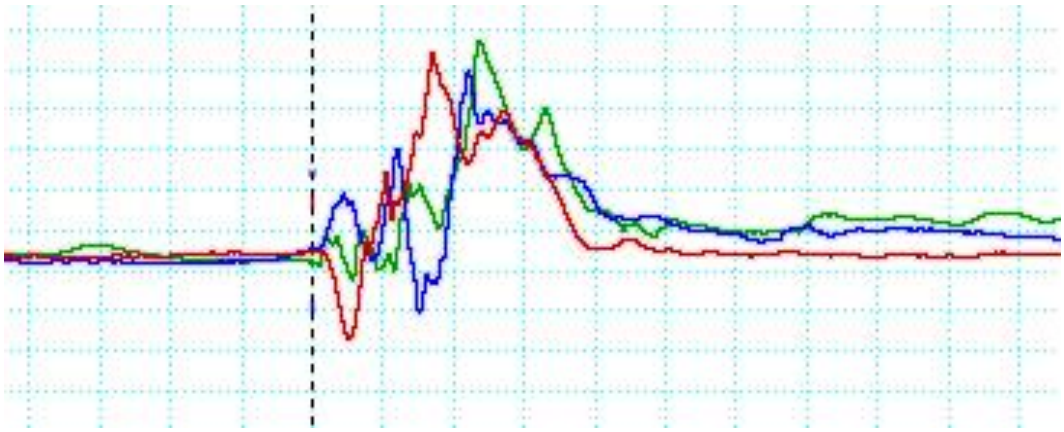


Figure 4-10: Subject 4 mid-lingual pressure.

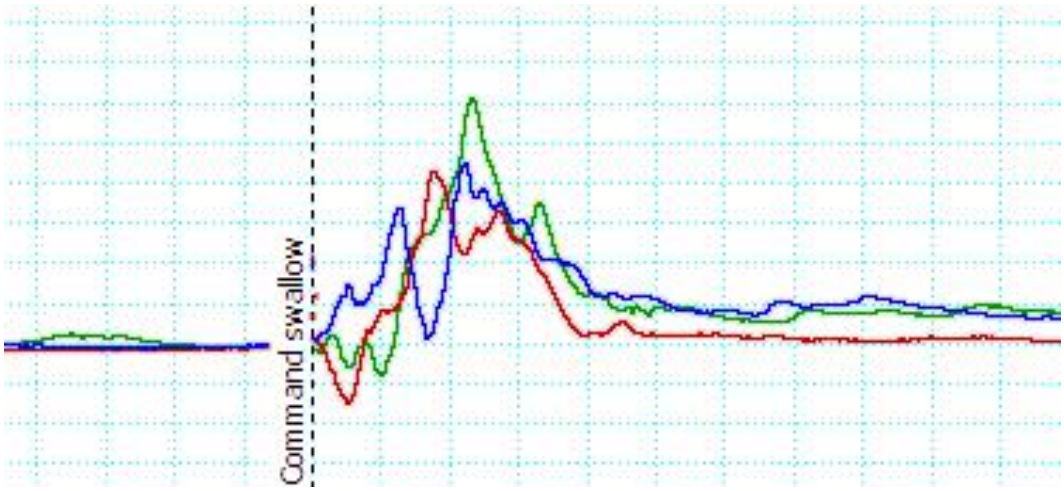


Figure 4-11: Subject 4 canine lingual pressure.

Subject 6

For subject 6, labial pressure increased with the 4.5mm tray when compared with the previous two trays (Figure 4-12, 4-13).

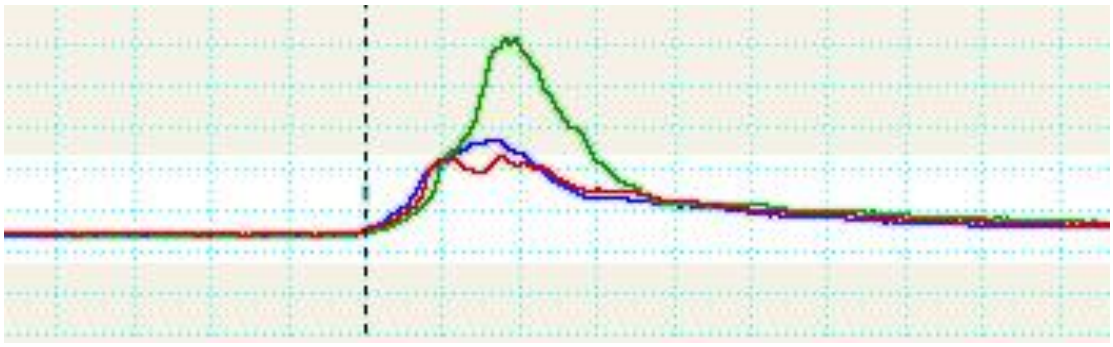


Figure 4-12: Subject 6 canine labial pressure. Note the increase in pressure with the 4.5mm tray shown in green.

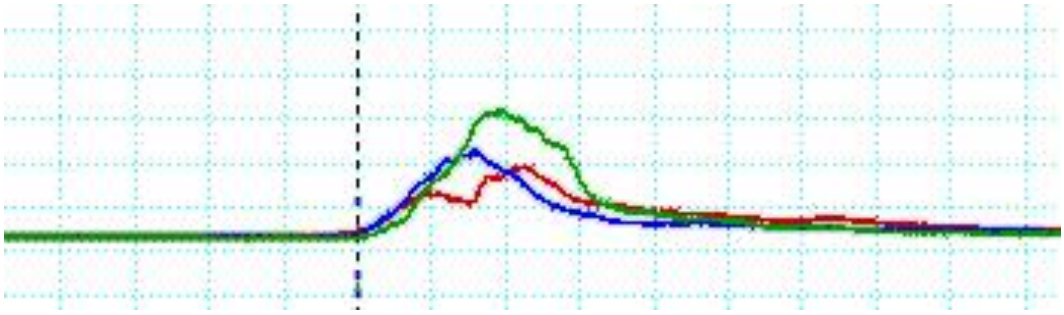


Figure 4-13: Subject 6 mid-labial pressure.

For the lingual pressure patterns, the pattern and timing remained very similar across the three different trays, although the peak pressure was reached slightly later for the 4.5mm tray when compared with the 0.5mm and 2.5mm trays (Figure 4-14, 4-15).

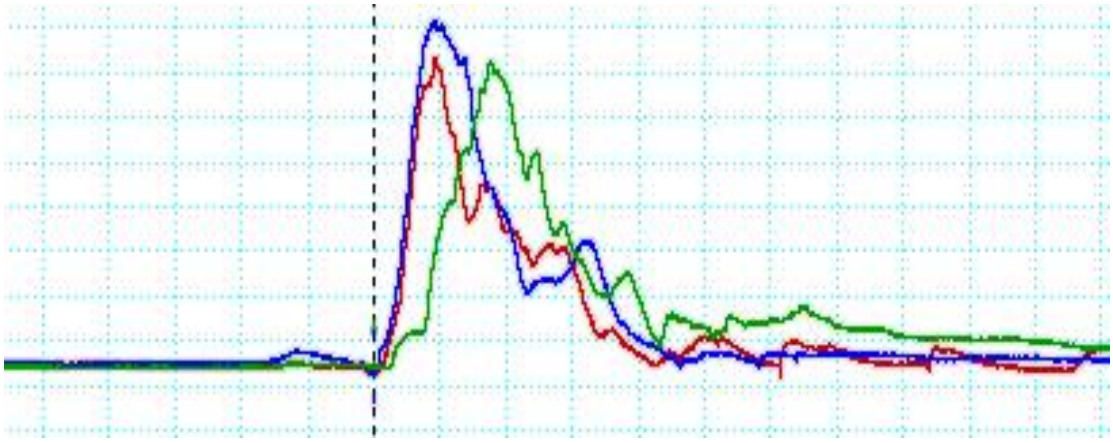


Figure 4-14: Subject 6 mid-lingual pressure.

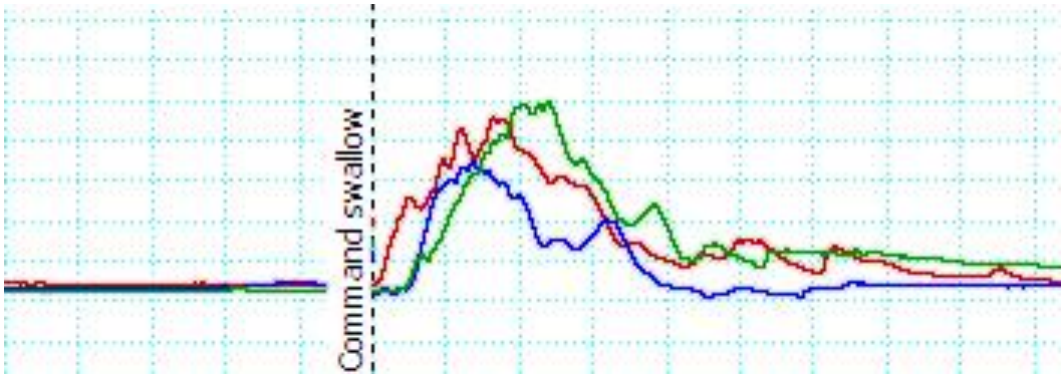


Figure 4-15: Subject 6 canine lingual pressure.

Subject 7

Subject 7 was another of the lip-incompetent subjects in our sample, and showed the most complex pattern of swallowing among our subjects at all four pressure sites (Figure 4-16 to 4-17). The swallow pattern remained relatively similar across all three tray thicknesses, with the pressure profile on the lingual surface of the lower incisors being more complex than on the labial surface.

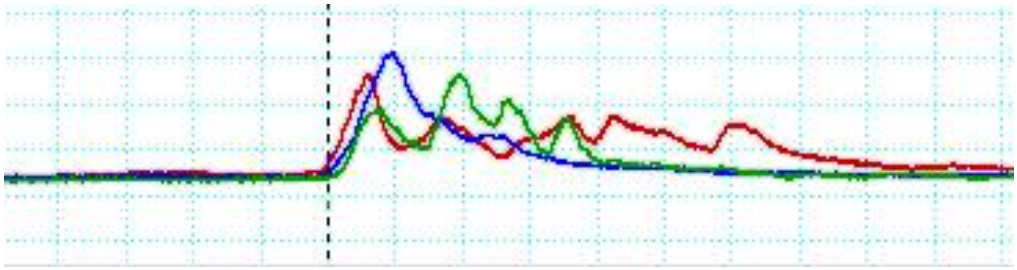


Figure 4-16: Subject 7 canine labial pressure. Note the multiple pressure peaks generated with the 4.5mm tray in place.

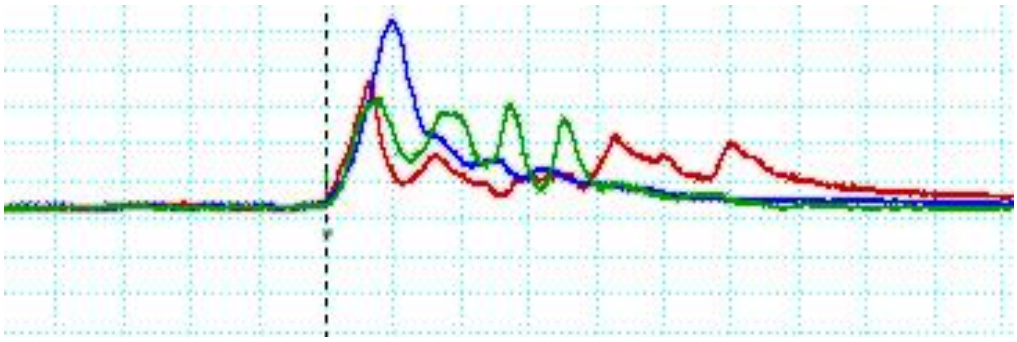


Figure 4-17: Subject 7 mid-labial pressure.

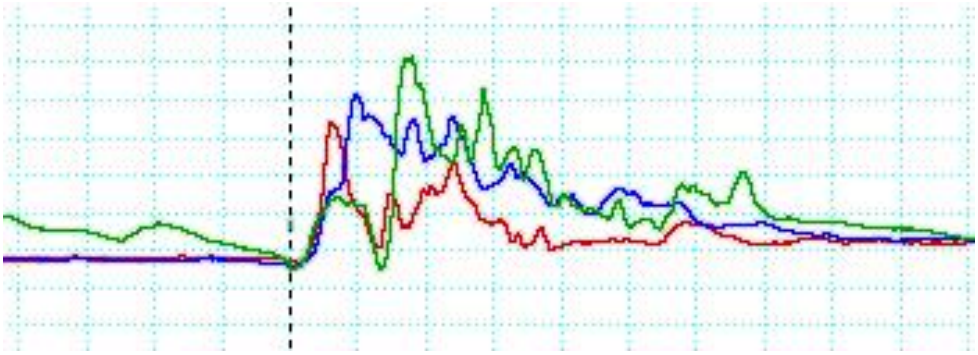


Figure 4-18: Subject 7 mid-lingual pressure. The pressure pattern in maintained as the lower lip is advanced, although there are more peaks with the 2.5mm (blue) and 4.5mm (green) trays. The shape and amplitude of the peaks are similar across all three trays.

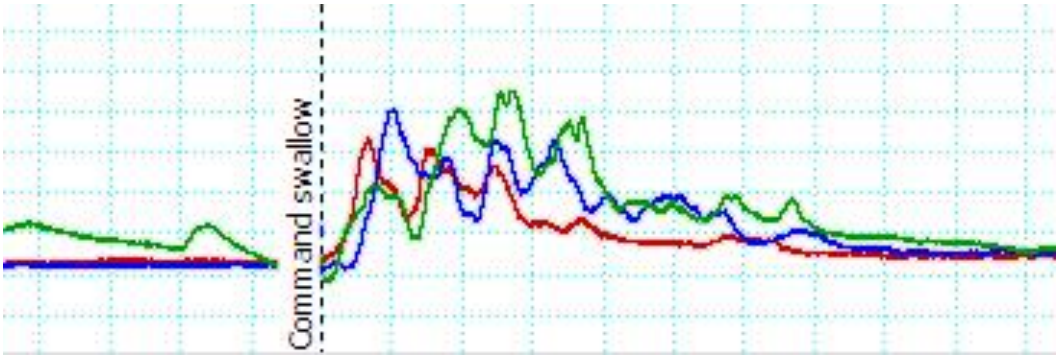


Figure 4-19: Subject 7 canine lingual pressure. Again, the pressure pattern is roughly maintained as the thickness of the tray increases, with each pressure profile showing four main peaks.

Subject 9

For this subject, the overall scale of lingual pressure had to be increased, as the pressure generated was much larger than any of the other subjects and would not fit into the scale used. Hence the grid the lingual swallows are displayed on is slightly higher in the vertical dimension than the labial swallows.

Pressure on the canine labial site stayed fairly stable with advancement of the lower lip as shown in Figure 4-20. The mid-labial site was also relatively similar, although more pressure was generated during the command swallow with the 0.5mm tray in place than the 2.5mm or 4.5mm tray (Figure 4-21).

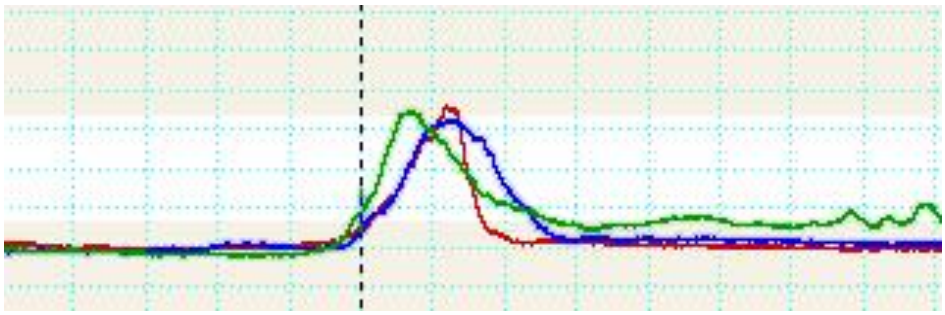


Figure 4-20: Subject 9 canine labial pressure. The pattern of pressure is maintained throughout advancement of the lower lip.

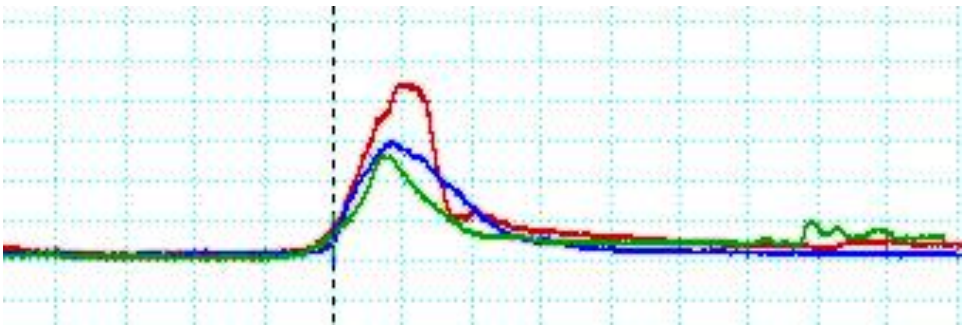


Figure 4-21: Subject 9 mid-labial pressure. The pattern of pressure is maintained for all three trays, although the pressure generated is slightly more for the 0.5mm tray (shown in red).

Pressure at the mid-lingual site was greatest during the 0.5mm swallow, which decreased with the 2.5mm swallow and decreased again with the

4.5mm swallow (Figure 4-22). At the canine lingual site, pressure was again greatest with the 0.5mm tray, and then decreased to a similar level for the 2.5mm and 4.5mm trays (Figure 4-23).

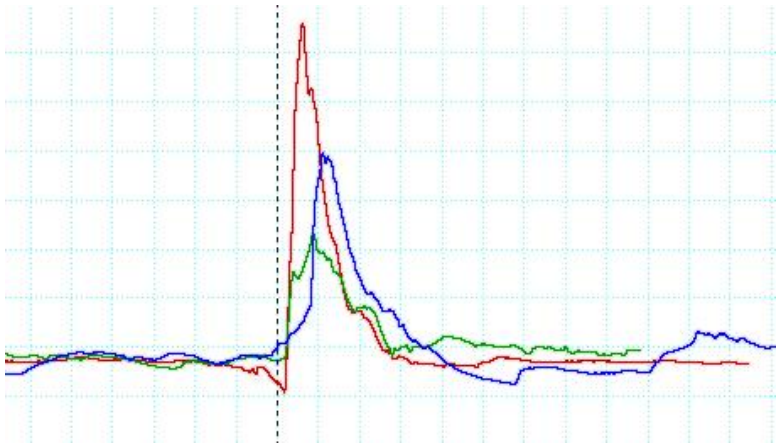


Figure 4-22: Subject 9 mid-lingual pressure. Again, the pattern of the pressure profile is similar across all three of the trays, although the peak pressure for the 0.5mm tray is similar.

