PHYSICAL PROPERTIES OF THE UPPER LIP MEASURED DURING SIMULATED TOOTH MOVEMENT

BY

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE

THE UNIVERSITY OF MANITOBA

DEPARTMENT OF

DENTAL DIAGNOSTIC AND SURGICAL SCIENCES

WINNIPEG, MANITOBA

0-612-23317-0

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FACULTY OF GRADUATE STUDIES
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ACKNOWLEDGEMENTS

I would like thank all those individuals who so generously helped to make this thesis possible. I was very fortunate to have been able to do work under the supervision of Dr. Laura Iwasaki and Dr. Jeff Nickel. I thank them for their patience and wisdom and for their commitment to this project. I would also like to thank Dr. Denny Smith for being my external committee member and providing his expertise to the project. As well, thank you to Dr. Ken McLachlan for allowing me to keep the "Goldometer" in his engineering laboratory.

Fincancial support was provided, in part, from the personal research resources of Drs. Iwasaki and Nickel. I would like to thank them for this generous contribution. As well, I would like to thank the Canadian Foundation for the Advancement of Orthodontics (CFAO) for their support of student research.

I was very fortunate to have the opportunity to learn from many excellent professors and clinical instructors. I always looked forward to clinic and I am sincerely thankful for the wonderful environment I was able to learn in.

Sincere thanks to the orthodontic support staff for all their help and kindness. There were alot of good laughs in the last three years.

I would like to thank my classmates, Mark and Rano, who

were the most important part of my orthodontic training. I am grateful for the special friendship I developed with Mark, and I will miss the both of them. As well, the friendships I developed with the other students in the program have been very special for me, and I have many excellent memories to take from Winnipeg.

DEDICATION

This thesis is dedicated to my parents, Bob and Myrna Hauta, and to my wife, Vicki. Their encouragement, love and support over all these years, has allowed me to pursue many personal and educational opportunities. Words cannot express how important this has been to me.

A special thank you to my family and friends for all they have done to help me along the way. Your interest and encouragement was always appreciated.

ABSTRACT

Investigations of the soft-tissue change associated with tooth movement have shown variable results. Consequently, precise, reliable predictions regarding how the soft-tissues will react to tooth movement cannot be made. Differences in the physical characteristics of the lips of different individuals could account for differences in the lip response to tooth movement between individuals. This study was designed to address this possibility. The hypothesis tested was that lip profile changes in response to orthodontic tooth movement are not predictably associated with the physical properties of the upper lip measured during simulated tooth movement.

This laboratory and cephalometric study involved seven adult subjects whose maxillary incisors were retracted during previous treatment at the University of Manitoba. An experimental apparatus was constructed to record the forces associated with the displacement of the relaxed upper lip. Customized acrylic facings that fit under the upper lip labial to the maxillary anterior teeth were fabricated in three sizes for each subject. A video camera was used to record the changes in lip position in profile view, as the facings were pulled forward, and to simultaneously record a measure of the force. Analyses were conducted on five trials for each flange at each of two recording sessions. Two theoretical models were presented to predict the upper lip position change and decompression with tooth retraction, based on the physical properties of the upper lip and the area of tooth retraction. The physical properties of the upper lip were quantified by the slope of the stress:strain and horizontal flange displacement:horizontal lip displacement (flange^{H}:lip^{H}) linear regression relationships, as determined using the video data. The area of tooth retraction (ATR) was determined by superimposing pre- and post-treatment occlusograms. These results were compared to pre- and post-treatment cephalometric data as a test of the hypothesis. Statistical analyses of the video data were performed using a one-way analysis of variance (ANOVA) and a multiple range test.

The recording apparatus was found to be more reliable for the wider flanges since they were relatively less affected by frictional resistance in the apparatus. The regression analysis showed a high level of statistical significance for both the stress:strain and flange^{H}:lip^{H} relationships ($p<0.001$), but these relationships were not found to be related. Both prediction models had a strong correlation to the cephalometric results ($r = 0.95$), with the most important variable being the ATR. The results of this study have demonstrated that by characterizing the physical properties of the soft-tissues and estimating the area of maxillary ATR, the prediction accuracy of the upper lip response to tooth movement can be improved.

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ABBREVIATIONS AND SYMBOLS

$<$	Less than
$\leq$	Less than or equal to
$\geq$	Greater than or equal to
Δ	Change from time 1 to time 2; movement or retraction
%	Percentage
η	Viscosity
σ	Stress
μm	Micrometer (micron)
A	A-point
ANOVA	Analysis of Variance
AP	Anteroposterior
ATR	Area of Tooth Retraction
CLR	Measured Lip Movement
cm	Centimeter
cm^2	Centimeter squared
df	Degrees of freedom
e and ϵ	Strain
E	Stiffness: Young's Modulus (Modulus of Elasticity)
EMG	Electromyographic
f	Force
FEM	Finite Element Method
FH	Frankfort Horizontal Plane
flange^H:lip^H	Horizontal Flange Displacement:Horizontal Lip Displacement
g	Gram
Ls	Labrale Superius
LVDT	Linear Voltage Differential Transformer
m^2	Meter squared
$M_{F/L}$	Slope of the flange^H:lip^H relationship
MHz	MegaHertz
mm	Millimeter
mm^2	Millimeter squared
MPa	MegaPascal
N	Newton
NLA	Nasolabial angle
NPg	Nasion to Pogonion Line
ns	Nanosecond
OJ	Overjet
p	P value
Pa	Pascal
r	Spearmean correlation coefficient
r^2	Spearmean correlation coefficient squared
SD or s.d.	Standard Deviation
sec	Second
SI	Superoinferior
SMAS	Superficial Musculoaponeurotic System
Sn	Subnasale
Sn-Pg'	Subnasale to Soft-Tissue Pogonion

ABBREVIATIONS AND SYMBOLS (CONTINUED)

SN	Sella to Nasion Line
Stm S	Stomion Superius
t	Time
TLM	Theoretical Lip Movement
UI	Upper Incisor
UIE	Upper Incisor Edge
UIP	Upper Incisor Point
W	Transverse distance at the lateral incisors
x	Displacement

CHAPTER 1
INTRODUCTION

INTRODUCTION

The mouth and lips perform several important physical functions essential to the quality of human existence. In addition, they have symbolic value which is important to the emotional aspects of human life. The changes in facial contours and movements of the lips relative to the dentition connote attitude and emotion. Personality traits can be attributed to a person based on the shape and use of the lips.

Orthodontic treatment has an influence on the lips since tooth movement can affect these structures. Many patients seeking orthodontic treatment desire an improvement, not only in dental esthetics, but also in facial appearance (Sarver, 1993). The influence of tooth movement on lip profile and facial esthetics was ignored by most early practitioners of modern orthodontics. Although Angle recognized the importance of facial esthetics to orthodontic treatment, he forbade the extraction of teeth and assumed that a "normal occlusion" (an aligned and intact dentition) would result in ideal facial esthetics (Angle, 1907). Calvin Case was one of the first orthodontists to recommend the extraction of teeth in cases with lip protrusion (Case, 1908), and this led to the extraction debate of 1911 (Dewel, 1964). Tweed became disillusioned with the Angle non-extractionist dogma after seeing severe lip protrusions and instability in many of his treated cases. He later developed orthodontic techniques designed primarily for extraction cases (Tweed, 1944).

Since the advent of cephalometrics in the early 1930's, a correlation between tooth position and lip position has been established. Ideal dentoskeletal relationships do not always result in ideal facial esthetics (Park and Burstone, 1986). The decision to extract teeth can be based entirely on one's desire to change the position of the lips (Bishara *et al.*, 1995a; Baumrind *et al.*, 1996). Unfortunately, the soft-tissue response to hard-tissue change is highly variable. The magnitude of inter-individual variation renders treatment predictions associated with large anteroposterior dental changes very unreliable.

Attempts to predict how the soft-tissue will react to tooth movement by examining a pre-treatment lateral cephalometric radiograph have met with little success. Predictions of soft-tissue changes have been based on a retrospective comparison of the two-dimensional radiographic images of pre- and post-treatment lateral cephalographs. One might expect that the differences in the anatomical, morphological and physical characteristics of the lips between individuals could account for the differences in the lip response to mechanical deformation (i.e. tooth movement). To date, little research exists concerning the physical characteristics of the lips and facial soft-tissue, let alone how the physical characteristics relate to changes in lip position as a consequence of tooth movement.

It was the purpose of this study to examine the response of the upper lip to simulated tooth movement by quantifying the stress:strain characteristics of the upper lip and to describe the compressive deformation of the upper lip under load. The stress:strain relationship for the upper lip was compared to the results of a cephalometric investigation and the anterior tooth position changes in a group of nongrowing subjects. These volunteer subjects had completed orthodontic treatment which involved maxillary incisor retraction.

The hypothesis for this study was that lip profile changes in response to orthodontic tooth movement are not predictably associated with the physical properties of the upper lip measured during simulated tooth movement.

CHAPTER 2
REVIEW OF THE LITERATURE

REVIEW OF THE LITERATURE

2.0 Introduction:

Changes in lip position and thickness can be related either to growth or treatment-induced changes. To understand the response of the upper lip to changes in tooth position it is necessary to understand the structure and anatomy of the lips, the teeth and their supporting structures, as well as the biomechanical properties of these tissues. For an overview of lip structure and anatomy and the literature associated with the biomechanical properties of lip tissues, the reader is referred to Appendix A.

Clinical interest in the physical properties of the lips has been concerned primarily with the force the lips place against the dento-alveolar arches during rest and during function. Forces exerted by soft-tissues are believed to influence the morphological development and the orthodontic relapse of the dento-alveolar structures.

Section 2.1 is a review of the literature associated with the influence of soft-tissue pressures on tooth position. In the next two sections, the changes in the lip and facial profiles due to growth (2.2) and treatment (2.3), as described in the literature, are presented.

2.1 Soft-Tissue Pressure:

Pressure is a measure of force per unit area. It should be noted, however, that in the clinical literature, pressure has commonly been expressed as a unit of mass, grams (g), per unit area (for example, grams per square centimeter (g/cm^2)). Much of the early interest in lip and cheek pressure revolved around the possible influence that soft-tissue pressure might have on tooth position (Gould and Picton, 1968; Posen, 1972, 1976).

There has been debate over which was more important, maximal (Posen, 1972, 1976; Ingervall and Janson, 1981), functional (Gould and Picton, 1968; Posen, 1976; Thüer *et al.*, 1985; Proffit and Phillips, 1988; Lindeman and Moore, 1990; Lindner and Hellsing, 1991; Soo and Moore, 1991) or resting lip pressure (Thüer *et al.*, 1985; Proffit and Phillips, 1988; Soo and Moore, 1991; Halazonetis *et al.*, 1994). Thüer *et al.* (1985) measured resting and functional lip pressure and electromyographic (EMG) activity in 27 children with normal incisor relationships. They found that lip pressure at rest depended on lip tonicity, whereas functional lip pressure depended on muscle activity. Ingervall and Janson (1981) used a dynamometer in 50 children between the ages of 7 and 13 years, with various malocclusions. They found lip strength measurements to be of limited value since they had limited reproducibility, and lip strength was not related to EMG recordings of lip activity. Lip strength was not related to tooth relations or lip or facial morphology as determined with dental casts and profile radiographs. Lubit *et al.* (1990) compared resting (tonic) upper midline pressure with maximal lip pressure in 100 subjects using a pneumohydraulic capillary infusion system. They found no correlation between the resting and maximal lip pressure and concluded that maximal lip pressures were of no clinical importance.

The current theory is that resting pressures have the most influence on tooth position because they are the most constant in duration (Proffit, 1978). Lip pressures are determined by the tautness of the lips and by their anteroposterior (AP) and vertical positions relative to the incisors (Proffit and Phillips, 1988). Gould and Picton (1968) found that lip pressures increased only slightly as the pressure transducer moved buccally from the surface of a tooth for approximately 2 millimeters (mm). Proffit and Phillips (1988) found variable results when comparing changes in resting lip pressures to postsurgical tooth stability in a group of 26 surgical orthognathic subjects. Lindeman and Moore (1990) compared foil strain gauges, load cells and pressure transducers in five subjects using seven functional exercises. They recorded mandibular functional pressures at the tooth surface and 7 mm anteriorly with a lip bumper on five consecutive days, and found functional lip pressures 7 mm from the tooth surface tended to be less than those at the tooth surface.

The resting pressures of the lips, cheek and tongue are so small that error in experimentation has resulted in variable conclusions. Lindeman and Moore (1990) used correlation coefficients to test instrument validity and reliability and concluded that the pressure transducer was the best overall measuring device, with the foil strain gauge being the worst.

Functional and resting lip pressures have been found to be higher in the canine versus the midline areas of the lips. Thüer *et al.* (1985) found the resting pressures in the upper midline area to be 2.2 ± 4.2 g/cm^2 (range -4.1 to 10.8). In the modiolar region they were 6.3 ± 4.2 g/cm^2. Proffit and Phillips (1988) also found differences in resting lip pressure when comparing midline (4.9 g/cm^2) and canine area (13.6 g/cm^2) pressures. Interindividual variations in lip pressure and EMG activity were large, and concluded to be of a "biological" nature. Intraindividual variation tended to be somewhat smaller on the second than on the first occasion. This may have represented a psychological effect, as the subjects became used to the test situation. When doing this type of research, it is important to have the subjects feel comfortable in spite of a foreign environment, and to use repeated trials to try to minimize the effects of heightened muscle tone associated with an unfamiliar testing apparatus.

Lindner and Hellsing (1991) measured cheek pressures at the canine and second primary molar during soother-sucking in 12 children. The pressures at the canine region were on average three times larger than at the second primary molar (54 versus 21 g/cm^2). Similar to resting pressures, functional pressures also varied depending on the area studied.

There has been controversy concerning the adaptation of lip and cheek pressures with changes in anterior arch form. McNulty *et al.* (1968) found a variable response to changes in arch form. Soo and Moore (1991) found a gradual reduction in resting lip pressure after the lip was held in a more protrusive position for as little as one week. They found less adaptation in the modiolar area, which suggested that the canine-premolar area may be less adaptable to changes in lip position. Halazonetis *et al.* (1994) used a similar apparatus to that of Thüer *et al.* (1985), and measured the change in cheek pressure at the first molar in response to rapid palatal expansion. With the 15 subjects in this study, there was an increase in resting cheek pressure from 3 to 9 g/cm^2 after expansion of at least 5 mm. At 3 to 4 months after expansion, there was no adaptation in the cheek pressures. These post-expansion pressures were similar to the pressures found by Thüer *et al* (1985) and Proffit and Phillips (1988).

The effect of head posture on resting lip pressure has also been uncertain. Ingervall and Thüer (1988) compared resting cheek pressures in 20 adults using natural and 15 degree extended head postures. They found that resting pressures, measured at the tooth surface, were slightly larger for the extended head posture as compared to natural head posture, 4.1 and 3.4 g/cm^2, respectively. However, Archer and Vig (1985) did a similar study and did not find any differences in labial lip pressure with changes in head posture.

These studies have shown that the resting lip pressures have appeared to be higher in the modiolar and alveolar regions. However, much of the variability in results has been related to differences in the accuracy of the recording instrument used, as well as the position of the recording instrument relative to the tooth surface. The change in resting soft-tissue pressure in response to altered tooth position varied between individuals. Generally, the change in resting pressure was less variable at the modiolar region.

2.2 Changes in Lip and Facial Profile Due to Growth:

2.2.1 Introduction:

Most studies of soft-tissue growth have involved lateral cephalometric records from non-treated samples followed longitudinally, with overall changes being studied (Subtelny, 1959; Mauchamp and Sassouni, 1973; Chaconas and Bartroff, 1975; Vig and Cohen, 1979; Mamandras, 1984; Bishara *et al.*, 1985; Nanda *et al.*, 1989; Genecov *et al.*; 1990, Prahl-Andersen *et al.*, 1995). Burke (1979) used life-size facial contour maps to study adolescent facial growth in 52 like-sexed twins, and Farkas *et al.* (1992) used six surface measurements to evaluate nose and upper lip growth in a cross-sectional sample of 1,593 subjects. The studies using cephalographs often gave varied results due to some investigators using a lip-together posture when taking the radiographs, and some investigators using a relaxed lip posture. In some investigations, the cephalometric radiograph protocol for subjects specified a relaxed lip posture (Vig and Cohen, 1979; Mamandras, 1984; Bishara *et al.*, 1985, Nanda *et al.*, 1989), in others a closed lip posture (Mauchamp and Sassouni, 1973; Zylinski *et al.*, 1992), and in still others, the lip posture was not specified (Subtelny, 1959; Chaconas and Bartroff, 1975; Genecov *et al.*, 1990; Prahl-Andersen *et al.*, 1995). According to Burstone (1967), "normally there are two postural positions of the lips. In the relaxed-lip position, the lips are relaxed, apart and hanging loosely. In the closed-lip position, the lips lightly touch to produce an anterior seal... To predict changes in lip position, use the relaxed-lip position to avoid lips being overly stretched or flattened". The use of a closed-lip posture can result in distortion of the lips and therefore will not accurately measure the changes in lip morphology.

The majority of studies have used Caucasian subjects (Mauchamp and Sassouni, 1973; Mamandras, 1984; Bishara *et al.*; 1985; Nanda *et al.*, 1989; Genecov *et al.*, 1990; Farkas *et al.*; 1992, Zylinski *et al.*, 1992; Peck *et al.*, 1992; Prahl-Andersen *et al.*, 1995). However, the results have not been consistent. This may be due to the use of different reference planes and the varied age ranges of the subjects. The majority of studies have looked at childhood and adolescent development (Subtelny, 1959; Mauchamp and Sassouni, 1973; Chaconas and Bartroff, 1975; Burke, 1979; Vig and Cohen, 1979; Mamandras, 1984; Bishara *et al.*, 1985; Nanda *et al.*, 1989; Genecov *et al.*, 1990; Farkas *et al.*, 1992; Peck *et al.*, 1992). Prahl-Andersen *et al.* (1995) studied soft-tissue growth as a combination of adolescent and adult growth changes. Zylinski *et al.* (1992) did a cross-sectional lateral cephalometric study comparing 31 preadolescent Caucasian males (average age 7.6 years) with 29 adult men (average age 26.2 years).

The findings from studies of lip and facial profile changes due to growth are summarized in the following sections.

2.2.2 Childhood and Adolescent Facial Growth Changes:

Overall, studies have shown that although soft-tissue growth reflects hard tissue growth, the relationship is not one to one (Subtelny, 1959; Mauchamp and Sassouni, 1973; Zylinski *et al.*, 1992). Almost all studies have concluded that the timing and rates of growth for the soft-tissue components vary and that there is a sexual dimorphism to soft-tissue growth. In general, males mature over a longer time span and attain larger facial dimensions than females. Females mature earlier than males, and males continue to grow into late adolescence (Subtelny, 1959; Mauchamp and Sassouni, 1973; Burke, 1979; Mamandras, 1984; Nanda *et al.*, 1989; Genecov *et al.*, 1990; Prahl-Andersen *et al.*, 1995). The soft-tissue profile (including the nose) has been found to increase with age primarily due to growth of the nose and midface, and the hard-tissue profile decreases due to greater growth of the mandible and chin.

Subtelny (1959) examined 30 sets of serial cephalographs from the Bolton Growth Study, half of which represented female subjects and half represented male subjects. The subjects' ages ranged from 3 months to 18 years. He found that hard-tissue facial convexity decreased with age while soft-tissue convexity (including the nose) increased with age. Soft-tissue convexity, excluding the nose, changed minimally with age. The increase in soft-tissue convexity was attributed to a greater growth in soft-tissue thickness covering the maxillary region as well as to significant growth of the nose.

Mauchamp and Sassouni (1973) used 21 male and 33 female Caucasian subjects from the longitudinal series of the Denver Child Research Council records. They reported results for the 6 to 18 year age span and found a decrease in hard tissue convexity with age. They measured deviations of individual growth curves from the mean growth curve, and concluded that, unlike the hard-tissue profile, the soft-tissue profile did not change significantly during aging (at least on an average basis).

Chaconas and Bartroff (1975) looked at longitudinal records between ages 10 and 16 years for an untreated Caucasian sample of 23 males and 23 females from the Bolton Growth study. They used multiple linear regression equations to predict the age 16-year measurements from the age 10-year measurements for the individuals in this sample and compared these predictions to the actual measured results. Statistical tests showed that the results from the prediction equations and the measured results matched quite well and were not significantly different at the 0.01 confidence level. However, since these equations were tested on the same data that was used to determine them, they would be expected to provide more accurate predictions than if they had been tested on an different sample. They found an increase in soft-tissue convexity with age. The male growth spurt was between 12 and 15 years of age, whereas the females showed little growth after 13 years of age. Bishara *et al.* (1985) investigated changes in soft-tissue convexity (with and without the nose), Holdaway's H-angle (the angle between a line from the chin to upper lip and the Nasion - B-point line), Merrifield's Z-angle (the angle between Frankfort Horizontal plane and a line from the chin to the upper lip) and the lip:E-plane relationship (the distance of the lip to a line between the chin and nose) using a longitudinal cephalograph series from the Iowa Facial Growth Study. The sample consisted of 20 male and 15 female untreated Caucasian subjects who had semiannual cephalographs between the ages of 5 and 12 years, annual cephalographs between the ages 12 to 17 and once in adulthood. They found that facial convexity increased primarily because of a greater increase in nasal prominence relative to the rest of the soft-tissue profile. With age, Holdaway's H-angle decreased and the Z-angle increased due to greater anterior growth at the chin. Zylinski *et al.* (1992) found that skeletal convexity, soft-tissue convexity (excluding the nose) and several other soft-tissue measurements had large standard deviations relative to their means, indicating great individual variability. They also found in their sample of males, that if the nose was excluded, the soft-tissue profile tended to straighten with age.

2.2.3 Growth of the Nose:

The nose has been found to grow downward and forward, however its vertical growth is greater than its increase in AP depth. Burke (1979) looked at growth changes in 26 males and 26 females who were like-sexed twins using life-sized facial contour maps of subjects between the ages of 9 and 16 years. Differential growth rates were also determined, with the nose showing the most significant growth changes. Farkas *et al.* (1992) looked at a cross-sectional sample of 1,593 Caucasian subjects between 1 and 18 years, using six surface measurements. They found that at 1 year, the nasal tip projection was the least developed of any nose or lip measure (51% of the average adult size). Nose growth was greater superoinferiorly than anteroposteriorly. Chaconas and Bartroff (1975) also found AP growth in the nose increased more than any other soft-tissue measurement. Similarly, Zylinski *et al.* (1992) studied white males and found that the AP nasal depth increased relative to the most protrusive lip and the chin with aging.

2.2.4 Growth of the Lips:

There are differing opinions as to the growth changes that occur within the lips. However, most authors have found that there is a sexual dimorphism, with males showing larger growth changes, a longer growth span and larger morphological features. Pre-adolescent males and females have been shown to have similar lip dimensions, but adolescent males have larger growth changes than females, and ultimately larger lip dimensions (Genecov *et al.*, 1990; Mamandras, 1984; Prahl-Andersen *et al.*, 1995).

Subtelny (1959) also looked at growth changes involving the lips and he found that superoinferior (vertical) lip growth was less than superoinferior nose growth. Growth in AP lip thickness was greater in the vermilion area than at A-point. Contrary to this, Nanda *et al.* (1989) found greater growth in lip thickness at A-point than at the vermilion border. Chaconas and Bartroff (1975) found upper lip thickness increased for all subjects except Class II females. They found that males had thicker upper lips with greater growth, 2 mm on average.