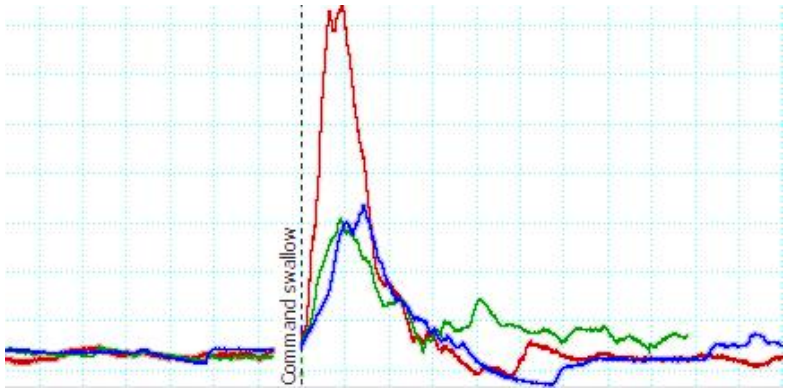


Figure 4-23: Subject 9 canine lingual pressure.

Subject 10

Subject 10 also showed differential pressure generation on the labial surface for each of the three trays (Figures 4-24, 4-25). The pressure for the 2.5mm and 4.5mm tray was greater than for the 0.5mm tray, although the pressure pattern for each tray was remarkably similar.

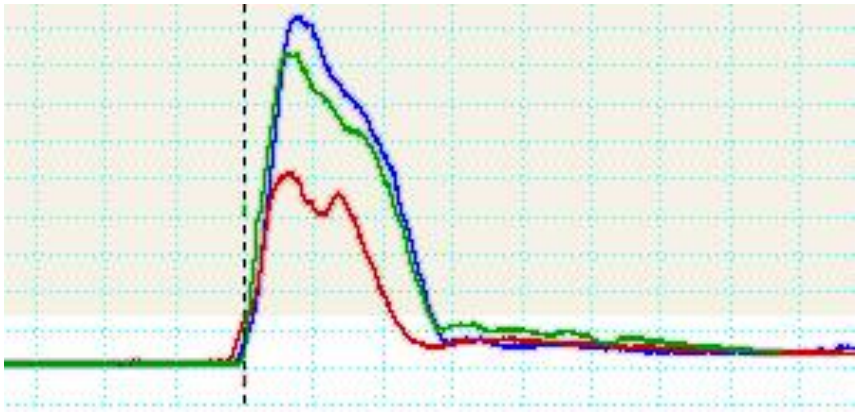


Figure 4-24: Subject 10 canine labial pressure.

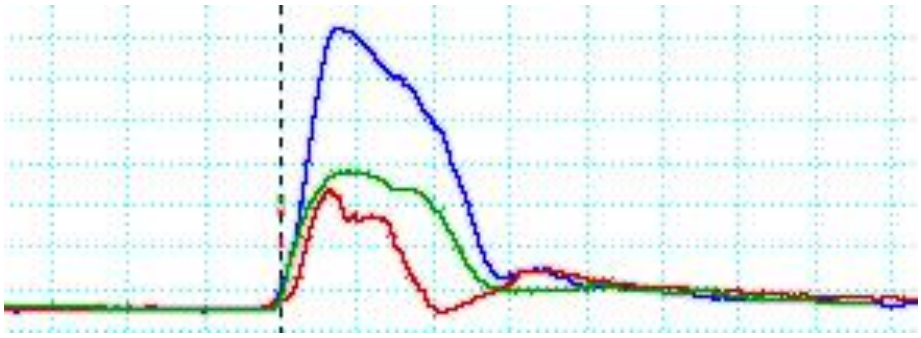


Figure 4-25: Subject 10 mid-labial pressure.

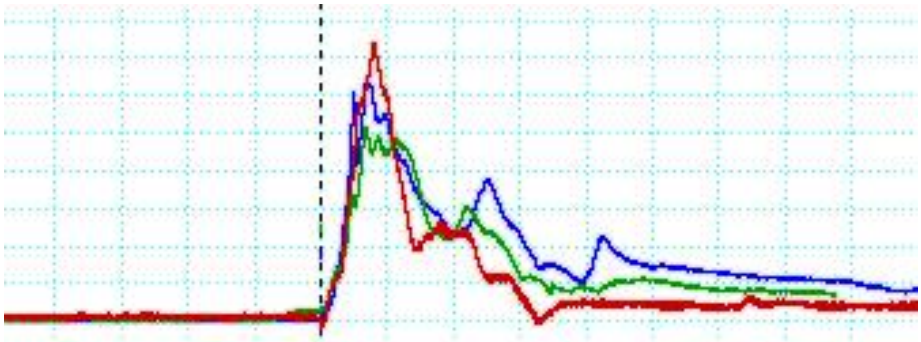


Figure 4-26: Subject 10 mid-lingual pressure.

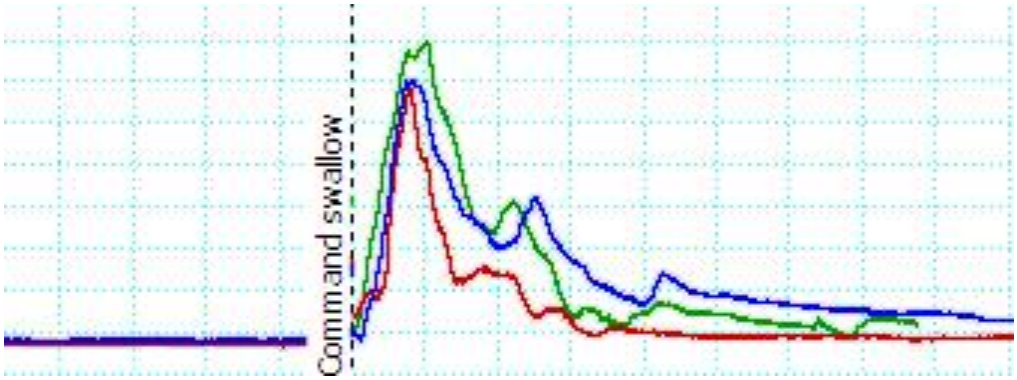


Figure 4-27: Subject 10 canine lingual pressure.

4.3.1 Swallow reproducibility

To assess intra-subject variability, the second, third and fourth swallow (if present) were overlaid using the initiation point as a reference. The variation between swallows was low, which suggests the pattern of swallow for each individual is reproducible and individual specific. Table 4-1 shows examples of swallows from subjects 8, 9 and 10. Each trial represents an individual swallow.

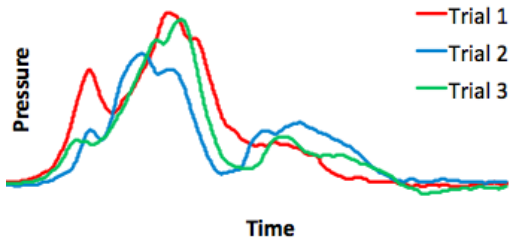
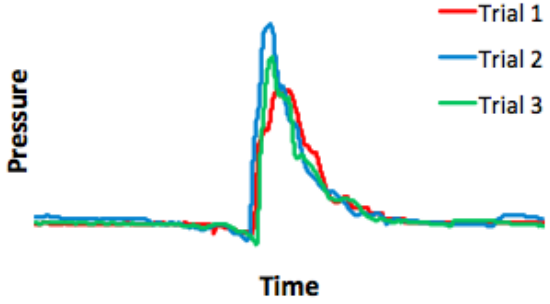
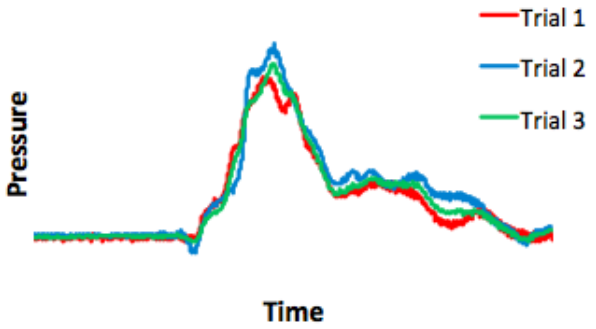
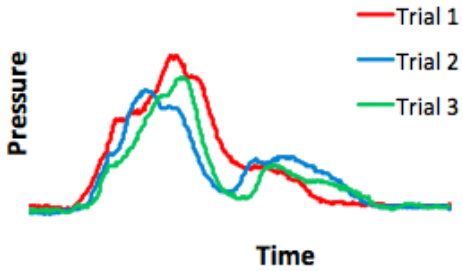
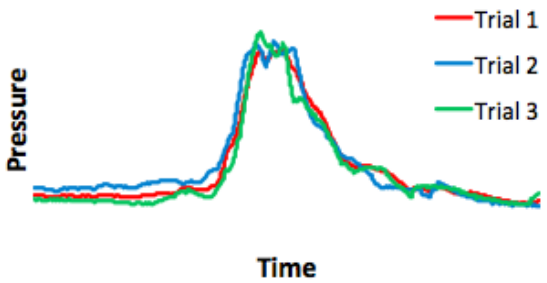
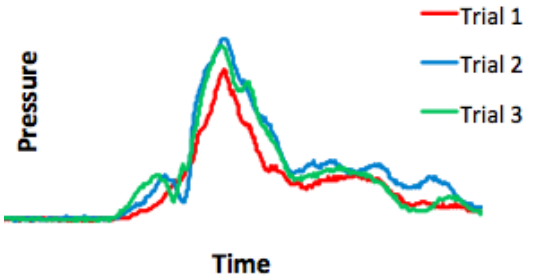
	Subject 8	Subject 9	Subject 10
Mid-lingual channel			
Canine lingual channel			

Table 4-1: Command swallows for subjects 8, 9 and 10 showing the mid-lingual and canine lingual channels. Note the reproducibility of the three swallows (trial 1, 2 and 3) on both channels.

4.3.2 Fourier analysis

The Fourier transform analysis described above was used to analyse the swallowing patterns of nine subjects. As stated above, subject 1 was removed from this portion of the analysis due to differences in the time lapsed between command swallows. The first swallow was also removed, as this was frequently a different pattern to the subsequent swallows (Figure 4-28 to 4-30).

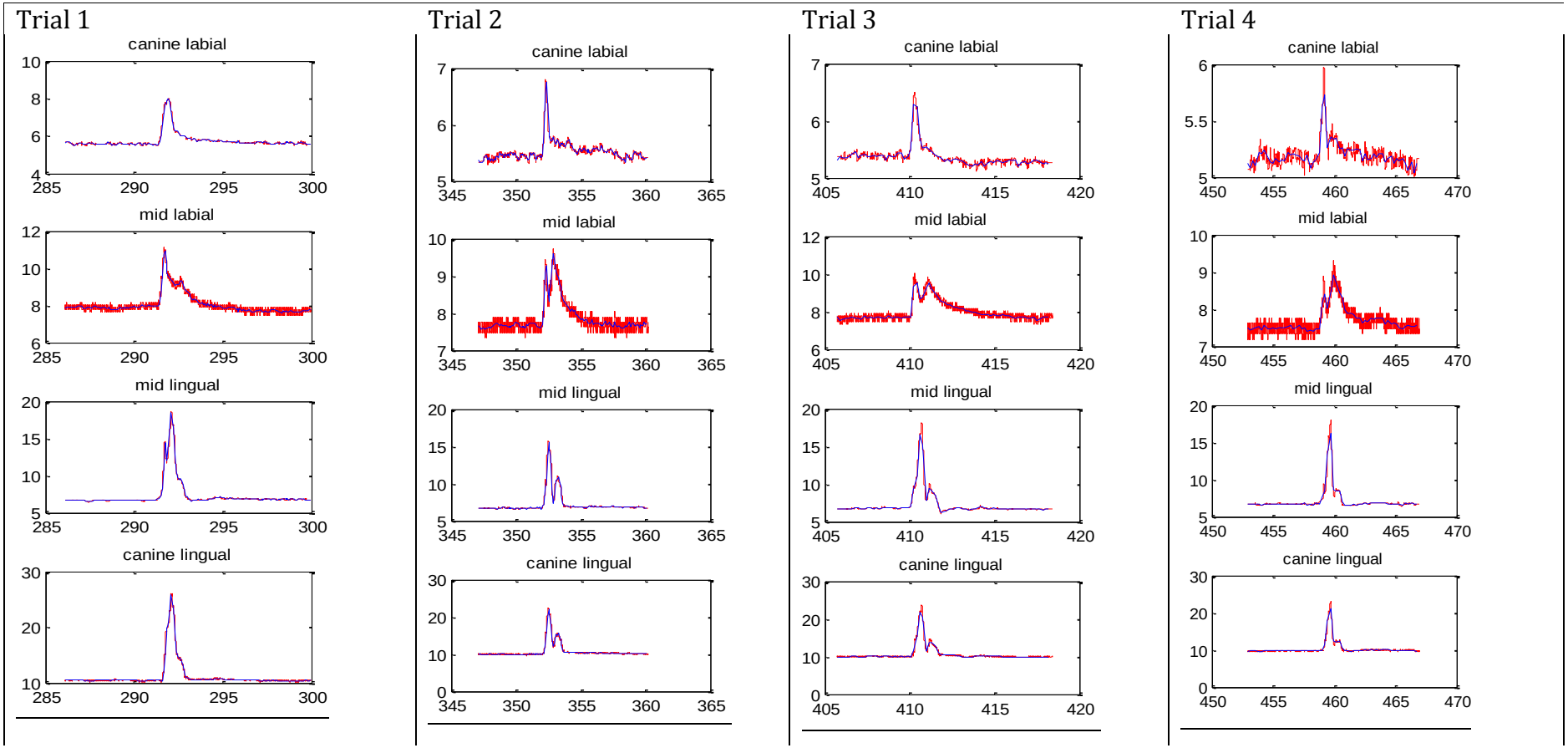


Figure 4-28: Graphs showing pressure on the y-axis and time on the x-axis for subject 8, 0.5mm tray. The red line represents the Fourier transform data prior to FFT smoothing, the blue line represents the data after smoothing.

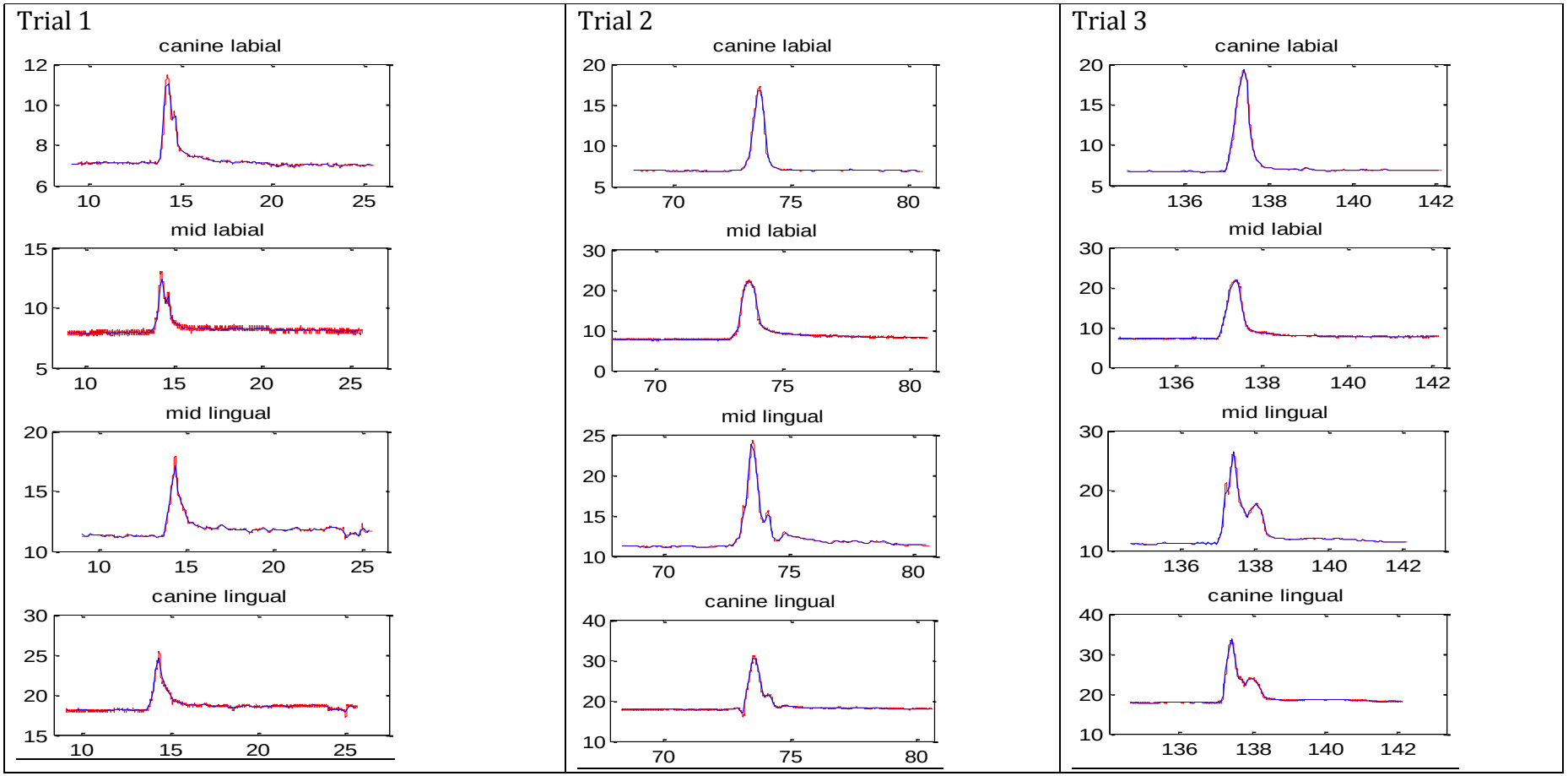


Figure 4-29: : Graphs showing pressure on the y-axis and time on the x-axis for subject 8, 2.5mm tray. The red line represents the Fourier transform data prior to FFT smoothing, the blue line represents the data after smoothing.