Nanda *et al.* (1989) used 17 male and 23 untreated Caucasian female subjects from the longitudinal records of the Child Research Council in Denver. The age range studied was from 7 to 18 years. They found that the mean increase in superoinferior lip height in males, was twice that of females (6.9 mm versus 2.65 mm). Those subjects with smaller superoinferior lip heights at seven years continued to have smaller lip heights in adolescence. Subtelny (1959) found that although the lips increase in superoinferior dimension, the vertical relationship between the inferior aspect of the upper lip (Stomion Superius) and the upper incisal edge did not change in untreated subjects after full eruption of the incisors (age 9 years).

Peck *et al.* (1992) recorded 5 frontal soft-tissue relationships and 2 vertical dental dimensions directly on the face, as well as three sagittal cephalometric measurements on a sample of 42 male and 46 female Caucasian subjects who were either in treatment or post-treatment. On average females had a 1.5 mm higher smile line than males, displayed more incisor crown length than males and had a larger, but statistically insignificant, interlabial gap. The female superoinferior upper lip height was 2.2 mm shorter on average. Unfortunately this sample was exposed to orthodontic treatment which could have influenced the lip-tooth relationship.

Vig and Cohen (1979) determined the relative and absolute lip growth changes and compared these to growth of the lower face. They used a serial cephalograph sample involving 50 untreated subjects, with cephalographs taken annually from age 3 or 4 years up to age 20 years. Interestingly, 7.7 % of the initial films gathered were rejected due to "posing" of the lips. They found that, absolutely and proportionately, the lower lip grew more than the upper. Total lip growth superoinferiorly exceeded growth of the lower anterior face height, which tended to reduce the interlabial gap. They did not find differences between male and female subjects.

Farkas *et al.* (1992) found the cutaneous upper lip height (the superoinferior dimension of the upper lip superior to the vermilion border) matured earlier than the vermilion upper lip height (the superoinferior dimension of the upper lip inferior to the vermilion border). The total upper lip height was 93 % developed at 5 years of age, with only 3.9 mm of growth, on average, after the first year of life. Female development preceded male development.

Mamandras (1984) studied changes in upper and lower lip areas due to growth in 28 untreated Caucasian children from the Burlington Growth Study. They found a 2 year sex difference at the beginning, peak and end of pubertal growth, with the mean peak velocity in girls at 12 years and in boys at 14 years.

Most studies have found that during adolescence the lips tended to recede in the profile due to a proportionately larger amount of AP nose and chin growth, and that this was greater in males (Chaconas and Bartroff, 1975; Nanda *et al.*, 1989; Zylinski, 1992).

Prahl-Andersen *et al.* (1995) found that the nasolabial angle decreased with age. However, maxillary superimpositions were done using the upper incisor apex, which is an unreliable reference point. Genecov *et al.* (1990) found that the nasolabial angle did not change more than 3 or 4 degrees from 7 to 18 years.

In general, the soft-tissue facial structures in females mature earlier than males. Males generally grow larger and for a longer period of time than females. The differences found between studies may relate to the different references lines used for superimpositions, to lack of suitable control groups and to various lip postures used when taking the lateral cephalometric radiographs.

2.2.5 Late Adolescent and Adult Facial Growth Changes:

Studies of soft-tissue growth into adulthood show small but important growth changes. There are two major studies that have verified this. Behrents (1985, 1989) recalled 113 subjects who were involved in the Bolton-Brush Growth Study. These were untreated subjects of primarily European, Sicilian and Negro ancestry. The age range represented by the material studied was from 17 to 83 years of age, and 90 of the 113 subjects still had partial or complete natural dentitions. Behrents found that soft-tissue changes were greater than hard tissue changes (a 2 to 10 % change in soft-tissue dimensions was seen), however, both tended to occur at the same time. The nose showed continued forward and downward growth, that was greater in males than females. The chin also moved forward, resulting in the lips becoming relatively less prominent. The nasolabial angle tended to decrease (it became more acute) with age as the tip of the nose moved inferiorly.

Sarnas and Solow (1980) studied 50 female and 101 male untreated Caucasian dental students using cephalographs at two occasions. The first cephalograph was taken on average at age 21, the second at age 26. For both sexes the mean changes were small (usually less than 1 mm or 1 degree), and the magnitude of the method errors were generally similar to, or larger than, the mean age tissue dimension changes. Thus any actual changes were masked by method error.

2.3 Changes in Facial Profile Due to Treatment:

2.3.1 Introduction:

Cephalometric studies that have tried to relate the upper lip response to tooth movement have shown variable results. Most authors have concluded that predicting the upper lip response to tooth retraction is not accurate. Many studies have used sample sizes of less than fifty subjects (Ricketts, 1960; Hershey, 1972; Angelle, 1973; Garner, 1974; Pike, 1975; Huggins and McBride, 1975; Roos, 1977; Jacobs, 1978; Stromboni, 1979; LaMastra, 1981; Waldman, 1982; Rains and Nanda, 1982; Oliver, 1982; Abdel Kader, 1983; Holdaway, 1984; Economides, 1988; Lew, 1989, 1992; Assuncao *et al.*, 1994; Bravo, 1994). Interestingly, those studies that used a larger number of subjects have not been able to appreciably increase prediction accuracy due to the large variation in individual response to tooth movement (King, 1960; Bloom, 1961; Rudee, 1964; Wisth, 1974; Koch *et al.*, 1979; Lo and Hunter, 1982;

Remmer *et al.*, 1985; Looi and Mills, 1986; Denis and Speidel, 1987; Talass *et al.*, 1987; Drobocky and Smith, 1989; Battagel, 1990; Diels *et al.*, 1995). Bloom (1961) has been the only author to conclude that the use of average ratios and regression equations was a predictable method. Even so, he acknowledged a large variation in individual response.

Economides (1988) and Yogosawa (1990) recommended a technique for predicting the upper lip response to upper incisor retraction, using a lateral cephalometric tracing. The amount of incisor retraction was predicted on the tracing and then the upper lip was rotated around Subnasale to maintain contact with the predicted incisor position. Economides (1988) tested this method to predict the upper lip response to tooth retraction, on a sample of 31 treated patients. He found that 23 % of his predictions had an error of greater than 4 mm.

A large part of the variation in results may be related to the differences between subjects. Age and sex differences have not been adequately controlled. The use of different lip postures when taking radiographs, and different reference planes and superimposition techniques to measure lateral cephalometric changes, also have made comparisons difficult.

Studies have most commonly involved samples of adolescent Class II Division 1 Caucasians, however Garner (1974) and Diels *et al.* (1995) looked at soft-tissue response in African-American subjects, Lew (1989, 1992) studied Chinese adults and

Yogosawa (1990) used a Japanese sample. The results from studies which have investigated other racial groups have not been appreciably different than the studies using Caucasian subjects, in that they too have shown large variability in the soft-tissue changes as a result of treatment.

Since changes in lip position are a combination of treatment and growth effects, most recent studies have included a control group or have considered growth effects (Hershey, 1972; Angelle, 1973; Roos, 1977; Jacobs, 1978; Koch *et al.*, 1979; Lo and Hunter, 1982; Rains and Nanda, 1982; Abdel Kader, 1983; Remmer *et al.*, 1985; Looi and Mills, 1986; Talass *et al.*, 1987; Lew, 1989, 1992; Battagel, 1990; Assuncao *et al.*, 1994; Bravo, 1994). The use of adult subjects eliminated or at least reduced these growth effects, but differences may have existed in the soft-tissue response of adolescents as compared to adults, as suggested by Holdaway (1983).

Studies comparing male and female responses have generally not found significant differences, but age-related changes have not been controlled (LaMastra, 1981; Lo and Hunter, 1982; Diels, 1995). Garner (1974) reported a different ratio for Labrale Superius (Ls):Upper Incisor (UI) retraction in adolescent males and females, however these differences probably related more to recognized differences in growth between male and female soft-tissues than to actual differences in response to treatment.

With regard to problems with the reference planes that have been used to measure soft-tissue changes as a result of treatment, many early studies have used the facial plane or Nasion to Pogonion line (NPg) as a vertical reference line to measure horizontal changes (Riedel, 1950; Stoner *et al.*, 1956; Birch and Huggins, 1963; Hershey, 1972; Anderson *et al.*, 1973; Garner, 1974; Huggins and McBride, 1975; Abdel Kader, 1983; Denis and Speidel, 1987). The facial plane is an unreliable reference plane in situations where growth or treatment induced changes in the position of either Nasion or Pogonion have occurred. In the past twenty years, most studies have used the Sella Nasion line (SN) (Roos, 1977; Remmer *et al.*, 1985), a line seven degrees inferior to SN at Sella (Stromboni, 1979; Rains and Nanda, 1982; Looi and Mills, 1986; Talass *et al.*, 1987; Assuncao *et al.*, 1994; Diels *et al.*, 1995), or Frankfort Horizontal plane (FH) (Lamastra, 1981; Lo and Hunter, 1982; Battagel, 1990) as the horizontal axis, and a perpendicular through Sella as the vertical axis. FH is generally less reproducible than SN because in the sagittal view it is formed by two landmarks, Porion and Orbitale, which are often difficult to locate on cephalographs. These areas also have greater growth changes associated with them than the area of the anterior cranial base. Drobocky and Smith (1989) measured lip position changes in relation to the E-line (nose-chin line) and the Subnasale soft-tissue Pogonion line (Sn-Pg'). This method related the lip position to the rest of the soft-tissue profile. However, since they used growing adolescent subjects, both of these reference lines would be expected to change with growth. It was then impossible to quantify which structures had actually changed.

Also, the application of superimposition techniques using other unstable reference lines or registration points that change with growth or treatment or are difficult to reliably identify has limited the usefulness of many studies (Brodie *et al.*, 1938; Stoner *et al.*, 1956; King, 1960; Rudee, 1964; Hershey, 1972; Garner, 1974; Huggins and McBride, 1975; Roos, 1977; Jacobs, 1978; Abdel Kader, 1983; Finnöy *et al.*, 1987; Battagel, 1990; Bravo, 1994; Assuncao *et al.*, 1994). More reliable superimposition techniques which have been supported by implant studies (Björk and Skieller, 1976, 1983) have been used by some investigators to alleviate this problem (Wisth, 1974; Pike, 1975; Oliver, 1982; Talass *et al.*, 1987; Denis and Speidel, 1987; Paquette *et al.*, 1992; Luppanapornlap and Johnston, 1993; Diels *et al.*, 1995). These studies have generally applied cranial base or regional "best fit" methods.

Studies using a lip-together posture for cephalometric films (Wisth, 1974; Pike, 1975; Jacobs, 1978; Stromboni, 1979; Oliver, 1982; Denis and Speidel, 1987; Yogosawa, 1990; Singh, 1990; Diels *et al.*, 1995) have had the problem of distortion of the actual superoinferior lip height, AP lip thickness and position, particularly for severe malocclusions (Burstone, 1967; Yogosawa, 1990; Birch and Huggins, 1963).

Investigations of the changes in specific soft-tissue areas and dimensions will be presented in the following sections.

2.3.2 Changes in Anteroposterior Upper Lip Position:

Since many studies have not controlled for growth changes, or have used cephalographs depicting a closed-lip posture in subjects with significant malocclusions, the results of these studies are difficult to interpret. Of those studies that controlled for growth effects and which used a standardized cephalometric technique, the percentage of Ls retraction to tooth retraction ranges from a low of 14.5 % (Battagel, 1990) to a high of 64 % (Talass *et al.*, 1987). Most of these studies have shown a range of 30 to 60 % (Hershey, 1972; Roos, 1977; Koch *et al.*, 1979; Lo and Hunter, 1982; Remmer *et al.*, 1985; Looi and Mills, 1986; Lew, 1992). The correlation coefficients of lip to tooth movement ranges from 0.42 to 0.86. Most correlations have been between 0.7 and 0.85 (Hershey, 1972; Rains and Nanda, 1982; Lo and Hunter, 1982; Looi and Mills, 1986; Talass *et al.*, 1987; Battagel, 1990; Lew, 1992). The use of more complex statistical analyses has only marginally improved the prediction accuracy of soft-tissue movement in response to tooth movement. As well, the inherent errors associated with using the lateral cephalometric technique limit the ultimate accuracy of any prediction technique.

Koch *et al.* (1979) compared 90 Class II Division 1 adolescents treated with functional appliances or headgear and 23 Class III patients treated with functional and fixed appliances, with an untreated Class II Division 1 control group of similar age. Subtracting the average growth effect, they found the upper lip followed 30 % of the amount of upper incisor retraction.

Assuncao *et al.* (1994) studied soft-tissue changes in a group of 25 Brazilian adult patients (primarily female) and subtracted the change in AP lip thickness of each lip from the total amount of lip retraction. Therefore, if the AP lip thickness increased with upper incisor retraction, this was included in the change in position. They concluded that the formulation of regression equations to predict changes were not accurate because changes in AP lip thickness masked the predictable final results, and these changes could not be predicted.

Rains and Nanda (1982) used a stepwise multiple regression analysis that involved seven dependent soft-tissue measurements and eleven hard- and soft-tissue independent variables to investigate lip changes in a sample of 30 post-adolescent females. They found that the upper lip response was related to both upper and lower incisor movement, mandibular rotation and AP movement of the lower lip. Dental movements did not correlate well with changes in the lips. They found lip retraction at Ls was more variable with greater amounts of upper incisor retraction. Talass *et al.* (1987) also used stepwise multiple regression analysis to establish prediction ratios using a sample of 80 Class II Division 1 females treated primarily by extraction of two maxillary premolars. They determined correlation coefficients using 12 dependent soft-tissue variables and 36 soft- and hard-tissue independent variables. They subtracted growth effects by using a matched control sample of 53 untreated females from the Burlington Growth Study. They found that the most important soft-tissue changes were the retraction of the upper lip, increase in lower lip length and increase in the nasolabial angle. A greater amount of upper lip retraction occurred with greater upper incisor retraction, thinner tissue at Sn pre-treatment, thicker tissue at Ls pre-treatment and a greater amount of superoinferior nose growth. However, all these factors only explained 48.5 % of the variability of the upper lip response (r^2=48.5 %). The authors concluded that predicting the upper lip response is not reliable.

Denis and Speidel (1987) compared three methods of predicting soft-tissue profile change using average ratios, bivariate correlations and stepwise multiple regression analysis. Comparisons were done using the standard error of the estimate (which is the standard deviation of the actual value minus the predicted value). Analysis was performed on a sample of 83 nongrowing patients from the University of Minnesota. The standard error of the estimate was 1.39 mm using mean ratios, 1.35 mm for bivariate regressions (r=0.56) and 1.1 mm using multiple regression analysis (r=0.75). For Ls, multiple regression only improved predictions by 0.29 mm. According to these authors, predictors for Ls movement were upper incisor movement and initial lip taper. Lip taper was defined as the difference between the lip thickness at Subnasale and the vermilion border. Greater pre-treatment lip taper resulted in less lip retrusion during retraction. Unfortunately, the cephalographs in this study were made using a lip together posture.

The reliability in repositioning the soft-tissue with the lateral cephalometric technique, has been investigated by two studies. Wisth and Bōe (1975) made repeat cephalographs on a sample of 30 Class I and 30 Class II Division 1 children and 30 Class I adults. They found the accuracy of locating soft-tissue measurements to be similar to that in locating hard-tissue landmarks. They emphasized the importance of instructing subjects how to relax, and allowing them to get used to the recording procedure before taking the cephalographs. Hillesund *et al.* (1978) found that the standard deviation for Ls was 0.91 mm. This represented the error due to patient posturing and represents the ultimate accuracy of any prediction technique. This is relatively large compared to the small soft-tissue changes usually seen with treatment, however, it is similar to the error in retracing hard-tissue cephalometric landmarks.

2.3.3 Changes in Anteroposterior Lip Thickness:

Most cephalometric studies of changes in anteroposterior lip thickness with tooth retraction have assumed that the lip always maintains contact with the facial surface of the incisors. Hershey (1972) found that with upper incisor retraction it was difficult to determine whether there was an actual increase in AP lip thickness or creation of a void between the lip and tooth.

In studies reporting AP lip thickness changes in orthodontically treated adolescents, the lack of control groups has meant that changes in AP lip thickness could be due to either treatment or growth changes (King, 1960; Birch and Huggins, 1963; Anderson *et al.*, 1973; Wisth, 1974, Stromboni, 1979; Oliver, 1982; Holdaway, 1983; Battagel, 1990). Even in studies which have attempted to factor out growth changes, there has been no consensus in the literature regarding AP lip thickness changes resulting from treatment. Quantification of the relationships has not been achieved. Differences also exist as to whether thin or thick lips retract more, given the same amount of tooth retraction.

Angelle (1973) compared 36 treated adolescents to a control group of 16 untreated subjects. It may be notable that the treatment group was somewhat younger, more Class II and less prognathic. Nonetheless, the author found that the upper lip thickened anteroposteriorly in the treatment group, and it thickened more with males. Roos (1977) studied 30 Class II

Division 1 adolescents (10 male and 20 female) and reported the results as a quotient of the SN distance to try to compensate for growth changes. This author also found that the upper lip at Ls was significantly thicker anteroposteriorly after treatment, however, using SN distance to compensate for facial soft-tissue growth has questionable validity.

Lo and Hunter (1982), on the other hand, investigated changes in the nasolabial angle and AP lip thickness with upper incisor retraction in a sample of 93 Class II Division 1 Caucasian adolescents. They used a control sample of 43 untreated subjects from the Burlington Growth Center. These authors could not find a correlation between upper incisor retraction and changes in AP lip thickness. Further to their 1986 study, Looi and Mills concluded not only that the more the teeth are retracted, the less the upper lip retracts, but also, the more it thickens anteroposteriorly.

Talass *et al.* (1987), stated that growth changes over a 2 to 3 year treatment period were minimal, and found that thick lips (measured at Subnasale) followed upper incisor retraction more closely than thin lips. King (1960) analyzed the cephalographs of 103 consecutively treated Class II Division 1 adolescents and found that thin lips did indeed follow incisor retraction more closely than thick lips. Unfortunately, no compensation for growth changes during treatment were made, and therefore the results are equivocal.

2.3.4 Changes in Superoinferior Lip Height:

Conflicting opinions and results exist as to the effect of anterior tooth retraction on superoinferior (SI) upper lip height. Most authors have determined SI lip height as the distance between Stomiom Superius and a horizontal reference line (SN or FH). Changes in upper incisor position are measured at either the incisal edge or the labial surface, however, differences between tipping and bodily tooth retraction have not been determined. While many studies have shown an increase in SI upper and lower lip heights with anterior tooth retraction (Angelle, 1973; Lew, 1989, 1992; Yogosawa, 1990), several studies have not found this increase (Rains and Nanda, 1982; Looi and Mills, 1986; Talass *et al.*, 1987; Assuncao *et al.*, 1994). Differences may be related to differences in sample selection.

Those studies that have found an increase in lip height, the changes have been quite small. In a sample of 32 Chinese adults treated with four premolar extractions, Lew (1989) found that on average, the upper lip height increased 1.9 ± 1.1 mm and the lower height increased 1.4 ± 0.8 mm. Yogosawa (1990) found that a height increase for both lips associated with anterior tooth retraction in a sample of 20 Japanese adult females (10 maxillary protrusion cases and 10 bimaxillary protrusion cases). In a separate study, Lew (1992) found that the upper lip height increased in 16 Chinese adult Class II Division 1 patients treated with premolar extractions. On average the upper incisors were retracted 5.75 ± 1.91 mm, and the upper lip lengthened 1.5 ± 0.6 mm. Inferior descent of the soft-tissue landmark Stomion was correlated to horizontal retraction of the upper incisors, such that 3.8 mm of tooth retraction resulted in 1 mm inferior repositioning of Stomion (r=0.57).

2.3.5 Lip Taper and the Soft-Tissue Response:

Holdaway (1983) suggested that normal AP lip thickness, as measured near the base of the alveolar process, should be 1 mm thicker than the AP vermilion lip thickness. If this difference was larger, the sagittal lip thickness profile was said to be tapered. Holdaway suggested that excessive taper was indicative of the thinning of the lip over protrusive teeth, and that excessive taper in the upper lip needed to be eliminated before the lip moved in response to tooth retraction. Older patients were an exception, where a lip with large lip taper was expected to follow the incisors more closely. Denis and Speidel (1987) and Yogosawa (1990) both found Holdaway's predictions to be true, with greater amounts of upper lip retraction demonstrated in lips showing less pre-treatment taper. Oliver (1982), in a sample of 40 adolescents with severe Class II Division 1 malocclusions, found a better correlation between tooth and lip retraction in the tapered lip subjects. These conflicting results may be attributed to the fact that the cephalographs in Oliver's study used a lip-closed posture. The lips therefore would be distorted as these patients with severe malocclusions forced lip closure.

2.3.6 Changes in the Nasolabial Angle:

Generally an increase in the nasolabial angle (NLA) with anterior tooth retraction has been demonstrated. Cummins *et al.* (1995) found a significant increase in the NLA in extraction, but not non-extraction groups. Lo and Hunter (1982) found their control sample had minimal changes in the NLA with growth. A stepwise multiple regression analysis of their data correlated changes in the NLA with upper incisor retraction (r=0.77), increase in lower face height (r=0.77) and increase in mandibular plane angle (r=0.46). They found that 1 mm of incisor retraction resulted in a 1.63 degree increase in the NLA, and a 1 degree increase in the mandibular plane resulted in a 2.8 degree increase in the NLA. Talass *et al.* (1987) also found the NLA did not change appreciably in their control sample, but increased 10.5 degrees on average with incisor retraction. Drobocky and Smith (1989) compared four extraction groups treated by one of four methods: the Tweed technique, a 0.022 inch preadjusted appliance, a Begg appliance or premolar enucleation. On average there was a 5.2 degree increase in the NLA, with large individual variation. Thirteen percent of the patients had an esthetic improvement in the NLA, whereas twenty percent had an esthetic worsening of the angle (the angle became too obtuse). Lew (1989) examined soft-tissue changes in 32 Chinese adults treated with four premolar extractions and the Begg appliance, and found on average the NLA increased 10 degrees. Lew (1992) recently reported the soft-tissue changes in 16 Chinese Class II Division 1 adult patients treated with extractions and maxillary lingual and mandibular ceramic fixed appliances. The average increase in the NLA was 10.8 ± 3 degrees. A weak correlation existed between the increase in the NLA and upper incisor retraction, where a 1 degree increase in the NLA occurred with each 0.5 mm of upper incisor retraction ($r=0.46$).

2.3.7 Changes in Post-Treatment Anteroposterior Lip Position:

Most studies have measured upper lip position at the end of treatment. Few studies have followed the changes seen in retention (Birch and Huggins, 1963; Angelle, 1973; Anderson *et al.*, 1973; Koch *et al.*, 1979; Denis and Speidel, 1987; Singh, 1990; Paquette *et al.*, 1992; Luppanapornlap and Johnston, 1993; Bishara *et al.*, 1995b, Cummins *et al.*, 1995). Several studies have shown that the adaptation of lip position to incisor retraction may take longer than the time between incisor retraction and exposure of the post-treatment cephalograph.