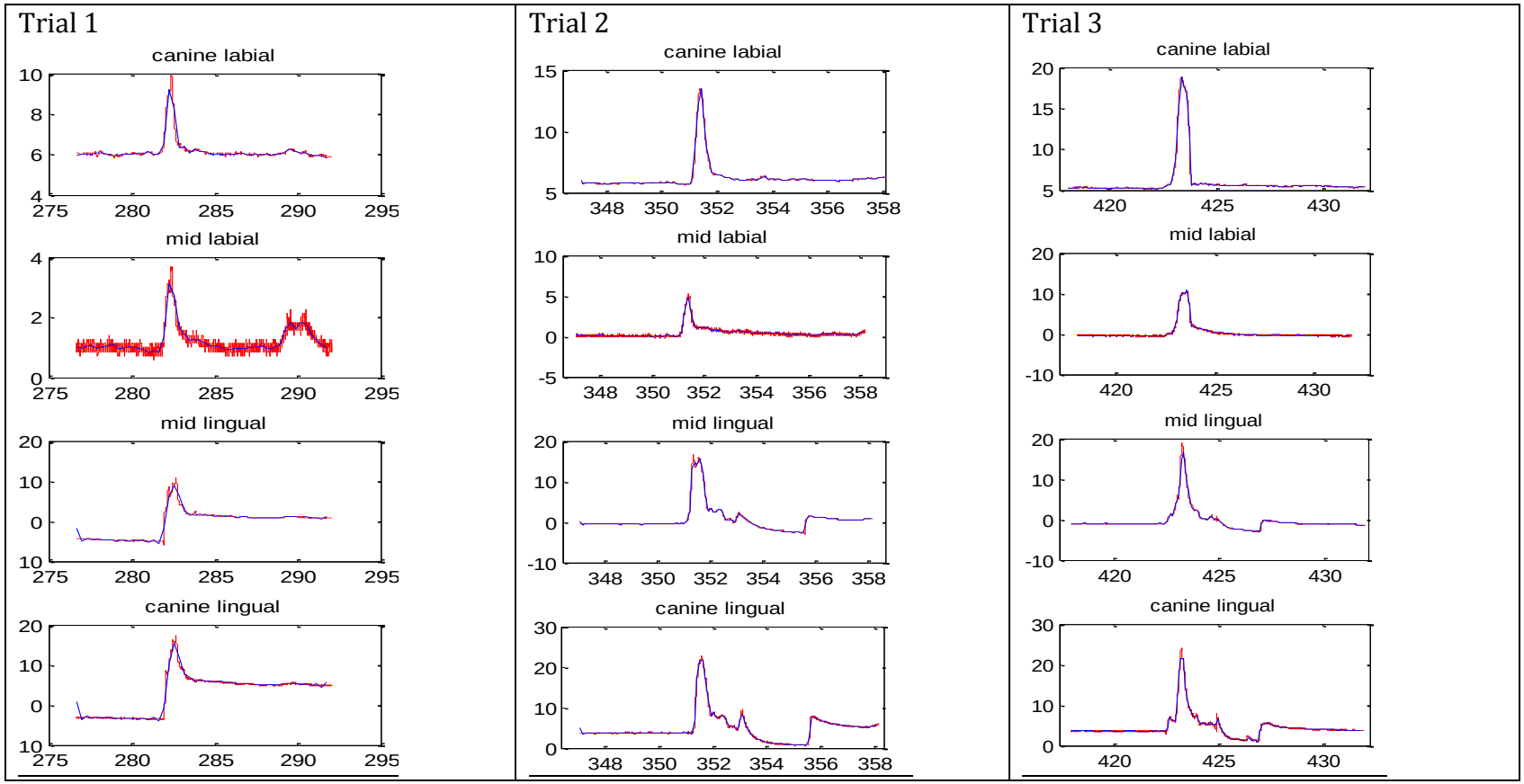


Figure 4-30: Graphs showing pressure on the y-axis and time on the x-axis for subject 8, 4.5mm tray. The red line represents the Fourier transform data prior to FFT smoothing, the blue line represents the data after smoothing.

MATLAB was used to plot the Fourier transforms of the averaged smoothed pressure time series, the plots of which are shown below. As discussed above, the plots were made using both a standard scale with the Fourier coefficient on the y-axis and the normalized frequency on the x-axis (Figures 4-32, 4-33). A semi-logarithmic base 10 scale was also used, and is represented in the graphs below with the log of the Fourier coefficient on the y-axis and the normalized frequency on the x-axis (Figures 4-34, 4-35). In both types of plot, higher points are more relevant than the lower ones (these are more likely to be signal interference), hence more attention should be paid to the higher points when interpreting the graphs. This is especially relevant when interpreting the semilog-y plots. The plots use the key as shown in Figure 4-31 to identify subjects.

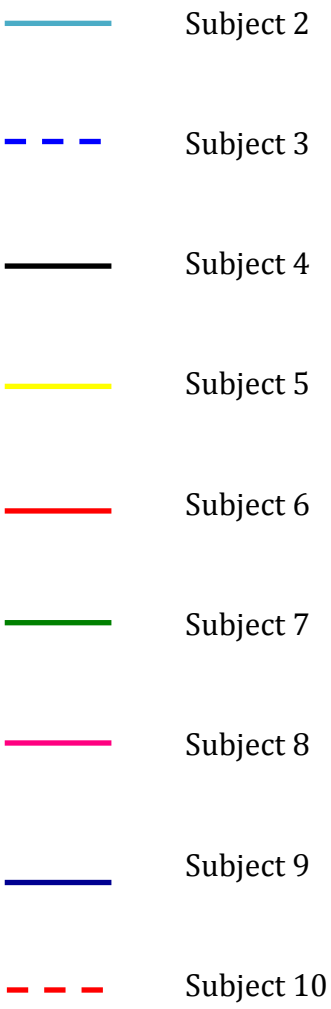
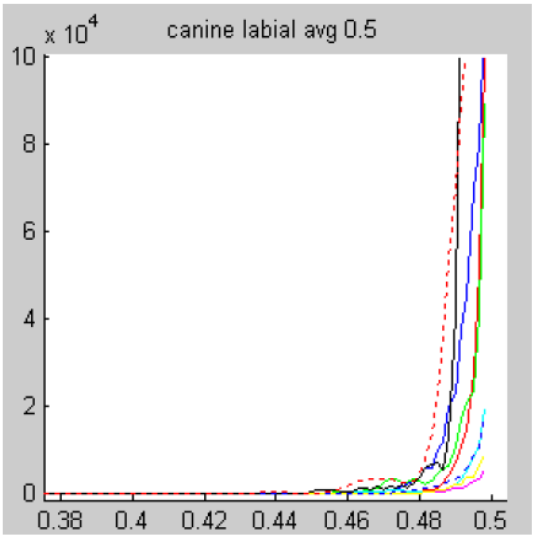


Figure 4-31: Key used to identify subjects included in the Fourier analysis

4.4 Fourier analysis for 0.5mm tray



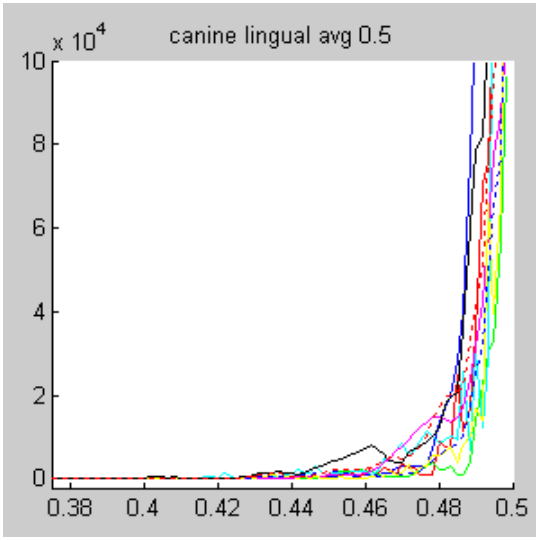
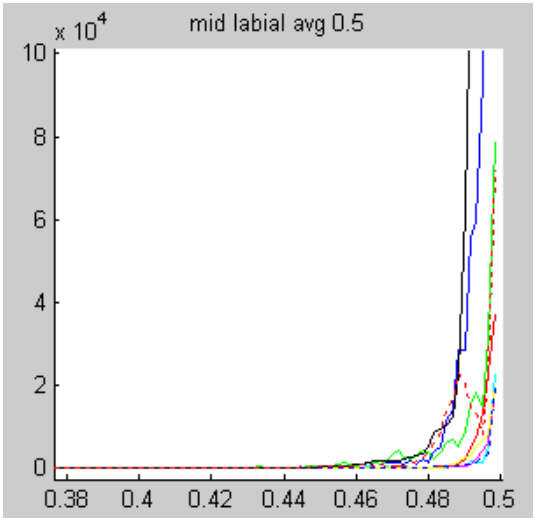


Figure 4-32: Part of the Fourier transform of averaged smoothed pressure time series at the canine labial and canine lingual sites with the 0.5mm tray, showing the relative positive frequencies.



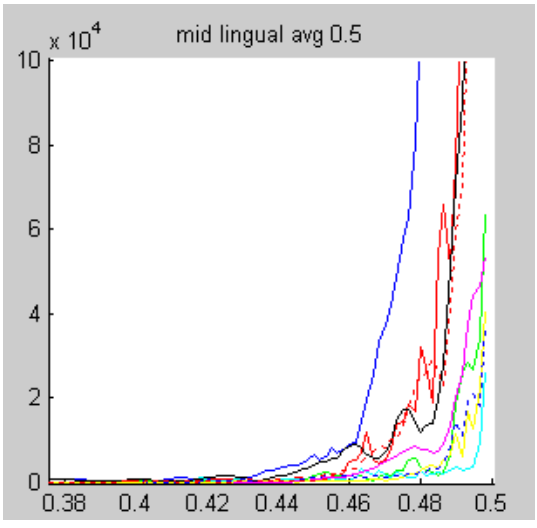


Figure 4-33: Part of the Fourier transform of averaged smoothed pressure time series at the mid-labial and mid-lingual sites with the 0.5mm tray, showing the relative positive frequencies.

On visual analysis of the 0.5mm Fourier analysis, it appears there is more variation among subjects in the command swallow at the midline than at the canine sites for both the labial and the lingual swallows. The mid-lingual site shows the greatest inter-individual variation between swallowing patterns for the 0.5mm tray.

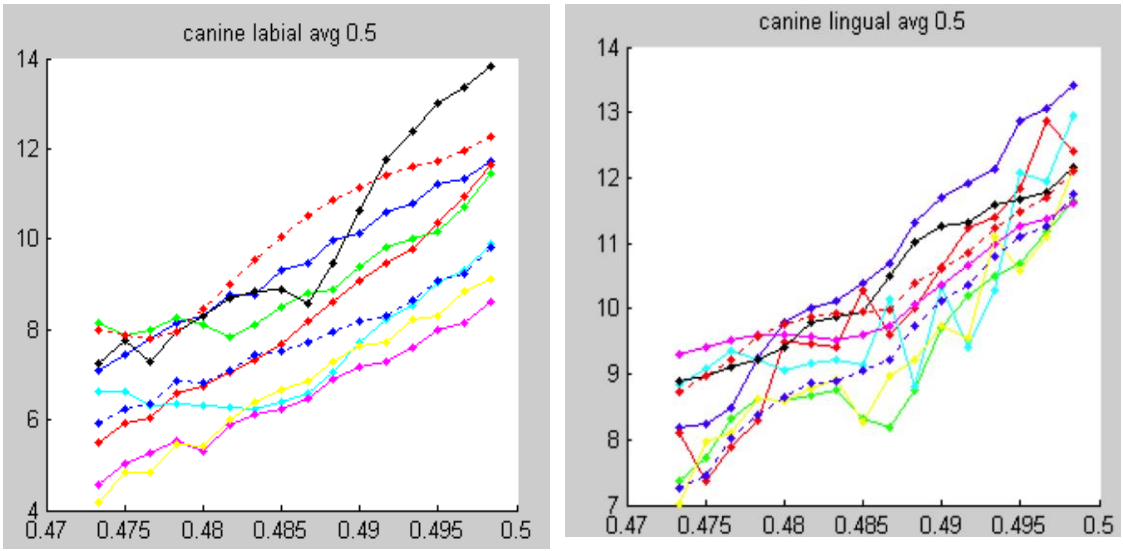


Figure 4-34: Part of the Fourier transform at the canine sites for 0.5mm tray, showing the relative positive frequencies on a semilog-y base 10 scale.

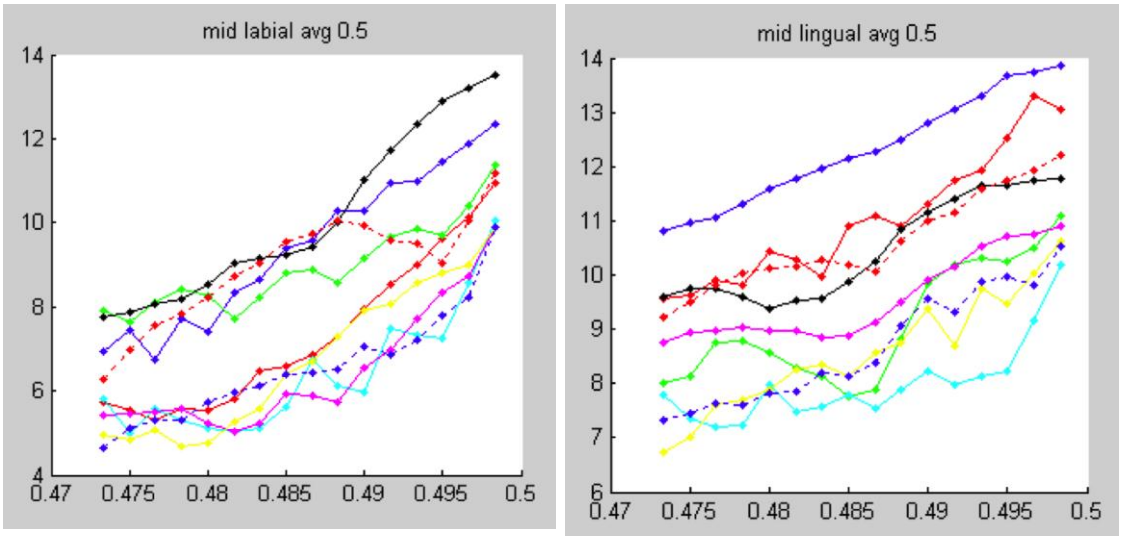


Figure 4-35: Part of the Fourier transform at the midline sites for the 0.5mm tray, showing the relative positive frequencies on a semilog-y base 10 scale.

4.5 Fourier analysis for 2.5mm tray

The 2.5mm tray showed the least amount of inter-individual variation of the three trays shown by the Fourier plot being relatively similar for each individual. There was very little variation between subjects for the canine and mid-labial sites, and slightly more variation for the lingual sites. (Figure 4-36 to 4-37).

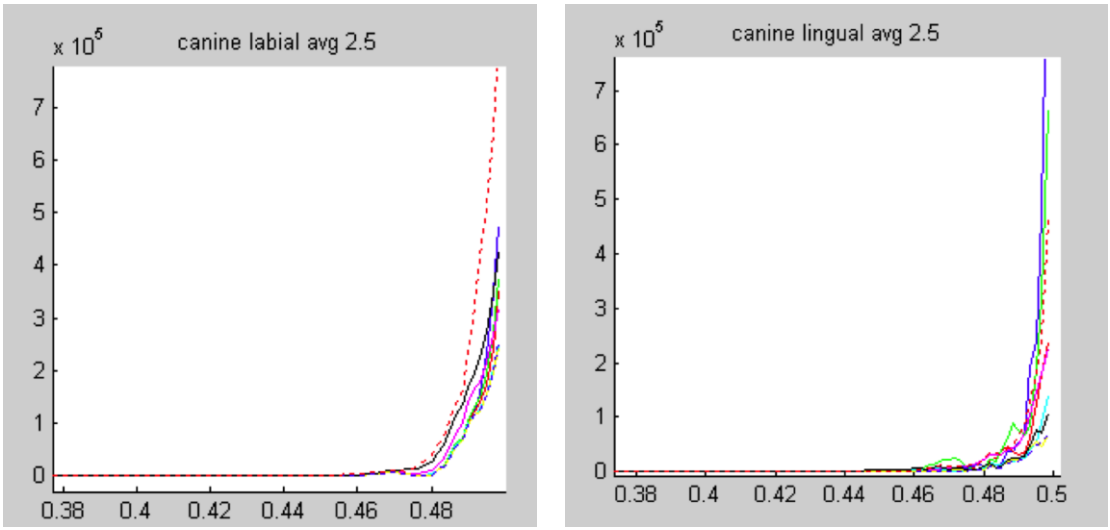


Figure 4-36: Part of the Fourier transform of averaged smoothed pressure time series at the canine labial and canine lingual sites with the 2.5mm tray, showing the relative positive frequencies.

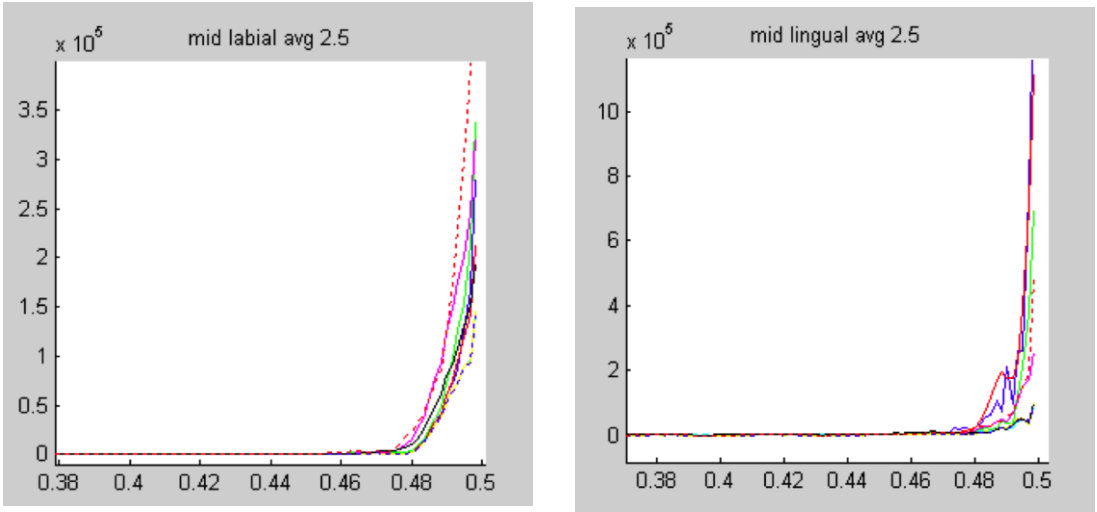


Figure 4-37: Part of the Fourier transform of averaged smoothed pressure time series at the mid-labial and mid-lingual sites with the 2.5mm tray, showing the relative positive frequencies.

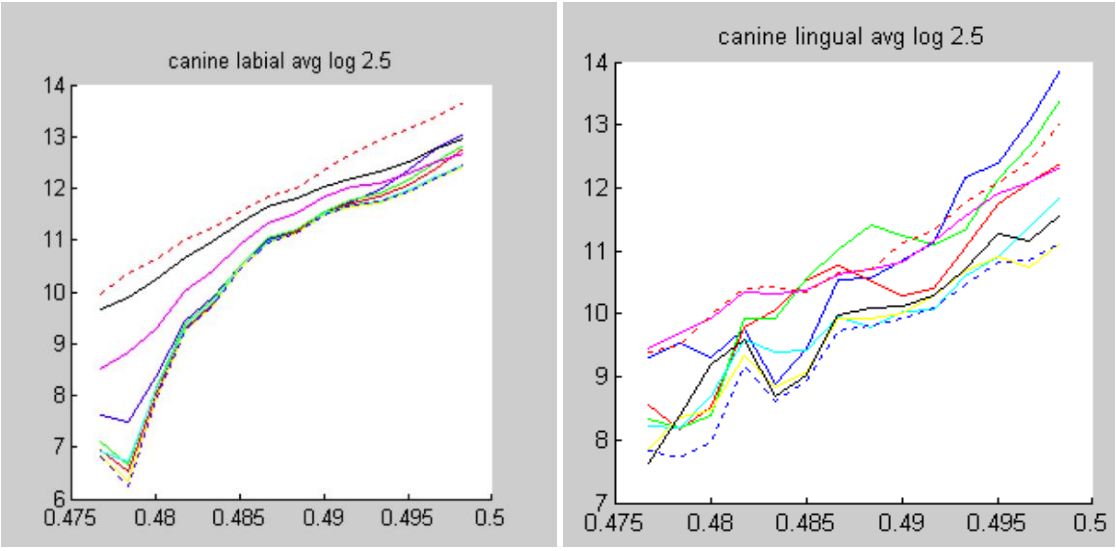


Figure 4-38: Part of the Fourier transform at the canine sites for 2.5mm tray, showing the relative positive frequencies on a semilog-y base 10 scale.

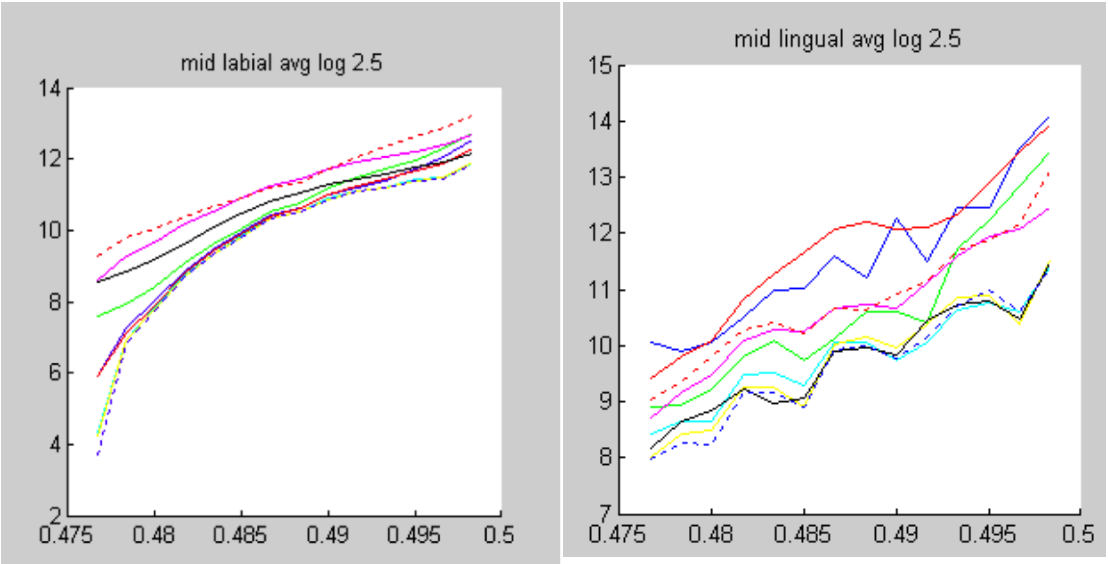


Figure 4-39: Part of the Fourier transform at the midline sites for the 2.5mm tray, showing the relative positive frequencies on a semilog-y base 10 scale.

4.6 Fourier analysis for the 4.5mm tray

Visual analysis of the Fourier plots for the 4.5mm tray shows an increased amount of inter-individual variation when compared with the 2.5mm tray. In contrast to the previous two trays, the 4.5mm tray shows more inter-individual variation at the labial sites than at the lingual sites. This suggests that advancement of the lower lip interferes with anterior oral seal, and each individual deals with this in a different manner.

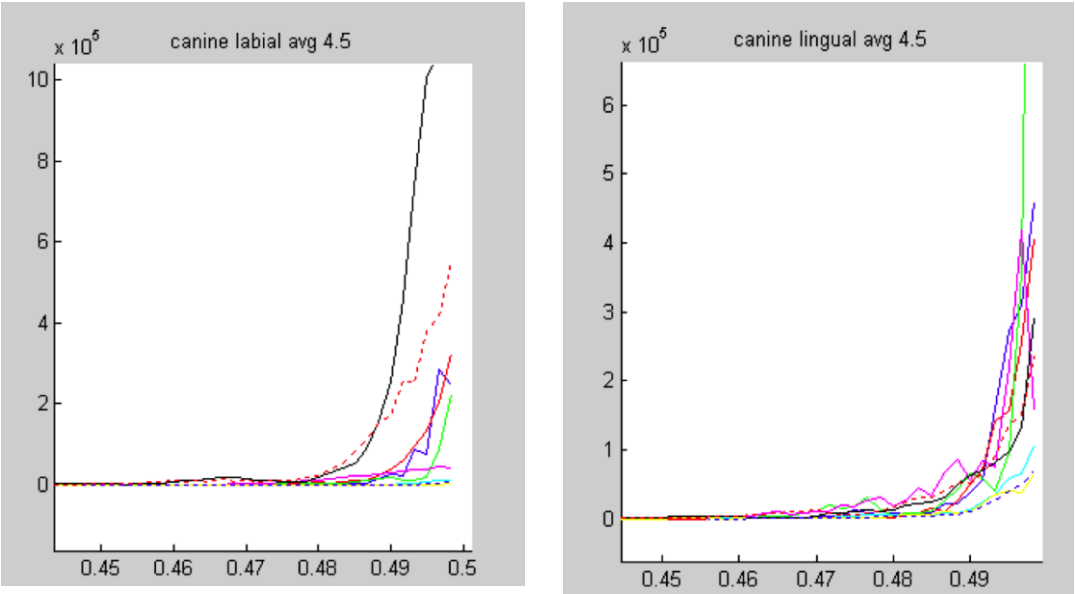


Figure 4-40: Part of the Fourier transform of averaged smoothed pressure time series at the canine labial and canine lingual sites with the 4.5mm tray, showing the relative positive frequencies.

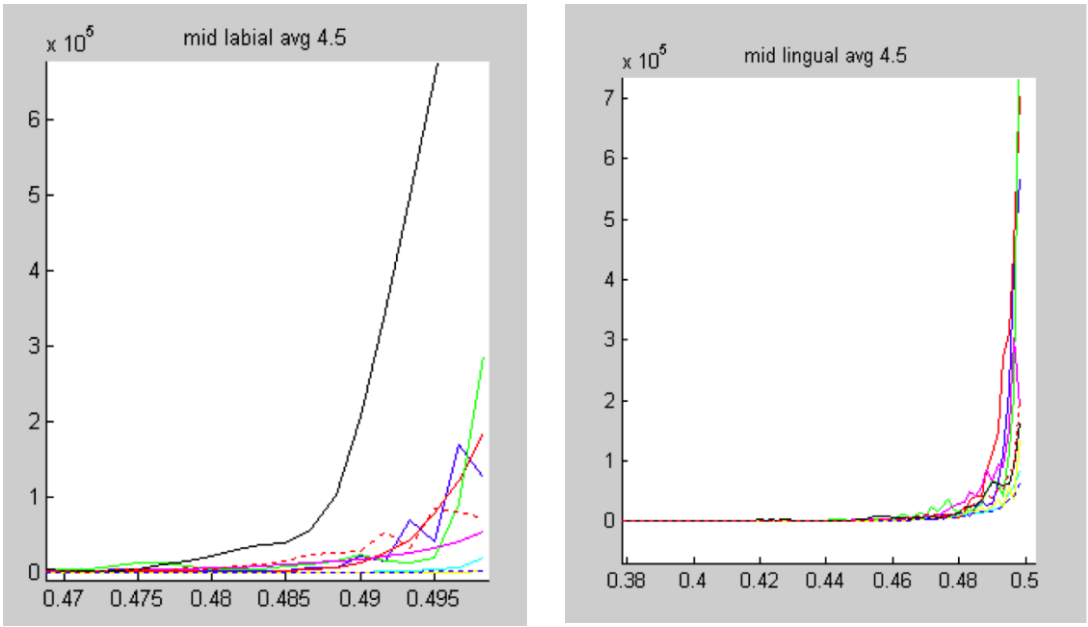


Figure 4-41: Part of the Fourier transform of averaged smoothed pressure time series at the mid-labial and mid-lingual sites with the 4.5mm tray, showing the relative positive frequencies.

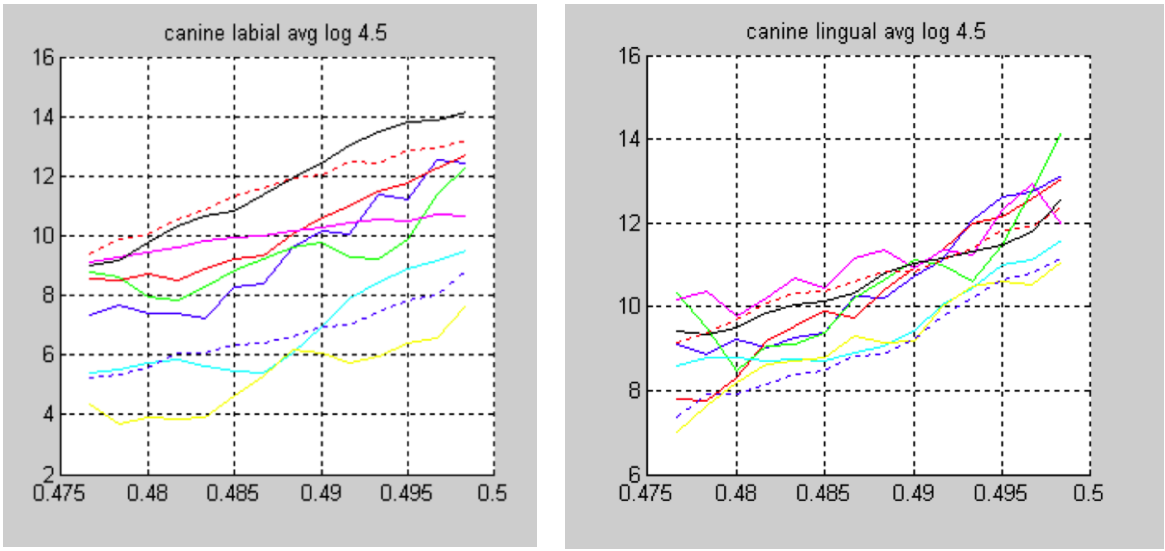


Figure 4-42: Part of the Fourier transform at the canine sites for 4.5mm tray, showing the relative positive frequencies on a semilog-y base 10 scale.

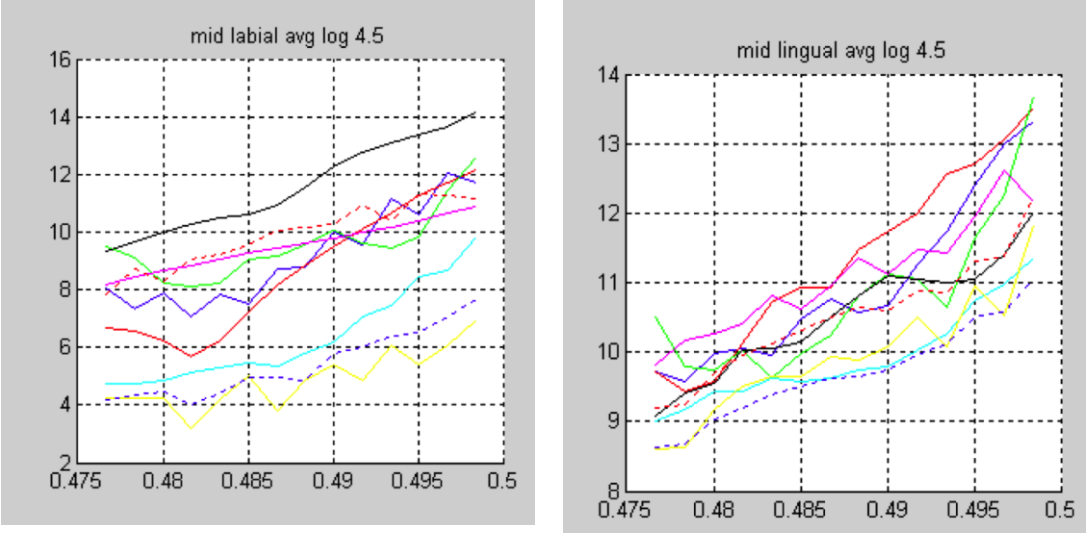


Figure 4-43: Part of the Fourier transform at the midline sites for the 4.5mm tray, showing the relative positive frequencies on a semilog-y base 10 scale.

5 Discussion

The purpose of the current study was to determine the effect of incrementally advancing the lower lip on oral pressure, electromyographic (EMG) activity and swallowing. Pressures at the midline and at the canine were recorded both at rest and during swallowing, during which EMG activities of the orbicularis oris and mentalis muscles of the lower lip were also measured.

5.1 Static tasks

5.1.1 Reliability of measurement

As discussed in the literature review, one of the difficulties with this research area is that the measurement techniques generally have large measurement errors. To compare the errors associated with our technique to similar techniques used by previous authors, the coefficient of variation was calculated and is listed in Table 5-1. The results from the current study have coefficients of variation which are generally lower than those reported in similar studies.

Table 5-1: Comparison of coefficient of variation (CV) between the present study and previous studies using similar methods.

Study	Type of sensor	Channel (lower arch)	Tray thickness	Mean pressure (g/cm^2)	Standard deviation ($g/cm^{2)}$	CV (%)
Present study	Pressure transducer	*Mid-labial*	0.5	14.6	6.4	**44**
			2.5	24.3	8.6	**35**
			4.5	28.2	8.0	**28**
		Canine labial	0.5	17.6	6.9	**39**
			2.5	19.3	10.6	**55**
			4.5	22.3	9.2	**41**

Study		Channel (lower arch)	Tray thickness	Mean pressure (g/cm^2)	Standard deviation ($g/cm^{2)}$	CV (%)
Moawad *et al.* (1996)	Pressure transducer	*Mid-labial*	Baseline	7.4	6.8	**92**
			2.5	13.5	6.8	**50**
		Canine labial	Baseline	4.5	4.3	**96**
			2.5	9.2	8.1	**88**
Archer and Vig (1985)	Strain gauge	*Mid-labial*	Baseline	3.8	3.7	**97**
Hellsing and L'Estrange (1987)	Strain gauge	*Mid-labial*	Baseline	8.6	4.1	**48**

5.1.2 Labial pressure generated at baseline

As discussed in the literature review, a number of methodological techniques have been employed over the years in an attempt to decrease the large experimental errors associated with this research area. This makes comparing the results of the present study with those of previous authors problematic. One investigation where similar experimental methods were used was the series of studies completed by Moawad *et al.* (1996) and Shellhart *et al.* (1996, 1997). The authors reported much lower resting pressures than those found in the present study. There are a number of possible explanations for this. Firstly, there were large coefficients of variation associated with the pressure recordings from both studies, as seen in Table 5-1. Secondly, the previous authors described their sample as containing Class I subjects; however, no description of the soft tissue characteristics of their sample was provided. As a convenience sample was used in our study, our sample contained subjects with varying soft tissue profiles, including three subjects with incompetent lips and protrusive profiles. It may be that the differences in soft tissue profile and muscular anatomy between the two samples led to differences in the magnitude of pressure generated. However, the relationship between soft tissue profile and muscle strength is currently unclear. Posen (1976) proposed that subjects with increased muscle tone generated more pressure on the incisor teeth than those with low muscle tone. In an attempt to further investigate this theory, Thüer, Ingervall, and Janson completed a series of studies in the mid-80's (Thüer *et al*, 1985; Thüer and Ingervall, 1986). The study sample comprised 50 children aged 7-13 years prior to orthodontic treatment. A range of occlusions (10 Class I, 38 Class II and one Class III) and cephalometric characteristics were studied. The initial investigations focused on the relationship between lip morphology, EMG activity and lip strength (which was assumed to equate to lip muscle tone) (Ingervall and Janson, 1981; Janson and Ingervall, 1982). No relationship was found between lip morphology (length or thickness) and either EMG activity or lip strength. To further clarify how this finding relates to incisor position, the authors attempted to correlate the above

factors with the position of the anterior dentition. Again, no significant relationship was demonstrated. The authors concluded that muscle forces generally have a small influence on incisor position.

To further investigate the conclusion drawn from the above study, Thüer and Ingervall (1986) investigated the relationship between lip morphology and strength and the pressure generated on the incisor teeth. Again, no relationship was found between these factors. The investigators concluded that this finding was in agreement with their earlier conclusion, and that lip morphology and tone have only a minor effect on incisor position. However, for a number of reasons the above findings should be interpreted with caution. Firstly, lip strength was measured with a dynamometer, and as discussed in the literature review, the subjects were asked to contract their lips and resist the pull of the dynamometer. Therefore, the lip strength recorded was the maximum lip strength generated by that individual. How this relates to the resting tone of the musculature is unclear. Secondly, the study sample was much younger than our subject group, with a greater range of malocclusions (all of our subjects had a Class I incisal relationship). Finally, the experimental errors in the measurements in the above studies were large, particularly for the lip strength recordings, with intra-individual variation often being higher than inter-individual variation. For these reasons, it remains unclear what the relationship between lip morphology, muscle tone and lip pressure actually is, and how the use of a convenience sample of differing soft tissue profiles would have affected our results.

5.1.3 Comparison between labial pressure sites

In this study, there was no statistically significant difference between the pressures at the mid-labial and canine labial sites. This is in contrast to previous research (Moawad *et al.*, 1996; Shellhart *et al.,* 1996) (Table 5-2).

	Moawad *et al.* (1996)	Present study
Mid-labial	7.5 ± 6.8	14.6 ± 6.4
Canine labial	4.6 ± 4.4	17.6 ± 6.9

Table 5-2: Comparison between baseline pressures recorded in the present study and by Moawad *et al.* (1996). Measured in g/cm² ± standard deviation.

5.1.4 Effect of lower lip displacement on lip pressure

A number of authors have reported that the pressure generated by the lip and cheek musculature increases significantly once a pressure sensor is positioned more than 2-3mm from the tooth surface (Gould and Picton, 1964; Weinstein *et al.*, 1963). Moawad *et al.* (1996) demonstrated a significant rise in the pressure generated at both the midline and canine labial site when the lower lip was advanced 2.5mm from the tooth surface. To further this idea, the lower lip was advanced a further 2mm in the present study, so that oral pressure was measured when the pressure transducer was located at both 2.5mm and 4.5mm from the tooth surface. It was initially hypothesised that as the lip was advanced, pressure would increase in a linear fashion at both the mid-labial and canine labial sites. However, a statistically significant increase in pressure was only detected at the mid-labial site, no significant pressure increase was recorded for the canine labial site at either 2.5mm or 4.5mm advancement. A comparison between our results and those of Moawad *et al.* (1996) is made in Table 5-3.

	Mid-labial baseline	Mid-labial 2.5mm advancement	Mid-labial 4.5mm advancement	Canine labial baseline	Canine labial 2.5mm advancement	Canine labial 4.5mm advancement
Present study	14.6 ± 6.4	24.3 ± 8.6**	28.2 ± 8.0**	17.6 ± 6.9	19.3 ± 10.6	22.3 ± 9.2
Moawad *et al.* (1996)	7.5 ± 6.9	13.7 ± 6.9**	N/A	4.6 ± 4.4	9.4 ± 8.3**	N/A

Table 5-3: Comparison of pressure changes seen when the lower lip is incrementally advanced. Measured in g/cm^2 ± standard deviation. ** denotes the pressure was significantly different from baseline pressure.