Birch and Huggins (1963) followed 39 of 70 Class II patients treated with extraction of two upper premolars using cephalographs taken 6 months after treatment. In eighty seven percent of the subjects, the incisors maintained their position, but fifty three percent of the subjects had "lip relapse" after six months (i.e. AP thickening of the lip). Anderson *et al.* (1973) had ten year follow-up cephalographs taken on 70 subjects. They found that upper lip movement in response to tooth retraction continued following treatment and was significant at all time periods. With most subjects, AP thickening of the upper lip associated with retraction was maintained post-retention. Looi and Mills (1986) compared 30 subjects with Activator appliances, 30 subjects with Begg appliances and 22 subjects who were untreated controls using pre-treatment, immediate post-treatment and one year post-retention cephalographs. They found that relapse of the incisors was not matched by protrusion of the lips, but rather AP thinning of the lips. Paquette *et al.* (1992) compared 30 borderline Class II extraction and non-extraction patients with cephalographs taken pre-, post- and an average of 14.5 years post-treatment. They found less protrusion of the teeth and lips in the cases with extractions. These post-treatment differences were maintained into the retention period. Bishara *et al.* (1995b) and Cummins *et al.* (1995) found that post-treatment changes between extraction and non-extraction groups were maintained 2 years after treatment.

The literature suggests that the adaptation of lip position to changes in tooth position may continue after fixed appliance removal.

2.3.8 Comparison of Treatment Types:

Several studies have compared the response to different forms of orthodontic treatment (Stoner *et al.*, 1956; Ricketts, 1960; Rudee, 1964; Stromboni, 1979; Lo and Hunter, 1982; Waldman, 1982; Remmer *et al.*, 1985; Looi and Mills, 1986; Finnöy *et al.*, 1987; Drobocky and Smith, 1989; Paquette *et al.*, 1992; Luppanapornlap and Johnston, 1993).

Remmer *et al.* (1985) compared soft-tissue changes between 25 adolescent Class II Division 1 subjects treated with an Activator appliance, 25 subjects treated with a Fränkel appliance and 25 subjects treated with an edgewise appliance which included headgear and elastics. There were no significant pre-treatment differences between the three groups, and the post-treatment results showed that there was little difference in the change in the soft-tissue profiles between the three groups. The upper incisor was retracted on average 1.5 mm more in the fixed versus the functional appliance groups. There was minimal change in the position of Ls with a mean posterior Ls movement of 0.9 mm in the fixed group and a mean forward Ls movement of 0.9 mm in the functional appliance groups.

Looi and Mills (1986) compared soft-tissue changes in a group of 30 adolescents treated with an Activator appliance and 30 patients treated with four premolar extractions and the Begg fixed appliance, with a control group of 22 untreated Class II Division 1 subjects. The fixed appliance group had, on average, 4 mm more upper incisor retraction, but only 1 mm more retraction of the upper lip. This led the authors to conclude that the relative amount of lip retraction tended to be less as the teeth were retracted more. They hypothesized that the lip moved back until it assumed a "natural position", then further retraction had little effect. Bishara *et al.* (1995b) compared the lateral cephalographs of 44 Class II Division 1 adolescents treated with extractions, with 47 Class II Division 1 adolescents treated without extractions. With treatment the extraction groups had a significant reduction in soft-tissue convexity and lip protrusion in relation to the E-line, whereas non-extraction groups had an increase in lip protrusion. This is not surprising considering that the extraction group would be expected to have some anterior tooth retraction, whereas the non-extraction group would be expected to have some forward incisor movement. Cummins *et al.* (1995) used a lateral and frontal photogrammetric analysis with this same sample, and found similar results.

In general, these studies have not demonstrated differences between the treatment types. It is unlikely that the soft-tissues would respond differently to different types of appliances if the same dental and skeletal changes were produced. For many of these studies, the patient group selected for one appliance or treatment strategy (e.g. extraction versus non-extraction) was not the same as the patient group selected for another appliance (Finnöy et al, 1987).

2.3.9 Comparison of Malocclusions:

Individuals with different malocclusions might be expected to have different soft-tissue responses to tooth movement because their soft-tissues could be at different states of relaxation depending on the position of their supporting teeth. As well, the lips might interact differently and the position of one lip might influence the movement of the other lip if they were in contact. Although there is a paucity of data in this area, there appear to be some small differences between different malocclusion types. However, the large interindividual variations appear to be more important.

Brodie *et al.* (1938) presented the cephalometric results of six treated Class I patients, two Class II and two Class III patients. Their results showed that "identical treatment of different individuals was followed by quite dissimilar effects". Hershey (1972) compared the soft-tissue response to treatment for 20 Class I, 15 Class II and 1 Class III patients. Most were treated with extraction of four first premolars and an edgewise appliance. He found that the soft-tissue response varied widely from individual to individual, but concluded that the upper lip followed the upper incisor slightly more in the Class II group. Wisth (1974) compared lip response to tooth movement in large (8 to 10 mm) and small (3 to 4 mm) overjet (OJ) groups. The cephalographs were taken with lip together posture, which may have resulted in lip distortion, particularly with the large OJ group. The mean changes in lip morphology were greater in the large OJ group with a great deal of variability in both groups, making predictions difficult. The ratio of change in UI:Ls for the small OJ group was 2:1 and for the large OJ group it was 3:1. There may have been less lip retraction in response to tooth retraction in the large OJ group as a result of a greater amount of lip flattening on the pre-treatment cephalographs, since a lip-together posture was used.

2.3.10 Factors that may Affect the Soft-Tissue Response:

Many authors have suggested other factors that may affect the soft-tissue response, factors that cannot be evaluated with a radiograph. Differences in the anatomical, structural and physical characteristics of the lip tissue cannot be evaluated with a radiograph.

Hershey (1972) found no difference in the soft-tissue response between ten subjects with lip redundancy (protrusion and eversion) and ten with lip incompetence. He concluded that predicting lip movement on an individual basis was not accurate due to the variable soft-tissue response. Hershey suggested that possible variables affecting the soft-tissue response were lip pressure, variations in soft-tissue anatomy, changes in intercanine width and the actual lip to tooth contact. Holdaway (1983) felt that the type of lip structure, age and sex of the patient may affect the soft-tissue response, although he offered no research data to support his ideas. Talass *et al.* (1987) could only explain 48.5% of the variability in soft-tissue response of their sample and they suggested that factors such as the anatomic interrelations between the various upper lip muscles and the anatomy of the "nose-lip" complex may be important to the soft-tissue response. In a review article, Attarzadeh and Adenwalla (1990) have suggested that tight lips should retract more than flaccid lips, changes in the intercanine width might alter perioral muscle tension, and patients may respond differently to tooth retraction due to differences in lip structure. Assuncao *et al.* (1994) stated that future studies should examine the relationship between lip retraction, lip tone and AP lip thickness.

Although several investigators have suggested that differences in the physical properties of the upper lip between subjects may influence the soft-tissue response to tooth movement, no studies have been performed to try and assess these factors. It was the purpose of this investigation to increase the understanding of the relationship between physical properties of the upper lip and the response of the lip to orthodontic tooth movement.

2.4 Summary:

Overall, the studies investigating the changes in lip position with tooth movement have been restrospective studies describing the changes in the morphological features and dimensions. These data have been of limited use for clinical applications on an individual basis. In order to more reliably predict treatment effects, there is clearly a need for studies investigating the physical characteristics of the soft-tissues and the individual factors influencing lip response.

CHAPTER 3
MATERIALS AND METHODS

MATERIALS AND METHODS

3.0 Introduction:

A laboratory trial was undertaken using seven adult subjects who had been orthodontic patients at the University of Manitoba. The experimental apparatus was designed to record forces associated with the displacement of the relaxed upper lip. An alginate impression of the subject's maxillary dental arch was made. From this a working cast was produced for the fabrication of three customized acrylic facings to fit under the upper lip, labial to the maxillary anterior teeth. Each acrylic facing was attached to a threaded metal connector rod, which provided a "handle" for the AP movement of a flange and for the force measurements. A video camera was used to record the changes in lip position in profile view, as the facings were pulled forward, and to simultaneously record the force readings. Each subject presented for two recording sessions.

The physical properties of the upper lip were quantified by the slope of the stress:strain and horizontal flange displacement:horizontal lip displacement ($flange^H:lip^H$) linear regression relationships, as determined using the video data. The physical properties of the upper lip were compared between subjects, sessions and flanges using a one-way analysis of variance (ANOVA) and a Scheffe multiple range test. Two theoretical models to predict the upper lip position change and lip decompression with tooth retraction are presented. The theoretical models were based on the physical properties of the upper lip, as determined from the video data, and the area of tooth retraction (ATR) as determined by superimposing pre- and post-treatment occlusograms. The theoretical models facilitated the testing of the hypothesis for this study, that is, that the lip profile changes in response to orthodontic tooth movement are not predictably associated with the physical properties of the upper lip as measured during simulated tooth movement.

3.1 Subjects:

Subjects were recruited for this study based on the patient records available at the Graduate Orthodontic Clinic, Faculty of Dentistry, University of Manitoba. Suitable subjects were patients who had completed the active phase of their orthodontic treatment, who had good quality cephalographs before treatment was initiated, and 2 years after their treatment was completed. In addition, as patients, suitable subjects had at least 2 mm of maxillary central incisor retraction (posterior movement) as a result of their orthodontic treatment. The subjects were a minimum of 14 years old before treatment, with minimal growth subsequent to treatment, as determined by serial cephalometric analysis.

Persons who were allergic to denture acrylic, who had difficulty in opening or who had signs and/or symptoms of temporomandibular disorder were excluded from the study. Seven volunteers, who fit the selection criteria, participated (Table 3.1). There were five female and two male subjects. The average age before treatment was 21 years 10 months, and the average age after treatment was 26 years 3 months. Informed consent was obtained from each subject at the initial appointment after the research project was explained fully. A medical/dental history form was completed to determine if allergies to acrylic or related compounds, or medical conditions existed that could affect the subject's participation in the project. Copies of the information sheet for potential subjects, informed consent form and ethics committee approval form are contained in Appendix B.

Once consent was obtained and the health status deemed acceptable, an alginate impression (Jeltrate®· Dentsply International Inc., Milford, DE) of the subject's maxillary dental arch was made. From this, a working cast was produced for the fabrication of customized acrylic facings to fit under the upper lip, labial to the maxillary anterior teeth.

TABLE 3.1. Research Subjects. Sex and ages before and after orthodontic treatment (where M=male, F=female, y=years, m=months).

SUBJECT	**Sex**	**AGE:** PRE-TREATMENT	**AGE:** POST-TREATMENT
KS	F	21y 9m	25y 7m
PH	F	30y 5m	37y 1m
DR	M	25y 3m	27y 8m
JC	F	21y 7m	25y 6m
CH	F	20y 7m	24y 0m
KC	M	18y 7m	24y 0m
JG	F	14y 6m	20y 2m
Average Age:		21y 10m	26y 3m

3.2 Experimental Apparatus:

The experimental apparatus consisted of five main components, and was designed to record forces associated with the displacement of the relaxed upper lip in human subjects (Figure 3.1). The apparatus was located in a dedicated laboratory space at the Faculty of Engineering, University of Manitoba. It was standardized before each recording session and its position was not changed, except for the video camera which was removed from the tripod between sessions.