The reason for the different responses seen in our study is likely due to site-dependent differences in muscular anatomy. As discussed in the literature review, the adaptation response for the canine site has been demonstrated to be more complex and difficult to predict. A number of muscles intersect adjacent to the canine, at a junction known as the modiolus (Norton, 2007). Hence, the muscle fibres in this area are greater in number and less homogeneous in direction. At the lower midline, the adjacent musculature comprises of the mentalis and the orbicularis oris muscles, which are generally smaller and more homogeneous. It is likely that in our subject group, the muscular anatomy at the canine site led to the pressure response to lip advancement being more varied and individual specific, than the response at the midline. The wide variation in response, combined with our small sample, means our study may have lacked the power to pick up a defined response profile at the canine site. It is probable that if the study were repeated with more subjects, a statistically significant change in muscle behaviour at the canine site would be recorded.

5.1.5 Overall pressure response profile at the mid-labial site

The overall response profile recorded at the mid-labial site showed a gradual increase in pressure as the lip was incrementally advanced, with more pressure change recorded from baseline to 2.5mm advancement than from 2.5mm to 4.5mm advancement. In other words, there was a significant quadratic term with a negative coefficient.

One of the difficulties in interpreting our findings and comparing them to previous research is that both the active and passive properties of lip muscle were investigated. In the present study, the mentalis and orbicularis oris muscles were stretched during lip advancement, which made attaining oral seal more difficult once the most advanced tray was in place. As the participants were asked to keep their lips together during the tasks, the lower lip was actively contracted to ensure oral seal. In most subjects, active contraction was most noticeable with the 4.5mm tray in place; however, the lip-incompetent individuals displayed active lip contraction

with all three trays. This leads to difficulty in understanding the muscle response seen, as it is due to both passive and active muscle properties.

The response of lip muscle to passive stretching has been well investigated in the literature (Chu *et al.,* 2009; Ho *et al.*, 1982; Barlow and Muller, 1991). Chu *et al.* (2009) laterally stretched the lower lip incrementally in an adult male population and recorded the change in lip pressure. Subjects were asked to keep the lips as relaxed as possible to ensure only the passive properties of the muscle were measured, which was verified by zero EMG activity being recorded as the lip was stretched. The authors demonstrated a positive quadratic relationship, with pressure gradually increasing as the lip was stretched (Figure 5-1).

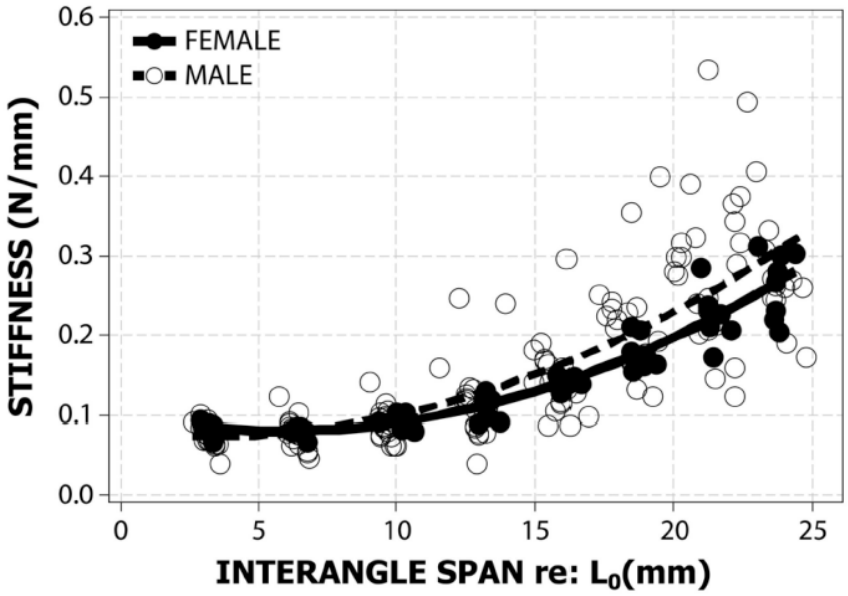


Figure 5-1: Regression functions for both male (dotted black line, open circles) and female subjects (solid black line, filled circles). A positive quadratic trend was demonstrated for both male and female subjects (Chu *et al.,* 2009; Seibel and Barlow, 2007).

As noted above, the relationship between lip stretch and pressure generated in the current study was also a quadratic equation, although the function was negative. There are a few possible explanations for the differences seen between our study and that of Chu *et al.* (2009). Firstly, the earlier study used only subjects with "good soft tissue profiles" where

our convenience sample included subjects with protrusive profiles and incompetent lips. Although no relationship has been demonstrated between lip morphology and lip pressure (Thüer and Ingervall, 1985; Ingervall and Janson, 1981; Janson and Ingervall, 1982), it is still a possibility that differences in lip morphology and thickness in our subject group may have led to a difference in lip behaviour seen with advancement. Secondly, Chu *et al.* (2009) only investigated the passive behaviour of the musculature to stretching. As our subjects were asked to maintain oral seal during our study, our measurements also include active contraction, particularly as the lip was advanced from 2.5mm to 4.5mm. Finally, Chu *et al.* (2009) investigated the lip response to lateral stretch, where we recorded the lip response to forward advancement.

5.1.6 Individual variation in response seen

At the midline, a highly significant subject/tray response was seen, which indicated that the response to lower lip advancement was dependent on the individual. Half the subject group showed increasing lip pressure as the lower lip was advanced, while the other half showed an inverted "v" shaped response profile, with pressure decreasing slightly between the 2.5mm and 4.5mm tray. One possible explanation for the decrease in pressure seen with the 4.5mm tray involves the properties of the skeletal muscle itself. Studies have shown that the total force generated by a skeletal muscle (assumed in our study to equate to the amount of pressure recorded on the teeth) is the summation of the passive forces and active forces, both of which are influenced by the length of the muscle. As discussed above, the passive forces generated increase exponentially as the muscle is stretched (Chu *et al.*, 2009; Gajdosik, 2001). The amount of active force generated is greatest at the muscle's "optimal length", which is often the same as its resting length. As the muscle is either lengthened or shortened away from this optimal length, the active forces generated decrease. As a result the active forces generated show a parabolic force-length relationship (Figure 5-2).

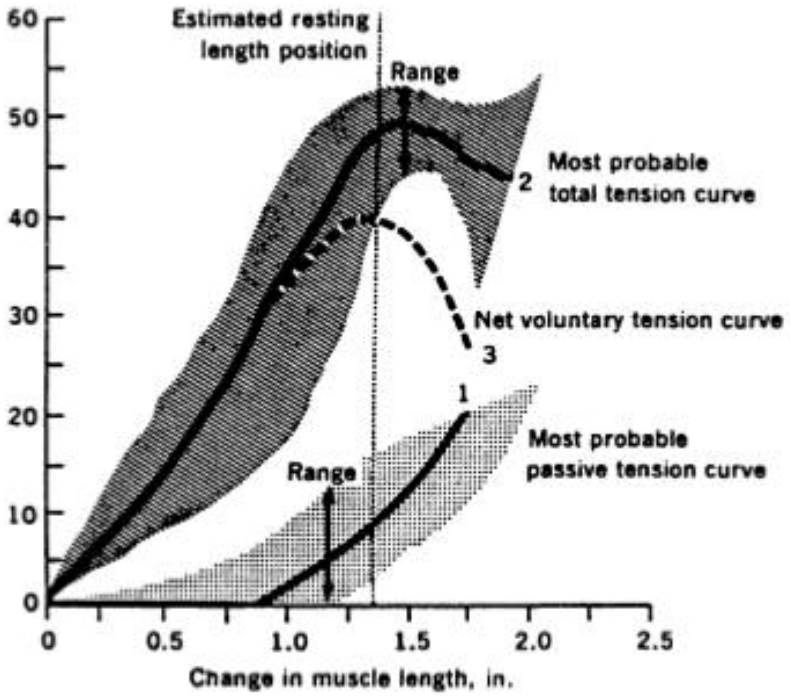


Figure 5-2: Classic length-tension curves for skeletal muscle. The lower line indicates that as the muscle is passively lengthened the force generated (shown on the y-axis) gradually increases. The middle line shows that the active force generated on muscle contraction decreases as the muscle is either lengthened or shortened away from the resting length position. The top curve shows the likely total tension curve, which is constructed from the combination of the passive and active muscle behaviours (from Astrand and Rodahl, 1986).

It is possible that in half our subject group, the lip musculature was stretched significantly beyond its optimal length, leading to a decrease in the active component of the force generated, which caused a decrease in the pressure recorded on the teeth with the 4.5mm tray in place.

5.2 Static electromyographic (EMG) activity tasks

5.2.1 Effect of lower lip displacement on EMG activity

As discussed previously, pressure from the oral musculature is derived from two sources, the inherent viscoelastic properties of the lip and electrical activity from the muscle itself (Ho *et al.,* 1982; Yemm, 1974). By recording both the EMG activity of the lower lip musculature and the

pressure on the lower incisors at the midline, a comparison of the two muscular properties can be made as the lower lip is advanced.

In this study, there was no significant increase in EMG activity with the first 2mm advancement of the lower lip. This indicates that the initial pressure increase on the lower incisors was likely derived from the viscoelastic properties of the lip, rather than from an increase in active muscle contraction. The lower lip was then advanced a further 2mm with the 4.5mm tray. With this tray in place there was a significant increase in the EMG activity of the orbicularis oris and mentalis muscles.

As all the subjects were asked to keep their lips together during the static tasks, this increase in muscular activity was most likely associated with an attempt to maintain anterior oral seal under challenging conditions. A number of authors have found that the mentalis muscle is the main muscle involved in maintenance of oral seal (Stavridi and Ahlgren, 1992; Gustaffson and Ahlgren, 1975), so it seems reasonable that when oral seal is challenged, active contraction in this muscle increases.

Although only three of the ten participants were lip-incompetent, it is interesting to investigate the individual response of these subjects. Two of the three lip-incompetent subjects showed a decrease in EMG activity when the 4.5mm tray was placed. They were the only subjects in this study to have that response, EMG activity either stayed at a similar level or increased for the other subjects. It seems likely that these subjects were unable to keep their lips fully in contact with the 4.5mm tray in place, leading to a decrease in EMG muscle activity at that level of lip advancement.

5.2.2 Effect of mandibular rest position on EMG activity

The effect of having the teeth together or slightly apart in mandibular rest position was statistically significant, with more EMG activity recorded with the teeth apart than when the teeth were in contact. However, the

differences in EMG activity were only slight, so it is unlikely the difference is clinically significant.

5.2.3 Clinical relevance of static tasks

There is still a lack of knowledge surrounding the response of the lower lip to advancement and how this response affects the long-term position of the lower teeth. In orthodontics, the anterior limit of the dentition is often advanced to create room for alignment of the teeth (Proffit *et al*, 2006). It has been proposed that excessive proclination of the incisors may impinge on the soft tissue space and may be unstable long-term (Ackerman and Proffit, 1997). This study showed that there was a significant increase in pressure generated by the lower lip with an initial advancement of 2.5mm. Subsequent advancement from 2.5mm to 4.5mm did not lead to a considerable increase in pressure. Electromyography measurements of the lower lip indicated that the increased pressure in the initial advancement was mainly derived from the inherent viscoelastic properties of the lower lip. In contrast, the pressure increase in the 2.5mm to 4.5mm advancement was derived largely from increased muscular activity. This is clinically relevant as it indicates that it is the first 2.5mm of advancement which generates the greatest pressure increase on the lower teeth, and that this increase is mainly due to the inherent viscoelastic properties of the muscle itself. There was also a significant subject x tray interaction in both the pressure and EMG response of the lower lip, which indicates that the response differed markedly across individuals. In some subjects the viscoelastic response was low, while in others it was high.

At present, there is a trend towards non-extraction treatment in orthodontics (Kandasamy and Woods, 2005), which involves expansion of the lower arch. This research indicates that the position of the teeth affects the amount of pressure generated by the lower lip, and also suggests that in patients with high viscoelastic muscle tone, the lower lip will generate more pressure. It is proposed that in these patients proclination of the lower labial segment would be less stable long-term. It is possible that in

future the assessment of the viscoelastic tone of the lip musculature may be a significant part of orthodontic records. This may assist the orthodontist determine how stable expansion treatment is likely to be in the long-term.

5.3 Swallowing tasks

As stated earlier, due to the amount of data collected, only the saliva swallow tasks will be discussed in the present thesis.

5.3.1 Ratio of tongue to lip pressure

The balance (or lack thereof) between the lip and the tongue pressures on swallowing has been extensively studied over the years. In the present study, significantly more pressure was generated on the lingual surface for all three trays. This finding supports previous research done by Proffit *et al.* (1964), Fröhlich *et al.* (1991) and Thüer and Ingervall (1985) who all found increased pressure on the incisors on the lingual surface compared to the labial surface. In 1978, Proffit suggested a tongue to lip pressure ratio of 50:20, or 2.5 to 1. The pressure ratio found between peak lip and tongue pressures during saliva swallow in this study was approximately 2:1 (Table 5-4).

	Midline site (lingual:labial)	Canine site (lingual:labial)
0.5mm tray	12.2 : 5.7 = **2:1**	13.7 : 6.2 = **2:1**
2.5mm tray	11.2 : 7.0 = **2:1.2**	12.6 : 7.8 = **2:1.2**
4.5mm tray	15.2 : 6.9 = **2:1**	14.4 :10.2= **2:1.4**

Table 5-4: Ratio of peak tongue to lip pressure recorded during saliva swallow in g/cm² (to one decimal place).

It is interesting that the tongue to lip pressure ratio was roughly maintained throughout advancement of the lower lip. As the mentalis muscle has been found to be the key muscle in maintaining anterior oral seal (Gustafsson and Ahlgren, 1975), one could speculate that more pressure would have been generated by this muscle once the oral seal was challenged with the 4.5mm tray, causing the ratio between the lip and tongue to become more even. Instead, the ratio between lip and tongue pressure remained fairly stable as the lower lip was advanced.

5.3.2 Swallowing pressures generated on the labial tooth surface

In the present study, most subjects displayed an increase in labial pressure compared with baseline during saliva swallowing. This finding is in agreement with the work of Proffit *et al.* (1964), Gould and Picton (1964) and Luffingham (1969), although it is in contrast to Winders (1958) who reported no significant change from resting lip pressure on swallowing, except in anterior open bite subjects. All the subjects in the present study demonstrated light lip pressures (<20 g/cm^2) on swallowing, which is in agreement with the findings of Proffit *et al.* (1969). As the lower lip was advanced, the majority of subjects maintained light lip pressure on the lower incisors, although two subjects did demonstrate slightly heavier forces.

5.3.3 Swallowing pressures generated on the lingual tooth surface

The mean pressures recorded on the lingual surface of the lower teeth in this study were considerably lower than pressures reported by previous authors. Proffit *et al.* (1975b) reported lingual mean peak pressures during saliva swallow of 120.5 g/cm^2 at the lower midline and 92.5 g/cm^2 at the lower right canine in his study of Australian Aborigines. Fröhlich *et al.* (1991) investigated lingual pressure in 25 young adults, and reported median pressure at the lower incisor on swallowing water of 332.9 g/cm^2. However, when this investigation was repeated, a much lower pressure of 110.8 g/cm^2 was reported (Fröhlich *et al.*, 1992). As discussed in the

literature review, differences in measuring techniques make comparison between studies difficult. In the studies by Proffit (1964, 1969, 1972, 1975a, 1975b) a strain gauge based design was used, where Fröhlich *et al.* used a hydraulic pressure measurement system. In our study, pressure transducers were used, as these have been found to be more accurate and less bulky than the strain gauge based designs (Shellhart *et al.,* 1997). It is likely that at least part of the reason such different pressure recordings were found is due to differences in the techniques and equipment used.

5.3.4 Negative pressure generation during swallowing

The role of negative pressure in bolus propulsion has been well-defined by a number of authors, and is a common event when measuring the pressures generated by the tongue against the hard palate (Kennedy *et al.,* 2010; Farland, 2011; Shaker *et al.,* 1988). In a study investigating tongue pressure generated against the palate during barium swallows, Shaker *et al.* (1988) described negative pressures at the mid-tongue that were associated with movement of the tongue away from the palate. Kennedy *et al.* (2010) measured water swallows in a group of six healthy volunteers, and found negative pressure generated at the anterior and hind palate in all subjects. Although negative pressures are a relatively common finding when investigating the tongue/hard palate interaction, this is not the case when studying the pressure generated on the lower incisors. Fröhlich *et al.* (1992) measured mean peak pressure generated on the lower incisors during water swallows, and found a few individuals demonstrated negative pressures, but this behaviour was not seen in the majority of the sample. Findings from the present study are in agreement with this, as only one subject (subject 4) showed consistent generation of negative pressures at both the midline and canine lingual sites across all three trays (Figure 5-3). However, comparisons between the two studies should be made cautiously, as our study investigated saliva swallows where the work by Fröhlich *et al.* (1991, 1992) looked at water swallows only. No studies were located that investigated the role of negative pressures in saliva swallows. If we

analysed the water swallows completed by our subjects, we may have found more negative pressure generated than during the saliva swallows.

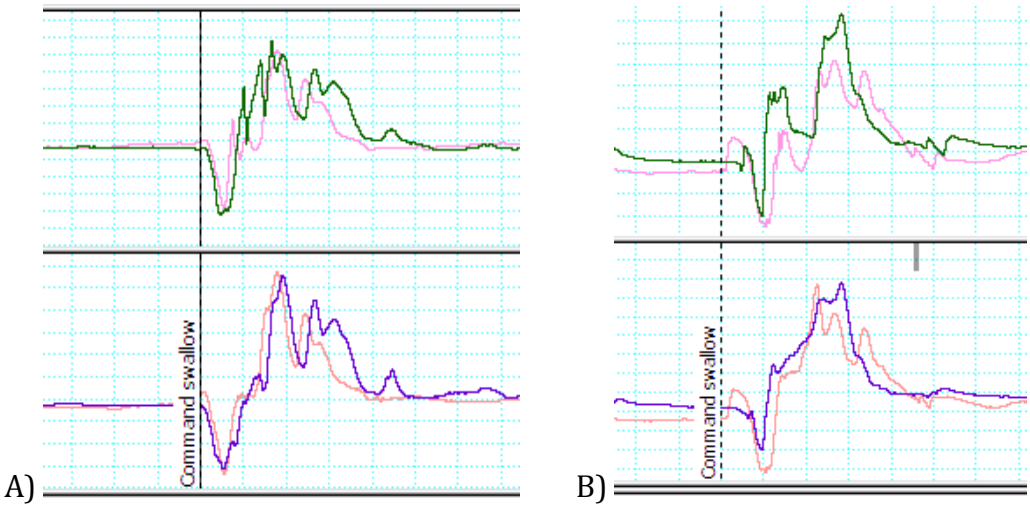


Figure 5-3: A) Subject 5 command swallow for the 0.5mm tray, and B) for the 4.5mm tray. The top channel represents the mid-lingual sensor, the lower channel the canine lingual sensor. The first command swallow is shown in the darker colour for each channel, the second swallow in the lighter colour. Note the initial negative pressure generated on both the lingual channels.