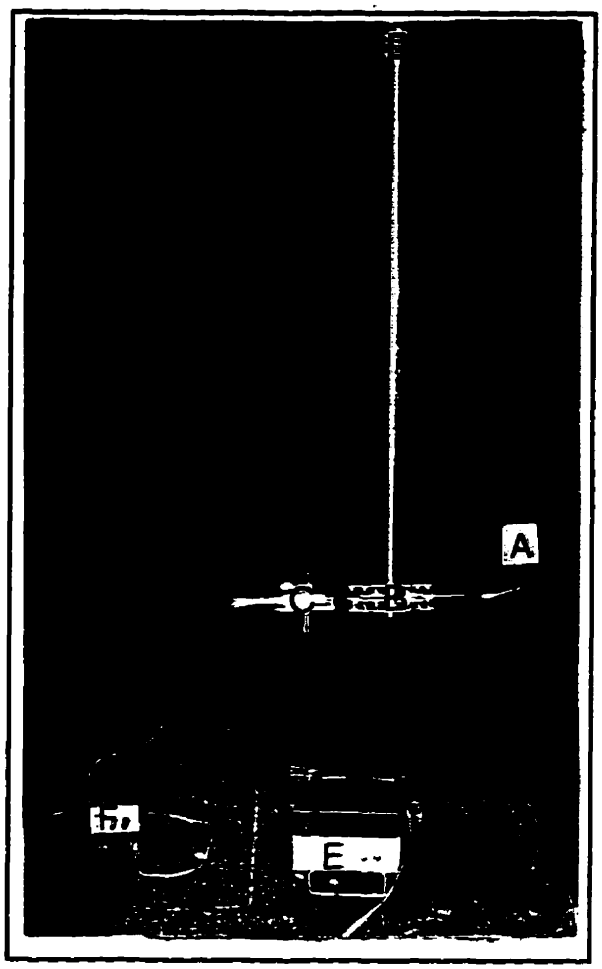


Figure 3.1 Experimental Apparatus.
A: Flange and Connector Rod
B: Quick-Connect System
C: LVDT on Stand
D: Pendulum Arm Hinge Mechanism
E: Voltmeter
F: 6-volt source

The first component was a set of customized acrylic facings, fabricated using methylmethacrylate monomer and polymer (Orthoresin®, Dentsply Limited, Weybridge, Surrey, England). The facings were 1 to 2 mm thick and extended to within 4 mm from the depth of the vestibular fold as determined on the plaster cast of the subject. Facings of three different widths were fabricated (Figure 3.2):

i) covering the maxillary incisors and canines plus additional width if necessary to ensure that the lateral flanges of the facing were wider than the corners of the mouth at rest position (wide flange).

ii) covering the maxillary central and lateral incisors (medium flange).

iii) covering the maxillary central incisors only (narrow flange).

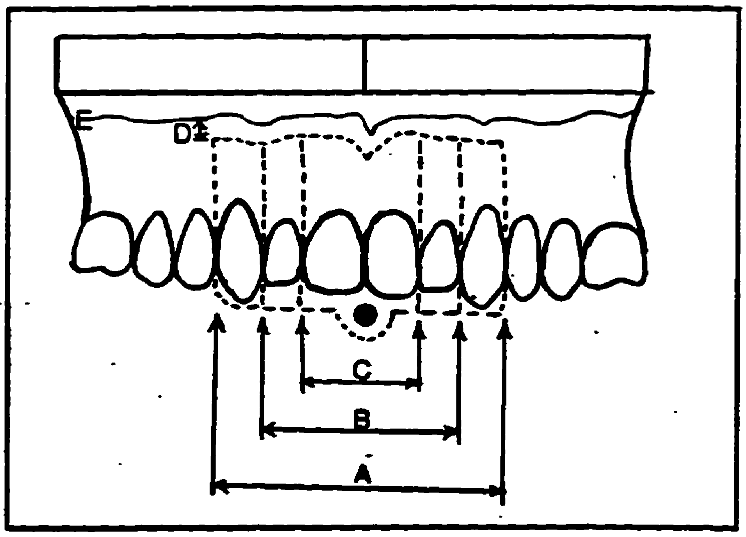


Figure 3.2. Flange Dimensions
A: Width of Wide Flange
B: Width of Medium Flange
C: Width of Narrow Flange
D: 4mm inferior to the vestibular fold - indicating the Height of the Flange
E: Vestibular Fold

The facings were pumiced to a dull finish so that the lip would not slide over them too easily. They were disinfected for intra-oral use by a 10 hour immersion in a sterilizing solution (Coldspor^MD®, Corporation De Recherche Metrex, Ville St. Laurent, Que.). Heat/steam sterilization was not used, since it might have damaged or distorted the acrylic facings.

The surface area of the three flanges for each subject are presented in Table 3.2.

Table 3.2. Surface Area of Flanges.

SURFACE AREA OF FLANGES (mm^2)			
SUBJECT	Flange Size		
	Wide	Medium	Narrow
KS	833	688	401
PH	989	719	334
DR	1139	814	556
JC	1076	699	385
CH	959	711	450
KC	911	599	379
JG	1145	765	489
Average:	1007	715	428

Each acrylic facing was attached to a threaded metal connector rod (7 mm diameter). The corresponding threaded hole for attachment of the rod was drilled into the acrylic facing, parallel to the occlusal plane and just incisal to the maxillary central incisors. Each of these provided a "handle" for the AP movement of a flange and for the force measurements (Figure 3.3).

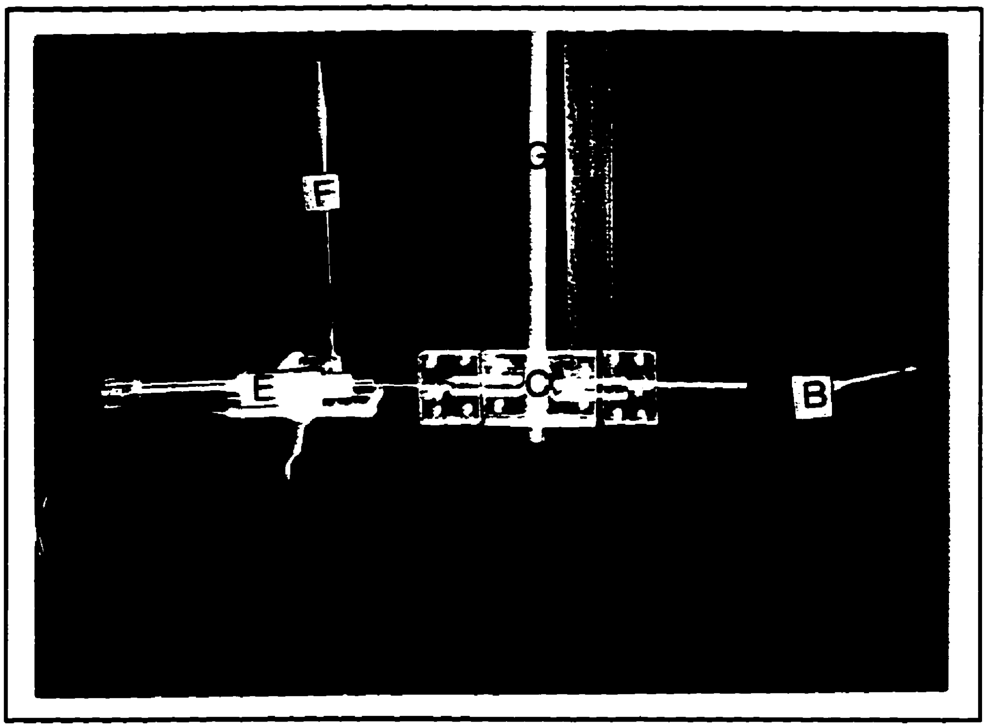


Figure 3.3 Flange-Connector Rod Attached to LVDT using Quick-Connect System (Side View).
A: Flange
B: Connector Rod
C: Quick-Connect System
D: Vertical Arm of Metal Stand
E: LVDT
F: Retort Stand
G: Pendulum Arm

The metal connector rods were autoclaved and then assembled with the disinfected flanges in preparation for each recording session. The connector rod was sectioned along its length, and rejoined at a 10 degree angle. This was done to approximate the angle between the occlusal plane and Frankfort Horizontal plane. The total length of the flange plus connector rod component was approximately 17 centimeters (cm).

The second component of the experimental apparatus consisted of a metal stand and hinge mechanism (Figure 3.4), which secured a long pendulum arm for controlled AP movement of the flange. The base for the stand was made of channel iron, with a 139 cm length of angle iron attached vertically to the base. The stand was located on top of a desk (73 cm in height), which allowed the subject to be comfortably seated on an adjustable stool in front of the flange.

A hinge mechanism (Figure 3.5) was made of 0.003 inch steel shim stock, attached to the top of the vertical angle iron. The steel shim stock hinges restricted movement of a pendulum arm to the AP axis of the subject, and was relatively free of frictional losses. The top of the hinge housing was bolted to the vertical angle iron. The bottom of the hinge was machined to receive the top of the pendulum arm.

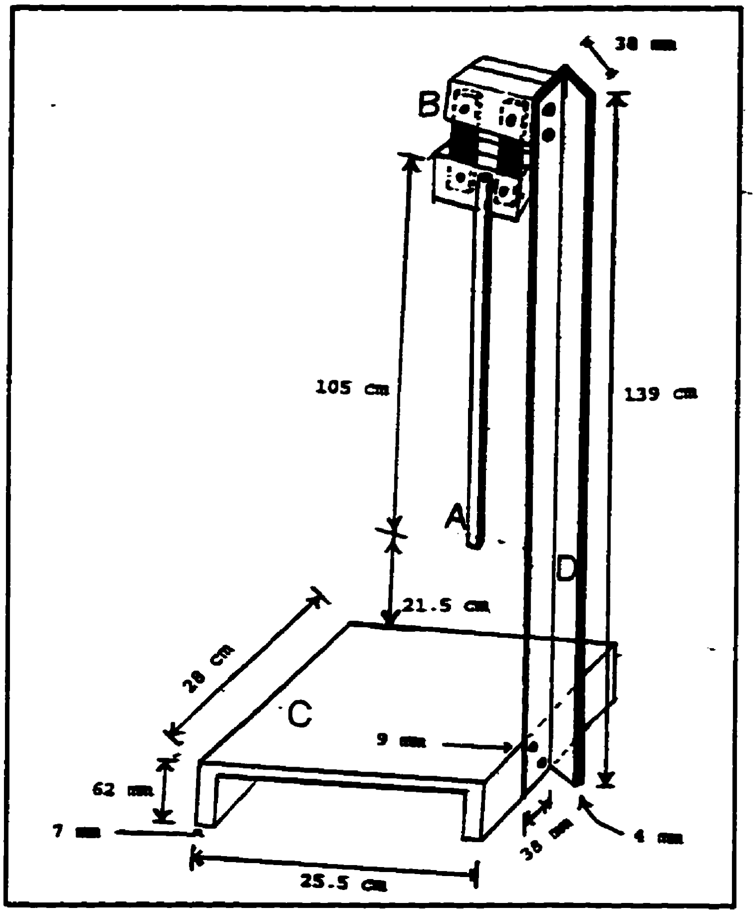


Figure 3.4 Desktop Stand for Hinge Mechanism and Pendulum Arm (Side and Rear-View Relative to Video Recording).
A: Pendulum Arm
B: Hinge Mechanism
C: Metal Stand Base
D: Angle Iron Post

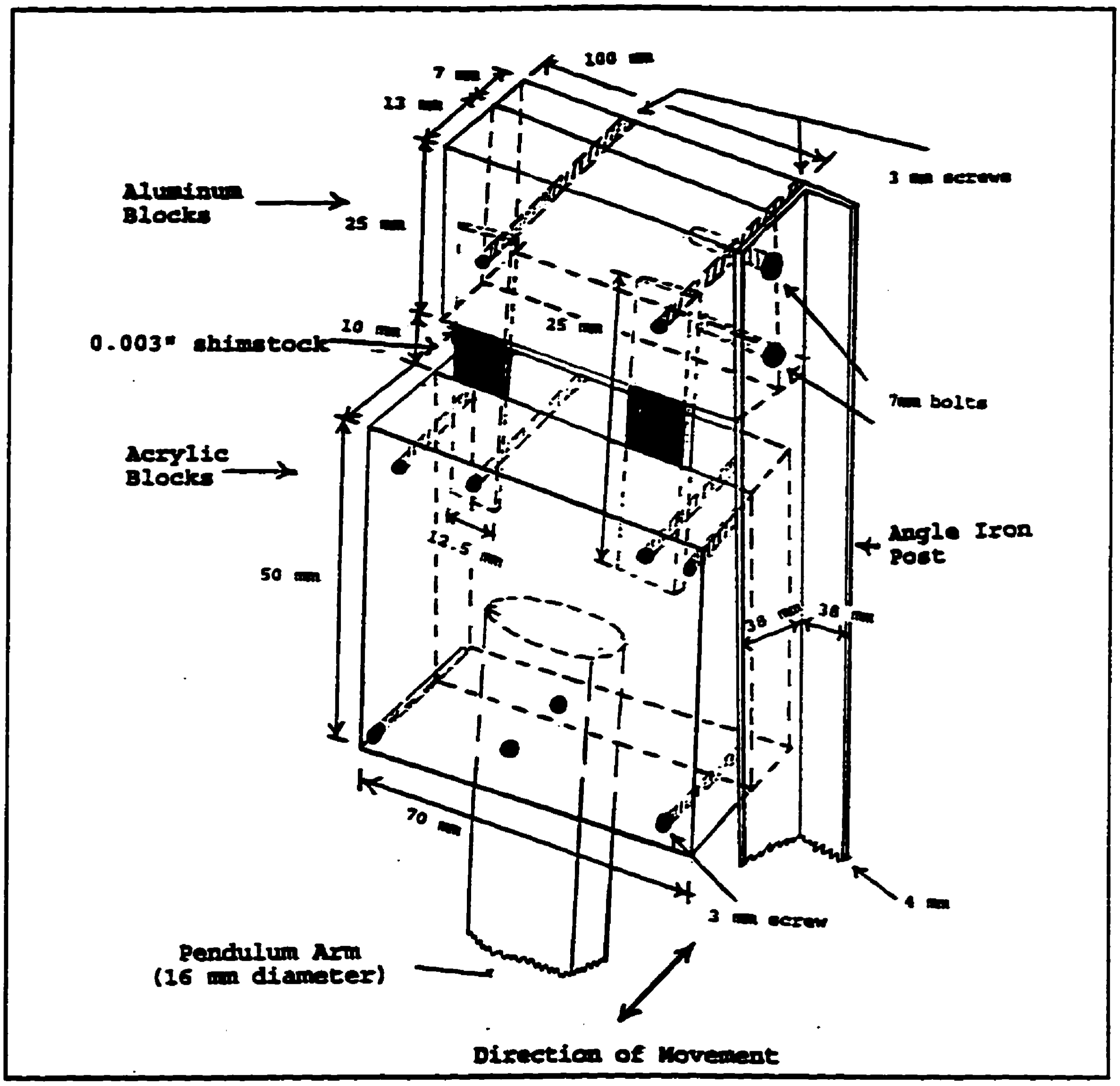


Figure 3.5 Hinge Mechanism. The top portion of Figure 3.4 is shown in detail. Only the superior portions of the pendulum arm and angle iron post are illustrated.

The third component of the apparatus was a linear voltage differential transformer (LVDT) which was attached to a voltmeter and was supplied by a 6 volt direct current power source. The LVDT housed a calibrated spring connected to a displaceable pin. The LVDT housing was supported by an acrylic guide. The guide for the LVDT housing was made of two pieces of acrylic (39 mm wide by 100 mm long by 3 mm thick), glued at a ninety degree angle and attached to a retort stand. The height of the guide was adjustable. The guide was of sufficient length to allow the housing to be pulled over a total distance of 10 cm. The guide prevented any lateral movement of the LVDT housing as it was pulled parallel to the AP axis of the subject's face. Each acrylic facing was attached to the LVDT through the connector rod, using the quick-connect apparatus (described below). Calibration of the force:displacement characteristics of the LVDT facilitated conversion of the LVDT electrical output, as recorded on a digital voltmeter, to a force application on the flanges.

The resistance force of the upper lip on the flange was determined by calibrating the LVDT, such that the following equation described this force:

$$\text{Force (grams}^{*}\text{)} = 90.2 + 49.4 \times \text{Voltmeter Reading}$$

* Note: In the clinical orthodontic literature, commonly, force has been expressed in "grams", which is otherwise regarded as a unit of mass. Clinical convention has been followed herein, although "Newtons" is a more appropriate unit.

The fourth component of the apparatus provided a system by which the flange with connector rod, the pendulum arm, and the LVDT were linked. This adjustable system, known as the "quick-connect system", was made up of six separate, but identical, pieces of acrylic (Figure 3.6).

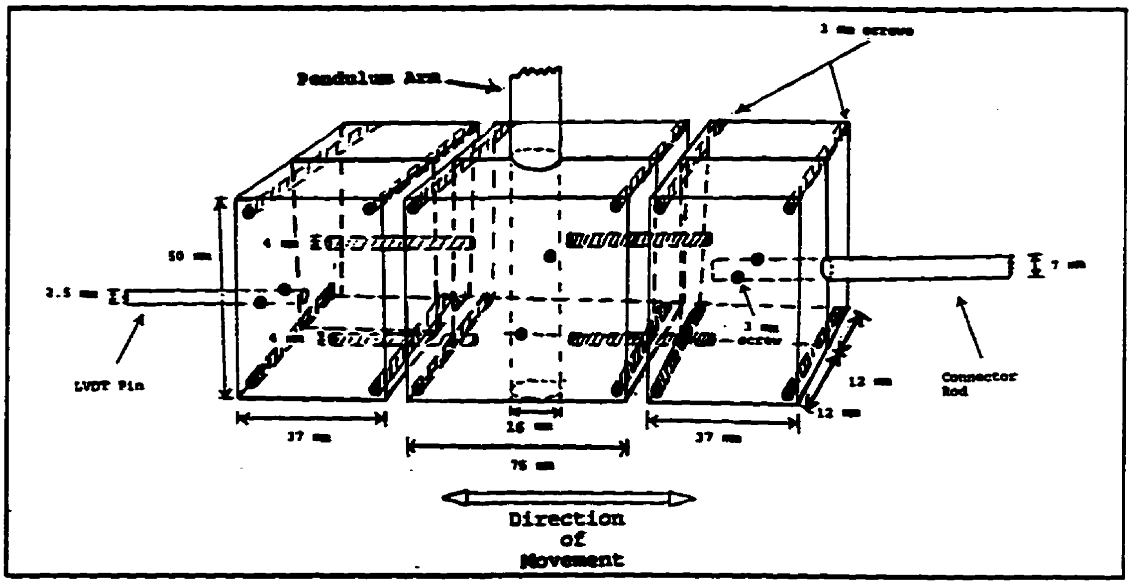


Figure 3.6 Quick-Connect System. The arrangement of the six acrylic pieces into three separate blocks for the linking of the connector rod, pendulum arm, and LVDT in an adjustable system is shown. Only portions of the connector rod, pendulum arm and LVDT pin are illustrated. (See text for details).

Two pieces of this acrylic were joined to form one of three main acrylic blocks, using screws placed into threaded holes in each corner of the acrylic pieces. The three acrylic blocks were then linked (perpendicular to the joining screws) using two lengths of threaded rod between each of the three blocks. The distal end of the connector rod was inserted into a hole (6.5 mm diameter) bored in the end of the first acrylic block. The pendulum rod was inserted in a larger hole (15 mm diameter) bored in the top of the second acrylic block and the LVDT pin was inserted in a small hole (2.5mm diameter) bored in the end of the third acrylic block. Two securing screws were bored into the face of each acrylic block to secure and allow independent adjustment or removal of the connector rod, pendulum arm or LVDT pin.

The fifth component of the experimental apparatus was a video camera (RCA®, ModelCC507, Ronks,PA) which was mounted on a tripod at a set distance of 62.5 cm from the connector rod (Figure 3.7). The video camera used cassette tapes (Memorex HG®, Memtek Products, Fort Worth, TX) to record the profile view changes in lip position as the facings were pulled forward, and to simultaneously record the voltmeter readings. The video camera had the following specifications:

Scanning: 525 lines/60 fields/30 frames

Image Sensor: 1/3 inch high/resolution, solid state CCD Imager

Lens: f1.8

8:1 (7-56 mm)

Diameter: 37 mm

Recording sessions used the VHS standard speed (SP).

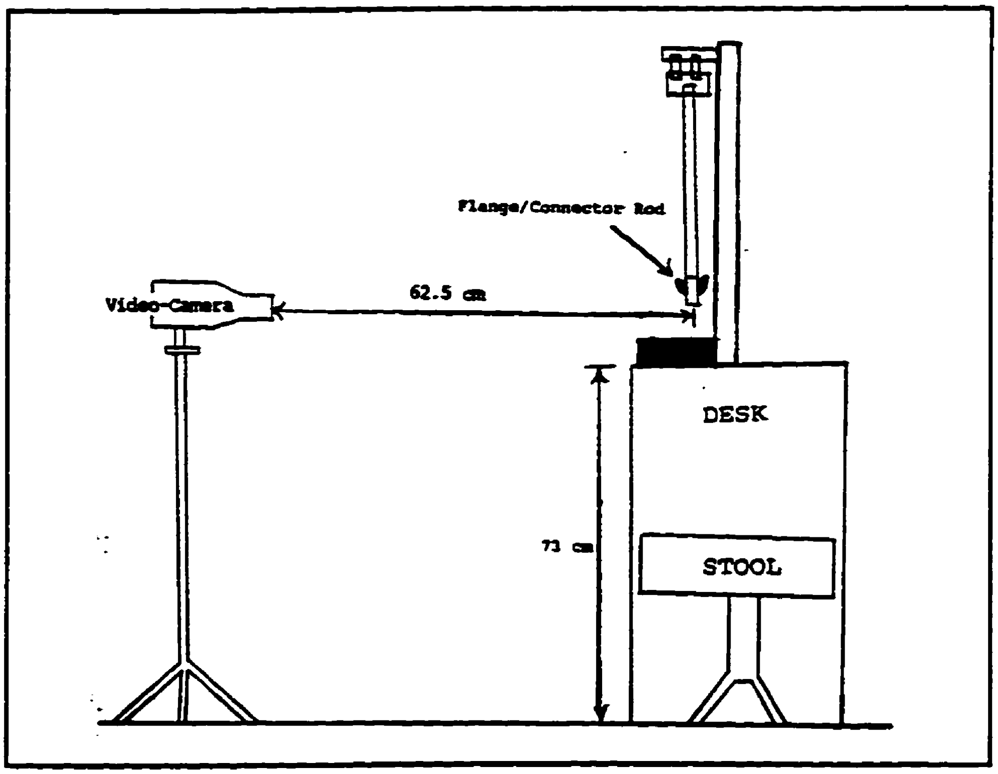


Figure 3.7 Schematic of Apparatus and Video - Camera in Position for Recording (View from the Front). During recording the subject was seated on the adjustable stool opposite the desk. The height of the stool was adjusted so that the flanges could be accommodated under the lip while the subject maintained a relaxed posture.

3.3 Experimental Protocol:

The subject was seated in an upright position, using a natural head posture. The height of the stool was adjusted so as to bring the maxillary teeth approximately level with the acrylic flanges. Three removable stickers were placed on the right side of the subject's face, one on the tragus, another on the infra-orbital notch (as determined by palpation) and the third one on the inferior aspect of the cheek. These stickers were used to define the Frankfort Horizontal plane and to form an orthogonal axes system for data analysis.

Each subject participated in two recording sessions. Each of these sessions involved recording the relaxed position of the patient's lips without a flange in place, followed by 5 to 10 "pulls" with a given flange, to allow the subject to practice keeping their lips relaxed during movement of the flange. Following these trials, a series of 10 "pulls" were recorded for each flange width. The subject was asked to relax their lips before and during each "pull", in order to record the passive lip tonicity. If the subject provided active resistance to the facing as it was pulled forward, the pull was repeated. The order of flange widths tested was randomly determined for the first session as either narrow-medium-wide or wide-medium-narrow. In the second recording session, 1 to 4 weeks after the first, the same protocol was used, but the opposite order was used. Subjects were given the opportunity to rest, stretch, and rinse their mouths or brush their teeth, during and after the recording sessions.