5.3.5 Pressures at the midline vs the canine site

The pressures generated at the midline and canine labial site were significantly different from each other with more pressure recorded at the canine site. This is in agreement with the findings of Thüer and Ingervall (1985), who also found the two sites were significantly different from each other with more pressure generated at the canine site. It seems likely that due to the more complex muscular anatomy adjacent to the canine, more pressure is generated at this site during function. No statistically significant difference was seen between the mid-lingual and canine lingual sites.

5.3.6 Effect of lip displacement on swallowing

Initially it was hypothesised that both the mean peak lingual pressure generated and the time taken to swallow would increase as the lower lip was incrementally advanced and oral seal was made more challenging for the subjects.

Effect on mean peak pressure on the lingual surface

As discussed in the literature review, individuals with incompetent lips achieve anterior oral seals by pushing the tongue forward to contact the lower lip (Gustafsson and Ahlgren, 1975). With the 4.5mm tray in place, the thick acrylic on the labial surface interfered with the subjects ability to seal their lips together, thereby making subjects less lip-competent. It was hypothesised that subjects may need to bring their tongue forward to make contact with the lip to achieve an oral seal, which in turn would result in increased pressure on the lingual surface. However, this did not occur. There were in fact no statistically significant changes in lingual pressure generated as the lower lip was experimentally advanced.

Effect on mean peak pressure on the labial surface

Initially, it was also hypothesised that lower lip advancement would be accompanied by an increase in lip activity seen at both the midline and canine sites, as subjects with lip incompetence display increased lip contraction on swallowing as the individual attempts to maintain anterior oral seal (Proffit *et al.*, 2006).

Mid-labial surface

There was no significant difference seen in the mean peak pressure at the midline as the lower lip was advanced. However, a highly significant tray/subject interaction was demonstrated for this site, indicating that the response of the lip to advancement was dependent on the individual. When the Fourier transforms were visually analysed it was clear that there was a large amount of inter-individual variation at the mid-labial site for each of the three trays. There seemed to be two distinct patterns of swallow at the baseline (0.5mm tray). Then, when the 2.5mm tray was inserted, the inter-individual variation decreased. The reason for this is unclear. It may be that there was an accommodation effect, as this was the second set of saliva

swallows the subjects had completed, so they were more accustomed to the apparatus, yet the advancement was not great enough to interfere with anterior oral seal. The largest variation was seen with the 4.5mm tray, which suggests that when anterior oral seal was challenged, each subject used their musculature in a different way to try and maintain anterior seal. As discussed earlier a small sample size was used in this study, so it may be that there was no difference in the pressure generated at the midline; or it may be that there was such a range of responses seen at this site, that statistically, one pattern of behaviour at the mid-labial site could not be defined. It is possible that if the study was repeated with a larger sample size, a definable pressure response profile for the midline site may be demonstrated.

Canine labial surface

Pressure generated on swallowing at the canine labial site increased significantly as the lower lip was advanced. Again, a highly significant tray/subject interaction was recorded, indicating that the pressure response at this site to advancement was individual dependent.

Length of the swallow

It was also initially proposed that the time taken to swallow would increase as the lower lip was advanced. This hypothesis was derived both from work completed within our department, and also from other sources (Farland, 2011; Tallgren *et al.*, 1995). It has been found that a number of factors increase the work done by the oral musculature, which also increases swallow duration. One example of this is increased bolus viscosity. A study completed by Farland (2011) reported an increase in the length of swallow when the bolus viscosity was increased from water to a honey-thick liquid. This was assumed to be due to the increase in work required by the oral musculature to swallow the bolus. Another example of increased swallow duration is found in subjects with removable prosthesis. It has been reported that as the tongue and lips must stabilise the prostheses, swallow duration increases (Tallgren *et al.*, 1995). It was

hypothesised that as more work would be required by both the lip and the tongue to swallow with the 4.5mm tray in place, the swallow duration would increase. However, no statistically significant differences were found in the length of the swallow for either the labial or lingual sites with lower lip advancement. One major difference between the earlier work cited and our study, is that while the earlier studies investigated the pressures on the hard palate, our study focused on the lower incisors. Hence, it may be that there was an increase in the time taken to move the bolus of saliva in our subjects, but our measurement apparatus may not have detected this, as the pressures generated on the hard palate were not recorded in the present study.

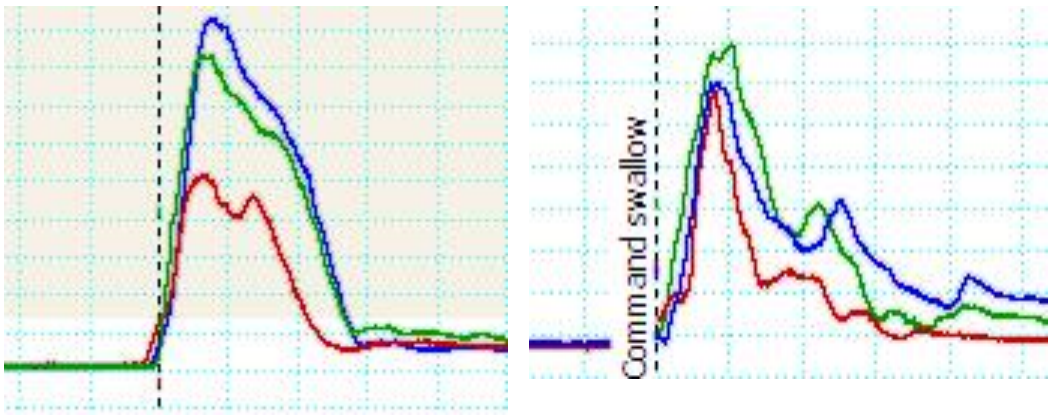
5.3.7 Individual analysis of saliva swallow

When interpreting the individual swallow graphs visually, a few initial conclusions may be drawn. Firstly, it appears that subjects fit into one of two categories of swallowing behaviour. Subjects 4, 6, 8, 9, and 10 showed short bursts of high pressure on swallowing, whereas, subjects 2, 3, 5 and 7 showed a lower pressure on swallowing that was generated over a longer time period. However, when these data were entered into SPSS software package to further investigate this finding, the relationship between time and peak pressure generated was not statistically significant ($p>0.05$).

The behaviour of the tongue also seems to be mirrored by the lip in most cases. A short, sharp pressure swallow on the lingual surface was often mirrored by a short, sharp pressure on the labial surface (Figure 5-4), a multi-peaked swallow on the lingual was often mirrored by a multi-peaked swallow on the lip (Figure 5-5). This is consistent with the findings of Proffit *et al.* (1975b) who investigated swallowing patterns in a group of young male Australian Aborigines. By analysing the swallow waveforms generated on both saliva and water swallows, he found that lip and tongue activity during swallowing lasted approximately the same length of time.

Subject 10 canine labial pressure profile

Subject 10 canine lingual pressure profile



Subject 10 mid-labial pressure profile

Subject 10 mid-lingual pressure profile

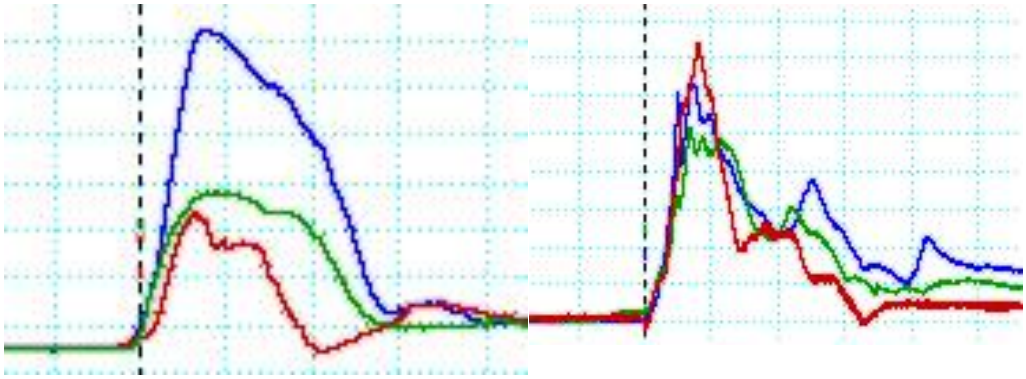
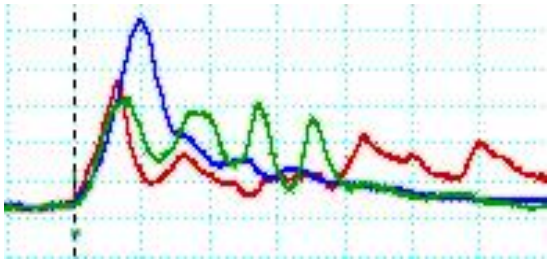


Figure 5-4: A short sharp pressure spike on the lingual surface was mirrored by a short pressure spike on the labial surface

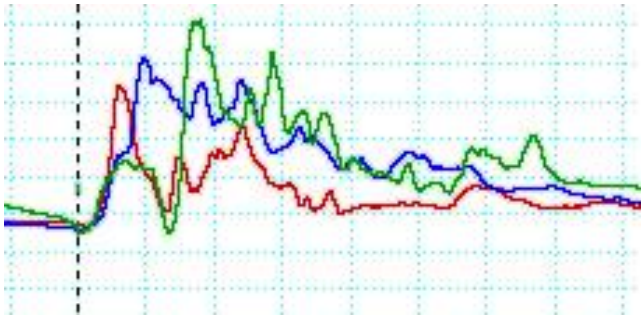
KEY

0.5 mm tray **2.5mm tray** **4.5mm tray**

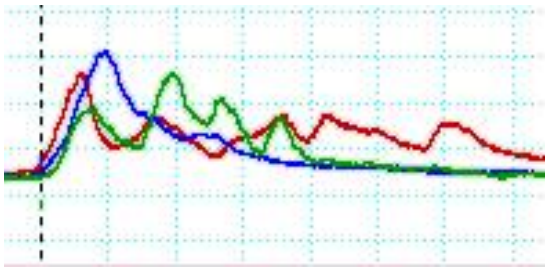
Subject 7 mid-labial pressure profile



Subject 7 mid-lingual pressure profile



Subject 7 canine labial pressure profile



Subject 7 canine lingual pressure profile

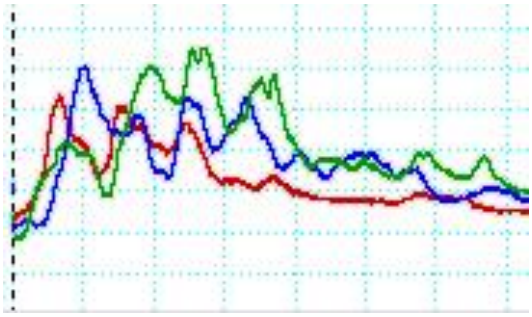


Figure 5-5: A multi-peak pressure profile on the lingual surface was mirrored by multi-peak pressure profile on the labial surface.

KEY

0.5 mm tray **2.5mm tray** **4.5mm tray**

There were three subjects in this study who were defined clinically as being lip-incompetent (subjects 3, 4, and 7). Two of these subjects showed complex lip behaviour on swallowing (subjects 4 and 7) which was mirrored by complex tongue behaviour on the lingual pressure transducers. The other lip-incompetent subject (subject 3) showed very little pressure on the labial surface.

5.3.8 The signature swallow

Earlier work on swallowing done within our department demonstrated that each person has a signature swallow, which remains consistent across swallows, even though external factors (such as bolus consistency/flavour) may be changed (Kennedy *et al.,* 2010; Farland, 2011). The findings of the present study are consistent with this concept. One consequence of incrementally advancing the lower lip was that anterior oral seal was challenged. Each individual coped with this interference in a unique manner, as shown by the significant subject-tray interaction seen in the initial SPSS analysis. When visually interpreting the individual swallow graphs, it is apparent that each person has a signature swallow, as the pattern of each swallow remains fairly constant, even though the timing and amplitude of the event may differ slightly. Interestingly, as the musculature adapts to the interference with anterior oral seal, the pressure pattern generated over the four sites remains remarkably similar.

5.3.9 Were the research hypotheses supported?

The original research hypotheses are outlined in section 3.3. The research outcome for each of the six hypotheses is summarized below.

1. That the lower lip pressure increases in a linear fashion when incrementally advanced. This hypothesis proved to be false. The pressure at the mid-labial site increased with increasing lip advancement, but the trend was quadratic, with a negative coefficient of the quadratic term. There were no significant differences in the pressures generated at the canine labial site as the lower lip was advanced.

2. That more labial pressure would be generated at the canine labial than at the midlabial site. Again, this proved to be false, with no significant differences in pressure found between the two sites.

3. That EMG activity of the lower lip would increase linearly as the lower lip was advanced. The EMG activity of the lip musculature did increase as the lip was advanced, but, again, the relationship was not linear.

4. That mandibular rest position would not affect the EMG activity of the lower lip. Again, this hypothesis proved to be false. There was a statistically significant difference in lower lip EMG activity between the two mandibular positions investigated, with more EMG activity recorded when the teeth were apart than when they were together. The difference was only slight, however, so it is unlikely that this finding is clinically significant.

5. That more lip pressure would be needed to achieve oral seal for swallowing with increased labial advancement. This hypothesis proved to be true, with increased lip pressure recorded as the lower lip was advanced, but this was only significant only for the canine labial site.

6. That the work done by the tongue and the time taken to swallow will also increase as the lower lip is advanced. This hypothesis proved to be false. There was no significant increase in the work done by the tongue, or in the time taken to swallow with incremental lower lip advancement.

6 Conclusions

To date, there has been little investigation of the response of the lower lip musculature to incremental advancement. Consequently, a lack of understanding surrounds the likely soft tissue response to changes in the position of the dentition. The present study set out to investigate the lower lip response to advancement through recording both EMG activity of the lower lip musculature, and the oral pressure generated on the teeth.

This study has demonstrated that the response of the lower lip to advancement is highly individual specific, both at rest and during function. This suggests that adaptation of the soft tissues to tooth position may be individual specific and that orthodontic relapse may indicate an inability for the surrounding soft tissues to adapt to the new tooth position. This agrees with the earlier work of McNulty *et al.* (1968) and Soo and Moore (1991). It was also demonstrated that the increase in oral pressure recorded with the first 2mm of lip advancement was due to the inherent viscoelastic properties of the lip. As the lower lip was further advanced, EMG muscle activity increased, leading to a further increase in oral pressure. This increase in muscle activity was likely due to subjects attempting to maintain oral seal under challenging conditions. However, as only a small sample was used in this study, further research is required to confirm our results, and also to define the EMG response of the musculature adjacent to the canine, as only the midline response was defined in the present study.

During swallowing, there was a lack of balance between tongue and lip pressures, which is similar to the findings of other authors (Kennedy *et al.*, 2010; Proffit *et al.*, 1978; Winders, 1958). In agreement with earlier work completed within this department (Kennedy *et al.*, 2010; Farland, 2011), the present study demonstrated that each individual has their own signature swallow, which remained fairly constant as the lower lip was advanced. It is proposed that once an individual develops a pattern of swallow, this is maintained although environmental factors (such as interference with anterior oral seal) are applied.

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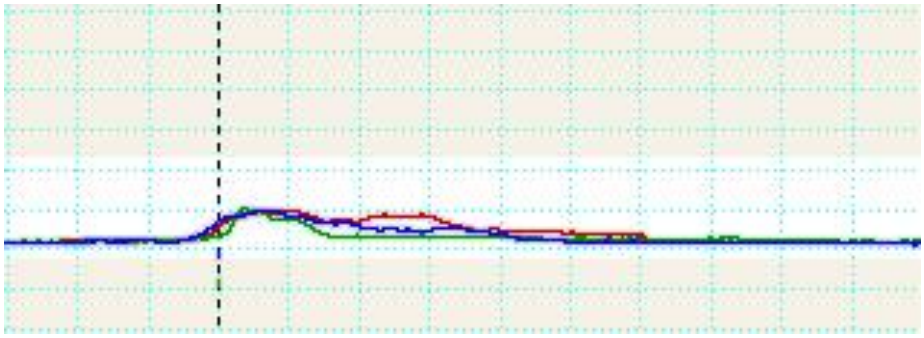
8 Appendix I – Individual saliva swallow graphs

KEY

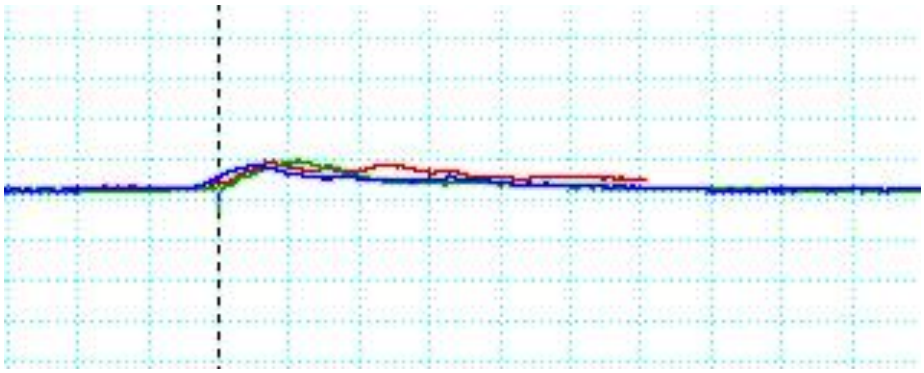
0.5 mm tray **2.5mm tray** **4.5mm tray**

For the graphs below, pressure is shown on the y-axis, with time on the x-axis.

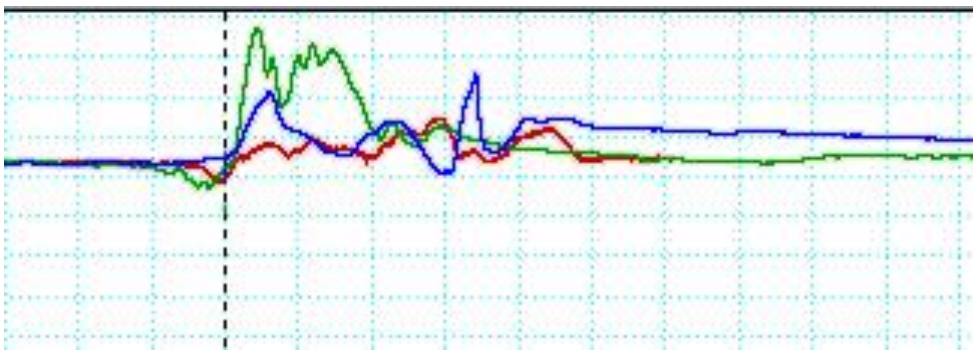
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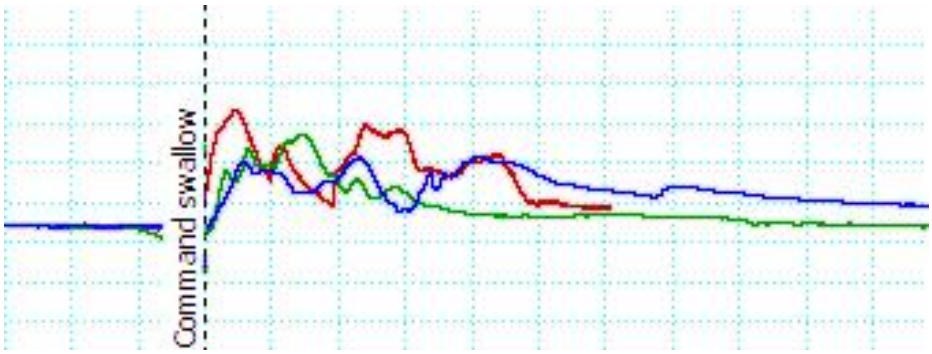
Subject 2 canine labial pressure



Subject 2 mid-labial pressure

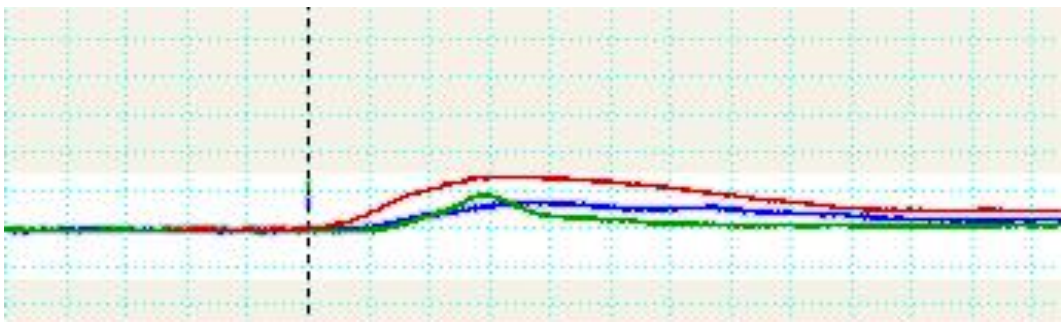


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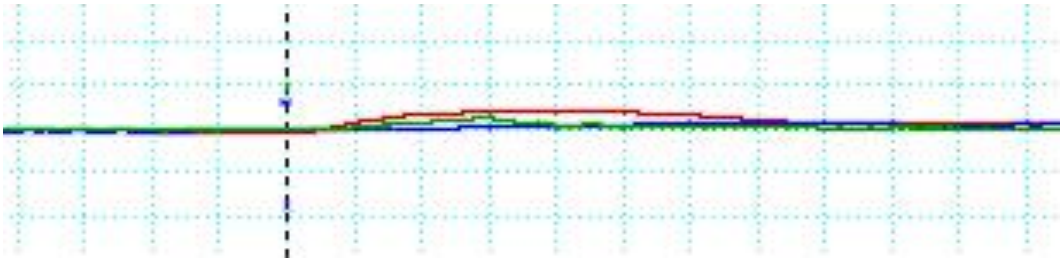


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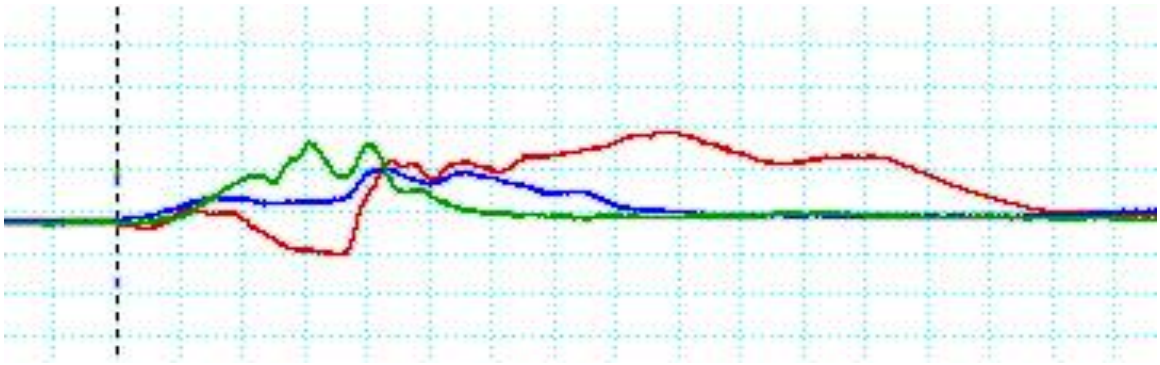
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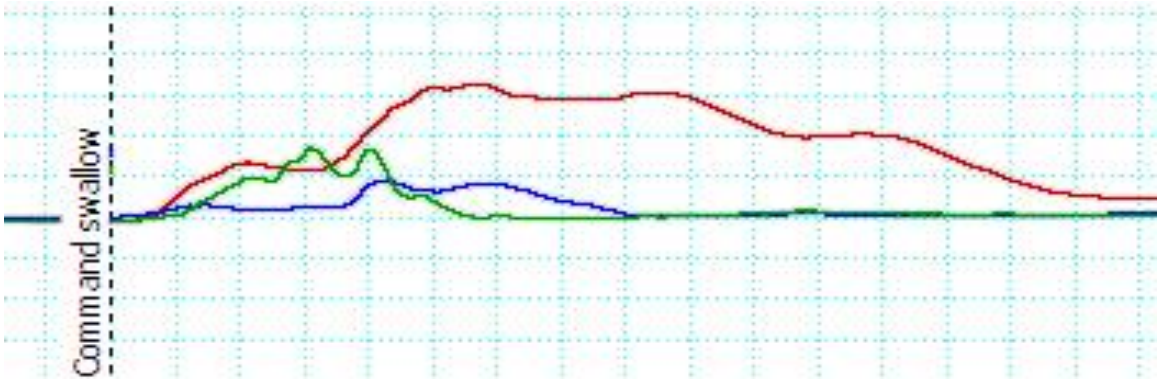
Subject 3 canine labial swallow



Subject 3 mid-labial swallow

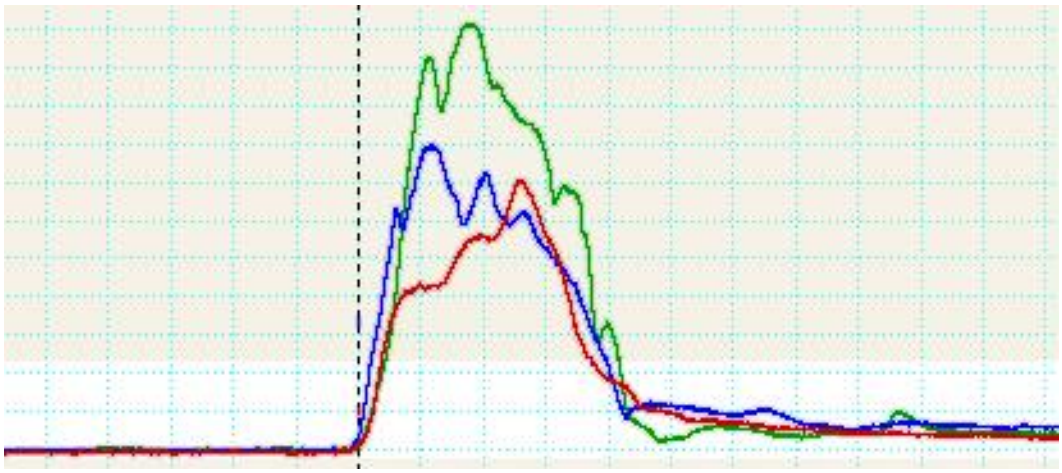


Subject 3 mid-lingual swallow

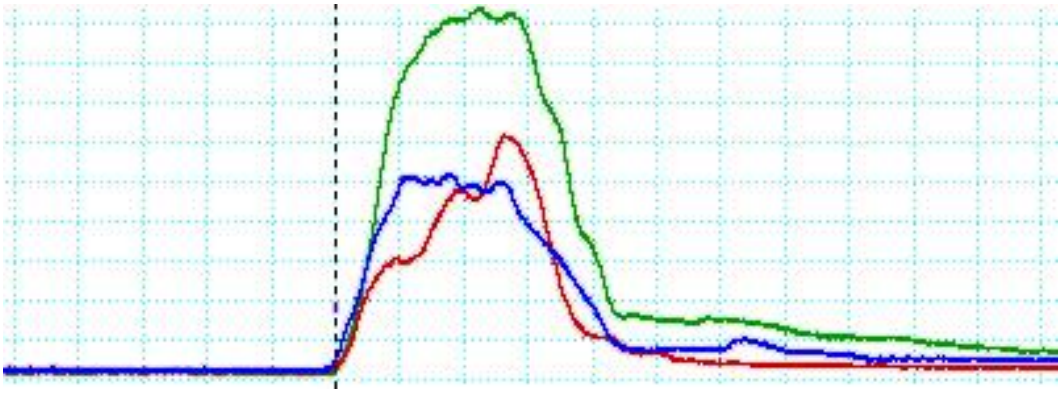


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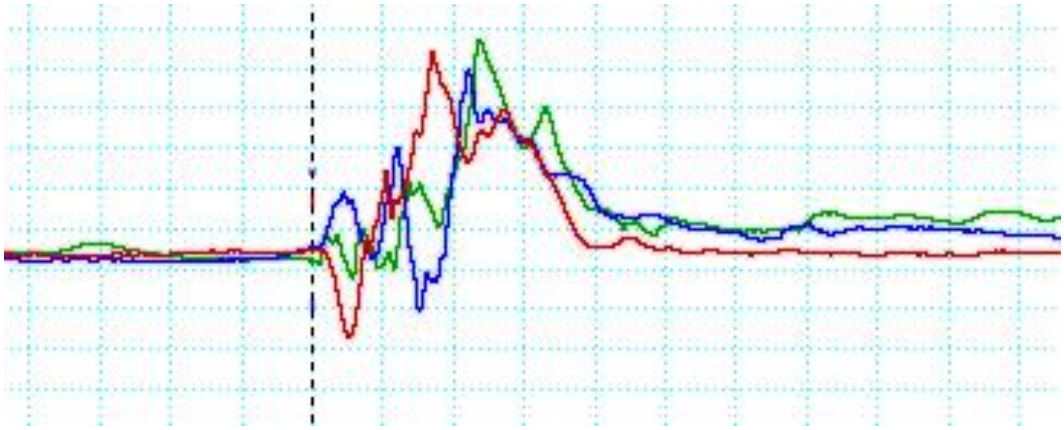
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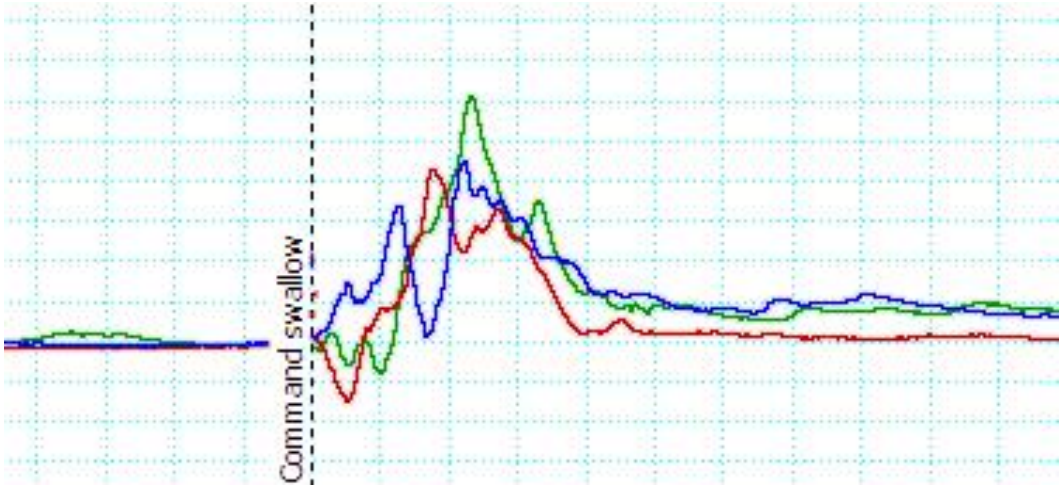
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Subject 4 mid-labial pressure

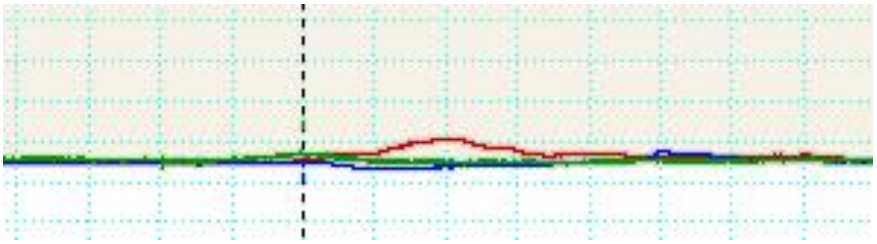


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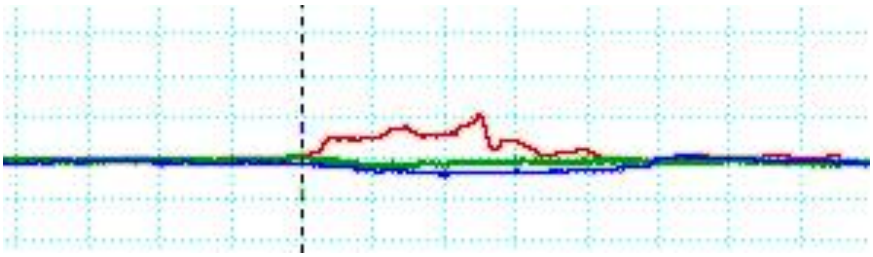


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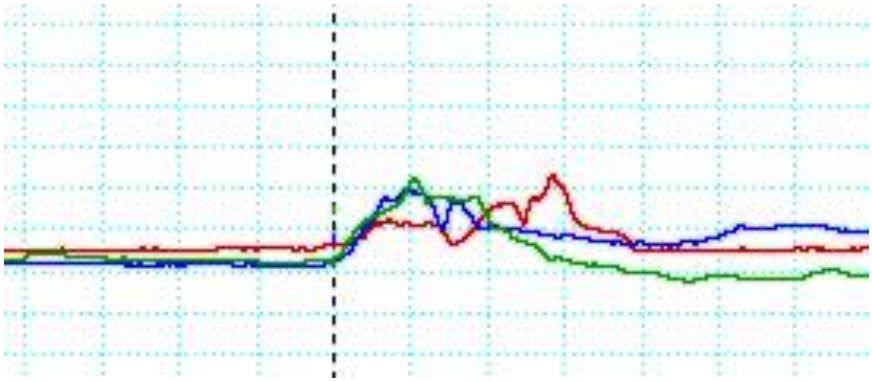
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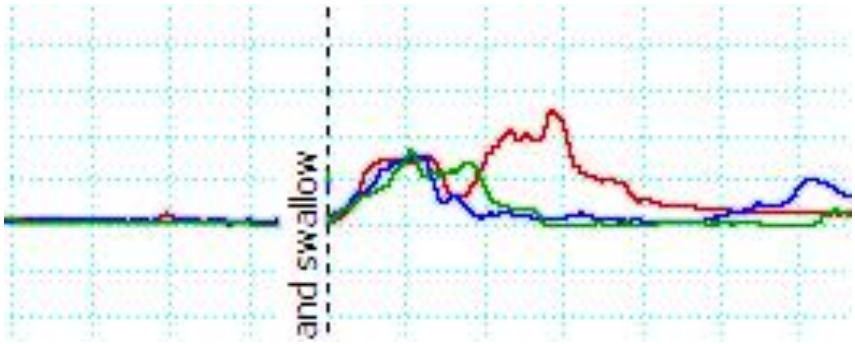
Subject 5 canine labial pressure



Subject 5 mid-labial pressure

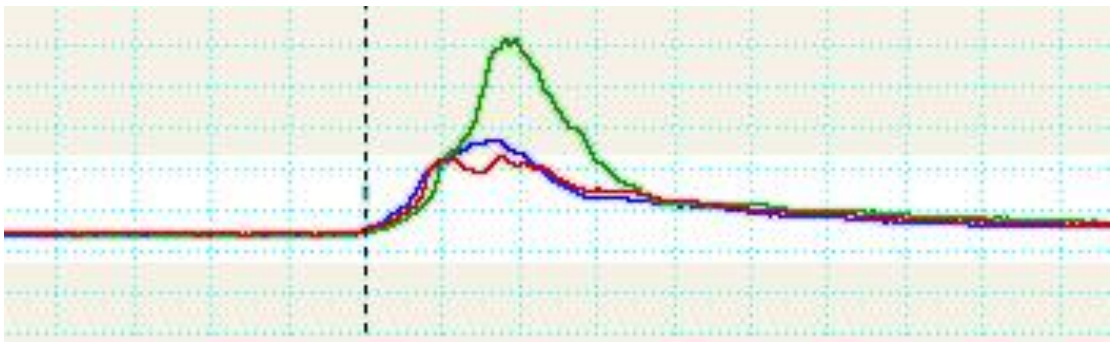


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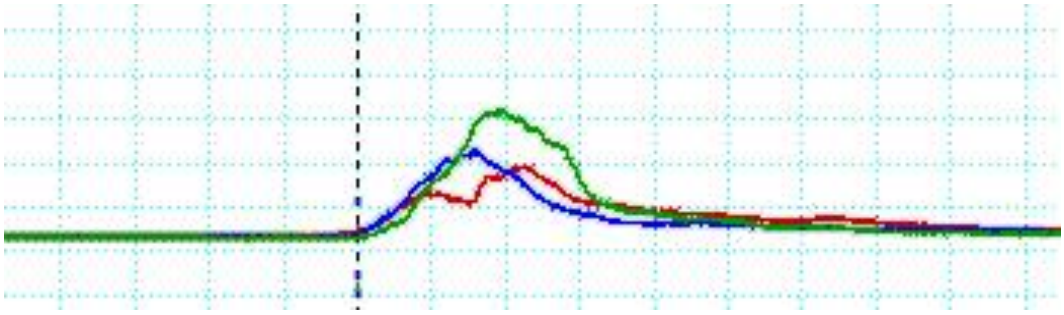


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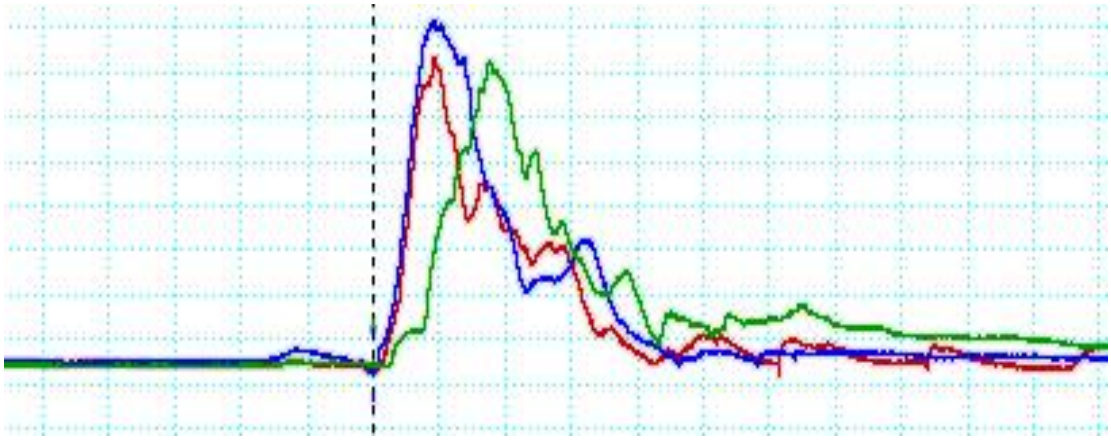
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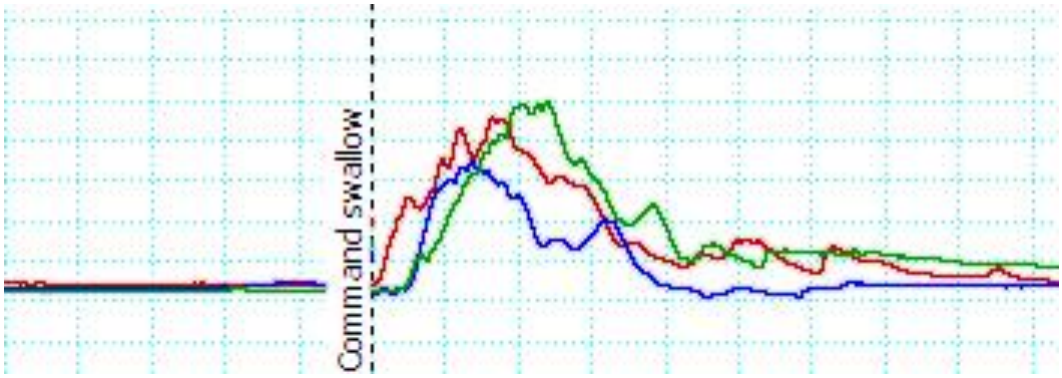
Subject 6 canine labial pressure



Subject 6 mid-labial pressure

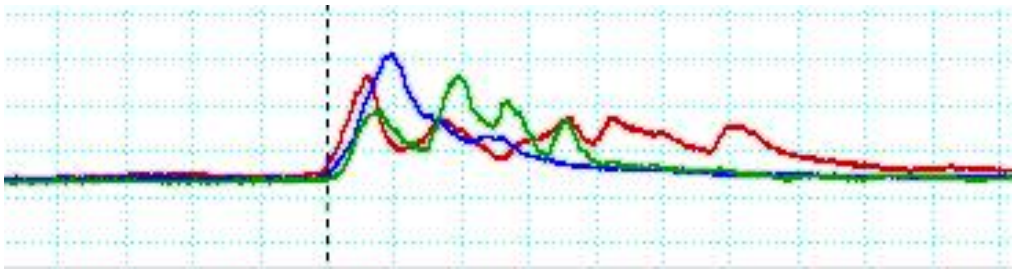


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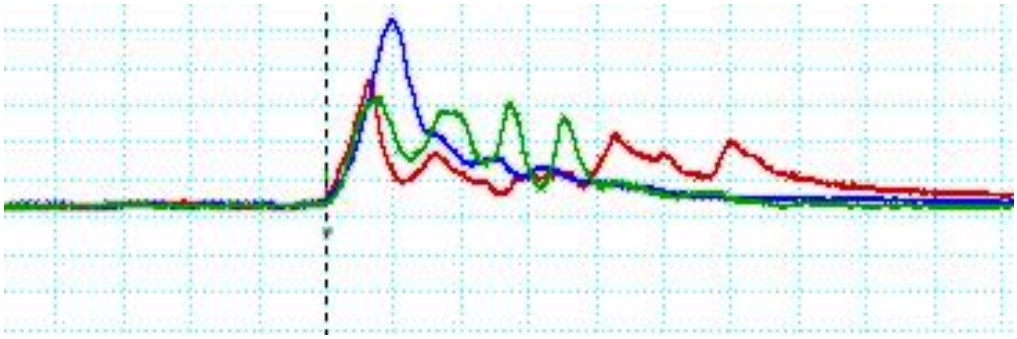


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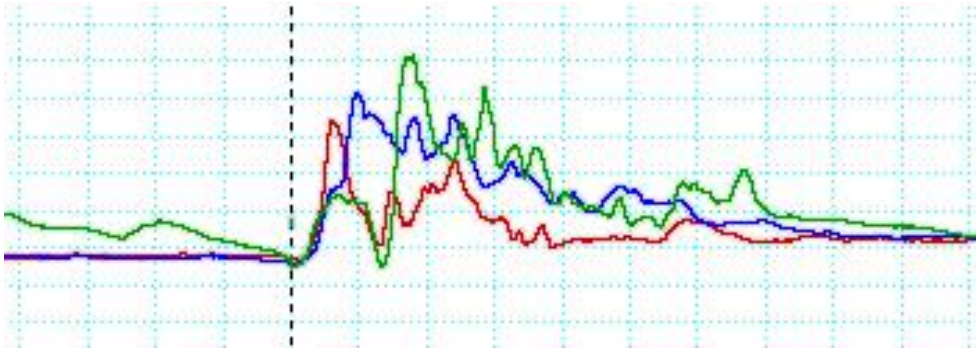
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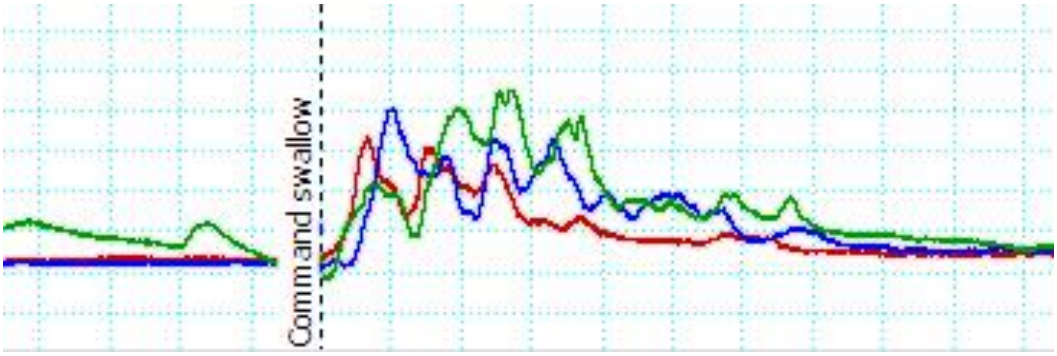
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Subject 7 mid-labial pressure

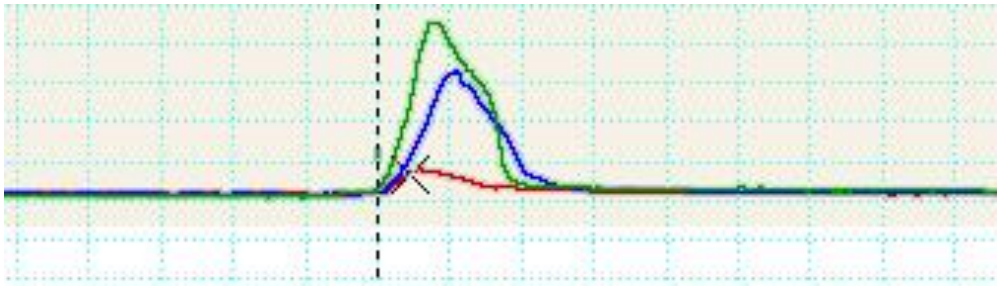


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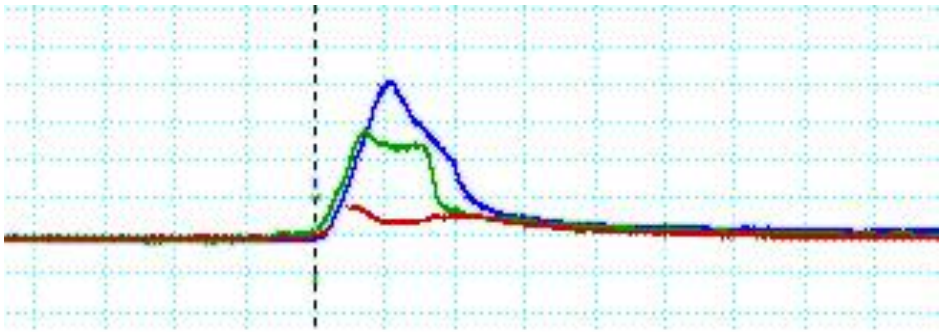


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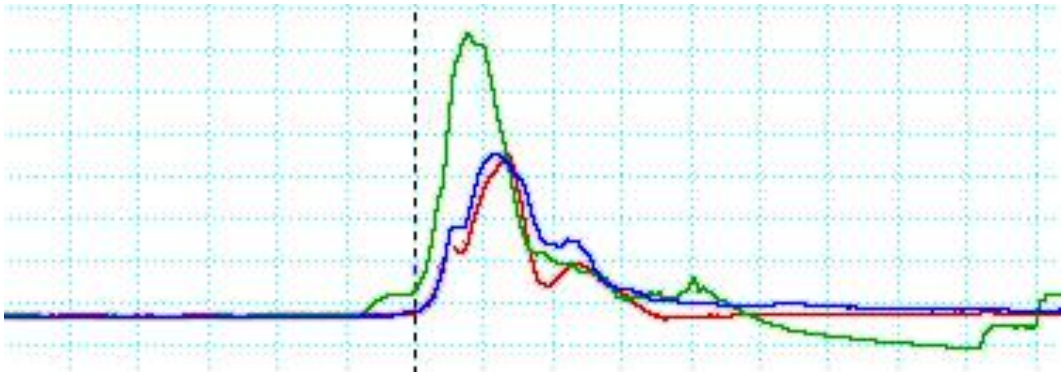
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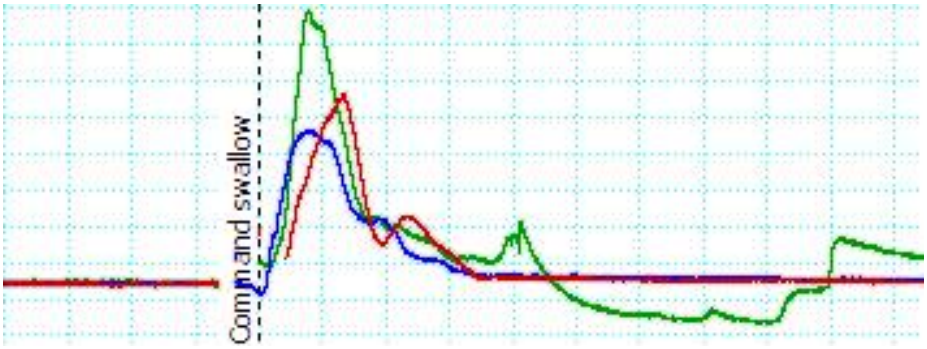
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Subject 8 mid-labial pressure

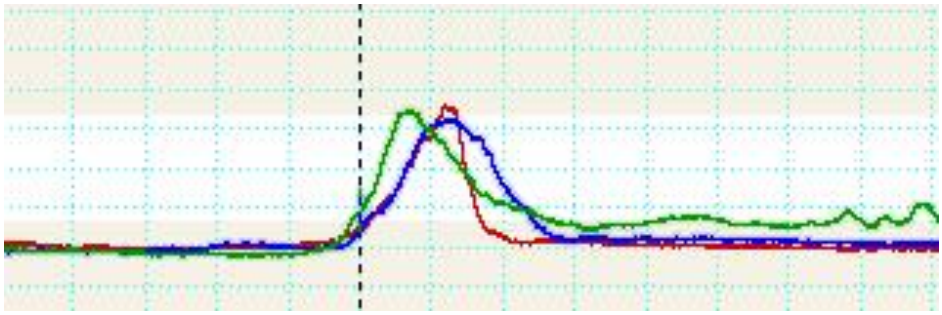


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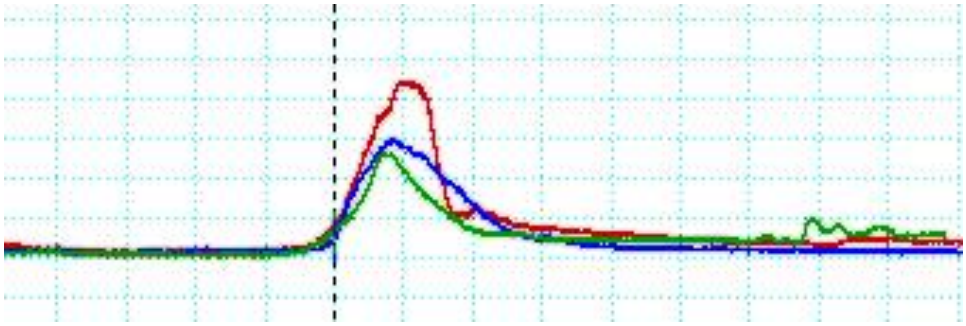


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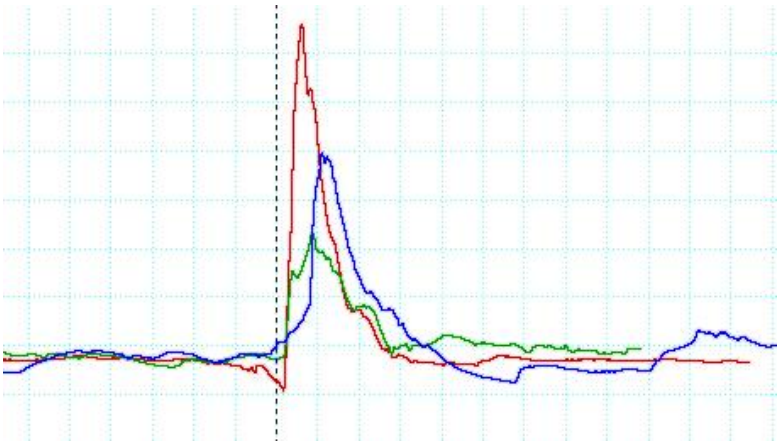
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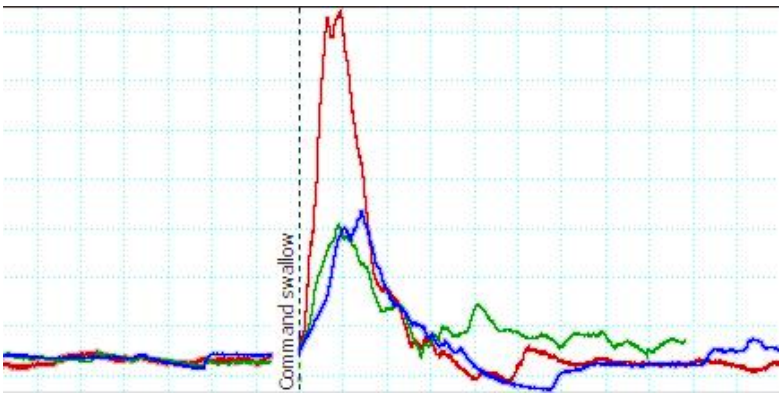
Subject 9 canine labial pressure



Subject 9 GF mid-labial pressure

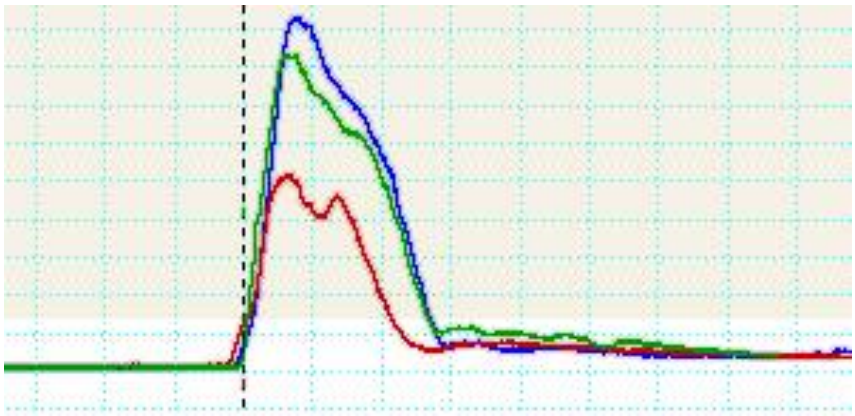


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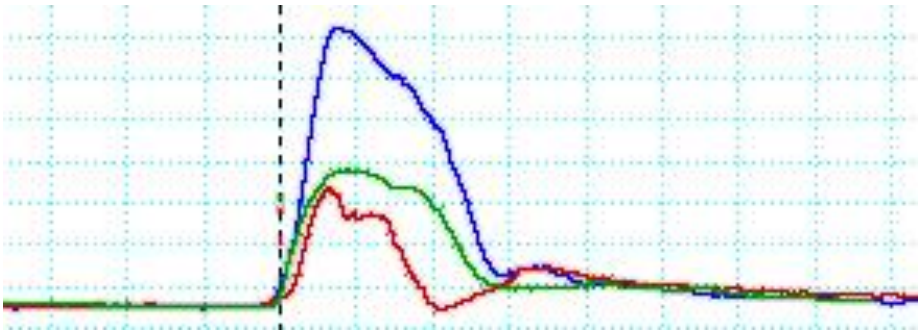


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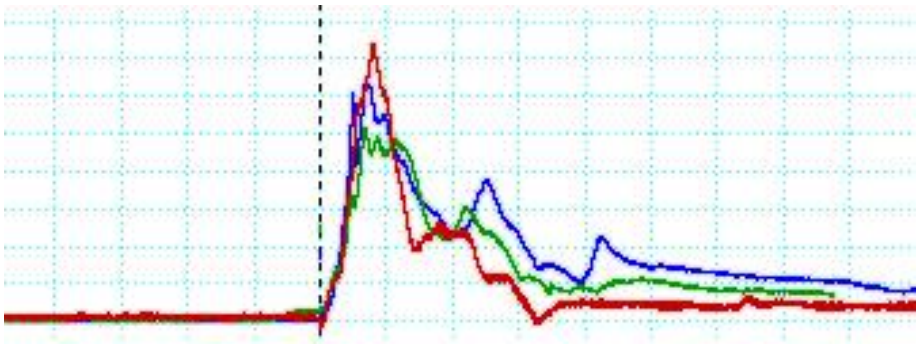
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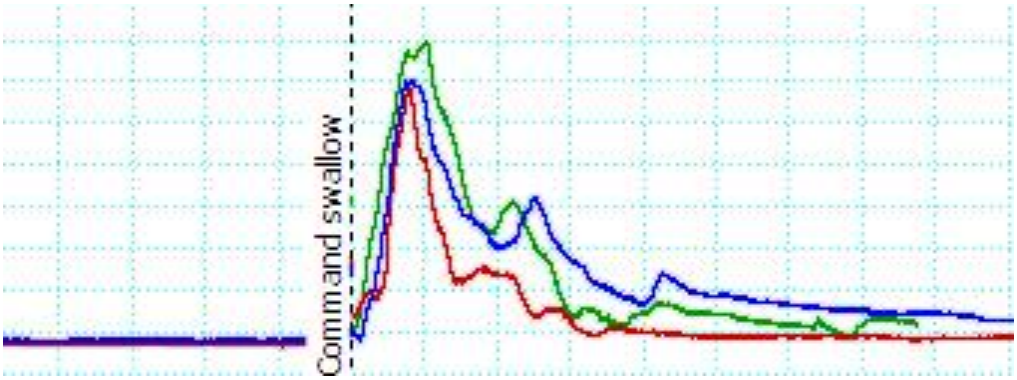
Subject 10 canine labial pressure



Subject 10 mid-labial pressure



Subject 10 mid-labial pressure



Subject 10 canine lingual pressure