3.4 Video Data Storage:

Video tapes were viewed frame by frame using a 4 head video cassette recorder (Sony®,Model SLV-585HF, Willowdale, Ont.) and a color television with a 14 inch screen (General Electric®,Model 13GP211A, Prescott, Ont.). Selected video images were digitized by a microcomputer (Hewitt Rand®, 486 microprocessor, Richmond, BC) using a computer program that allowed connection of the video cassette recorder to the computer (Snappy Video Snapshot System®, Play Incorporated, Ranch Cordova, CA), with the following specifications:

Frequency response: > 12.5 MHz

Pixel Resolution: 35 or 70 ns

Color Resolution: 16777216 (24-bit, true-Color)

Sampling Rates: Field (1/60 sec); frame; multi-frame.

3.5 Criteria for Data Analysis:

3.5.1 Cephalometric Data:

The lateral cephalometric radiographs were traced using tracing acetate. Both pre-treatment and post-treatment radiographs were traced at the same sitting. The most recent post-treatment radiograph was selected unless it was of poor quality or showed obvious posturing of the lips. Pre- and post-treatment tracings were superimposed using the anatomical best-fit technique (Björk and Skieller, 1976, 1983). The superimpositions were then used to analyze changes in lip and tooth position.

3.5.2 Video Data:

Each flange pull sequence was digitized using the following frames:

i) the initial (at rest) frame.

ii) a series of 8 to 10 intermediate frames, selected on the basis of a minimum of 0.2 voltmeter units change between frames (3.6 gram equivalent).

iii) the final image was defined as the last frame before the flange slipped out from under the upper lip.

A total of five sequences per flange were chosen as representative data for each recording session. A minimum of 3 mm of horizontal lip movement was required for a given pull sequence to be included for data analysis. Thus, where the smaller flange widths did not appreciably displace the lip, either the sequences involving these flanges were not used for data analysis or fewer than five pull sequences were used. Those sequences that exhibited obvious muscle tension or active resistance by the lip to flange movement, were not included. After digitizing the chosen video image frames, a computer program (Paintbrush application of Windows 3.1®, Microsoft Incorporated, Bethel, WA) was used to define and highlight the labial contour of the upper lip, attachment rod and stickers by applying the zoom function of the program. As well, background images were erased to decrease the storage requirements of each image. The trial number and associated voltmeter recording were typed onto each image (Figure 3.8).

The images were then each printed onto an 8.5 inch by 11 inch sheet of paper using a 24 pin dot matrix printer (Panasonic KX-P2123®, Secaucus, NJ).

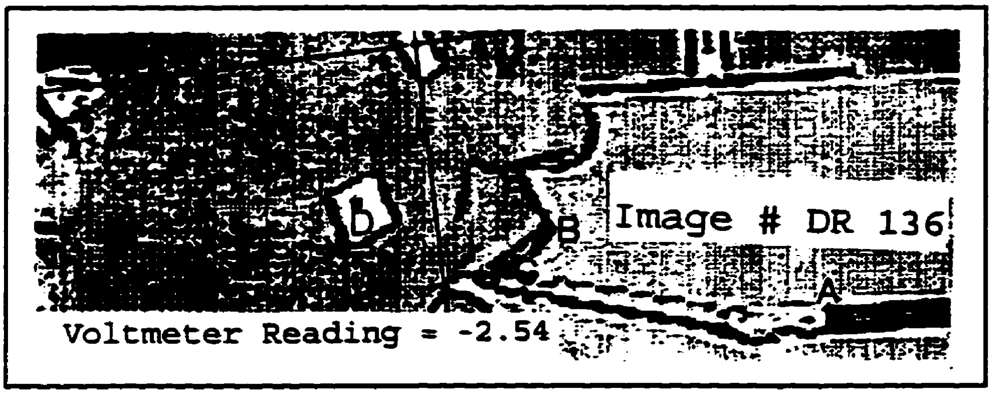


Figure 3.8 Video Image Printout with Profile Image Identification.
A: Flange Displacement Marking on Connector Rod
B: Labrale Superius
C: Stomion Superius
D: Removable Sticker
E: Y-Axis
F: X-Axis.

3.6 Data Analysis Protocol:

3.6.1 Cephalometric Data:

The following landmarks and reference planes were used to analyze the lateral cephalometric superimpositions (see Figure 3.9 for hard-tissue and soft-tissue landmarks):

i) X-Axis - Frankfort Horizontal plane (using anatomic Porion and Orbitale). Measurements made inferior to this axis were recorded as positive numbers.

ii) Y-Axis - a line perpendicular to the Frankfort Horizontal plane, through Porion on the lateral cephalometric tracings. Porion was selected since it is more reliably identified on the lateral cephalographs. Measurements made anterior to this axis were recorded as positive numbers.

iii) Labrale Superius (Ls) - the most anterior point on the convexity of the upper lip.

iv) Stomion Superius (Stm S) - the lowermost point of the upper lip.

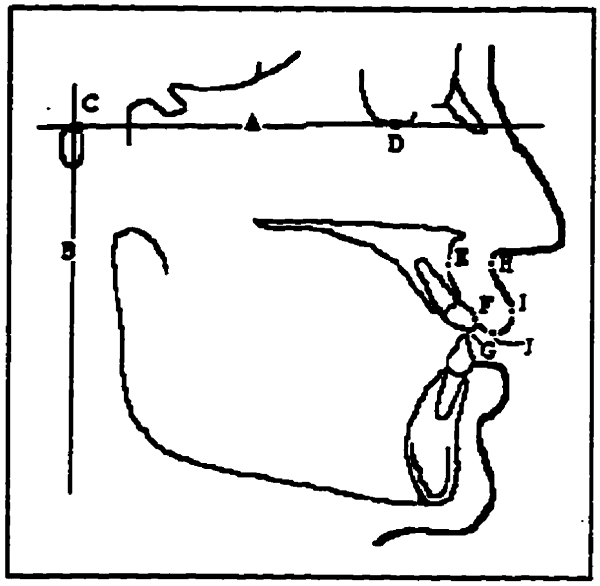
v) Subnasale (Sn) - the point of convergence of the nose and the upper lip.

vi) Upper Incisor Point (UIP) - the most anterior point on the crown of the upper incisor.

vii) Upper Incisal Edge (UIE) - the point of greatest convexity on the upper incisal edge.

viii) A Point - the deepest point in the midsagittal plane between the anterior nasal spine and Prosthion.

Figure 3.9
Lateral Cephalograph Tracing with Hard- and Soft-Tissue Landmarks and Reference Lines.
A: X-Axis
B: Y-Axis
C: Porion
D: Orbitale
E: A Point
F: Upper Incisor Point
G: Upper Incisor Edge
H: Subnasale
I: Labrale Superius
J: Stomion Superius
(See text for details)



Horizontal changes in Ls relative to the Y-axis were determined from the pre- and post-treatment radiographs. Vertical changes in Stm S were determined relative to the X-axis from the pre- and post-treatment radiographs. Horizontal changes in UIP were determined relative to the Y-axis, and vertical changes in the UIE were determined relative to the X-axis from the pre- and post-treatment radiographs.

Changes in AP upper lip thickness and upper lip taper were determined by comparing the linear measurements for both preand post-treatment radiographs. Basic upper lip thickness (Holdaway, 1983) was defined as the linear distance from A point to Sn on a line parallel to Frankfort Horizontal plane. The vermilion upper lip thickness was defined as the linear distance from Ls to the labial surface of the upper incisor on a line parallel to Frankfort Horizontal plane. Upper lip taper was defined as the basic lip thickness measurement (A-Sn) minus the vermilion lip thickness (UIP-Ls) (Figure 3.10).

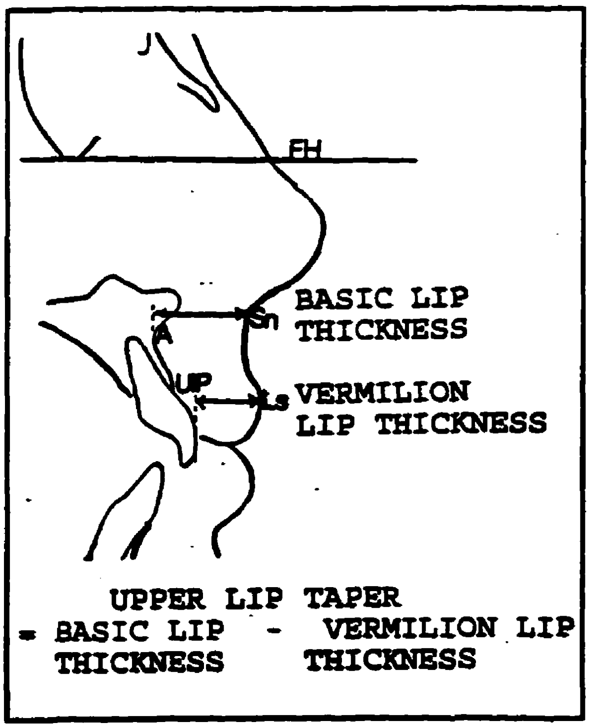


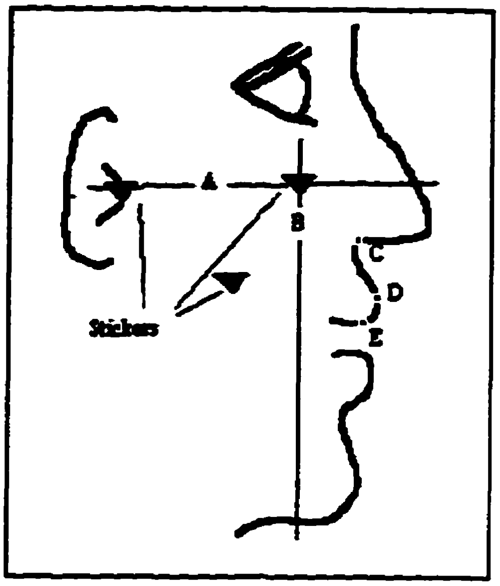
Figure 3.10 Lip Thicknesses and Taper of the Upper Lip. The anterior portion of a lateral cephalometric tracing is shown between Nasion and B-point, to illustrate basic and vermilion upper lip thicknesses. Where, FH = Frankfort Horizontal plane, Sn = Subnasale, Ls = Labrale Superius, A =A-point, UIP = Upper incisor point.

The method of quantifying lip taper from a lateral cephalometric tracing is illustrated in Figure 3.10. There was a magnification factor associated with the cephalometric images. Based on the standardized set up employed at the University of Manitoba, the magnification factor for the mid-sagittal structures was 9.8 % (Talass, 1986). All cephalometric data were corrected for magnification, except the data collected for the analysis of error in cephalometric tracing and landmark identification. The latter are presented in Appendix E.

3.6.2 Video Data:

Changes in lip position were analyzed by forming orthogonal axes using the Frankfort Horizontal plane as the X-axis and a line perpendicular to this, through the center of the infra-orbital notch sticker, as the Y-axis. The infra-orbital notch was used as the Y-axis intercept for the video data, so as to keep it as close as possible to the measured landmarks. The infra-orbital and tragal points were equal in reliability of identification. Changes in lip position were determined by applying a similar method to that used for the cephalometric data (Figure 3.11).

Figure 3.11 Soft-tissue Landmarks and Reference Lines as Applied to the Video Images. (Profile View of Subject's Right Side).
A: X-Axis
B: Y-Axis
C: Subnasale
D: Labrale Superius
E: Stomion Superius
(See text for details)



Horizontal movement of the flanges was determined by measuring the distance between the Y-axis and a line scribed on the connecting rod. Because the flange was attached to the end of a pendulum, it was expected that there would be vertical changes in the position of the flange, depending on the tangent of the angle of deflection of the pendulum. In order to reduce the magnitude of this vertical movement, the length of the pendulum arm was made as long as possible. However, vertical movement still occurred and was measured. The amount of vertical movement of the flange from a position 10 cm anterior or posterior to the rest position was 0.8 mm. This vertical flange movement was not corrected for, since it was considered a minimal amount of vertical movement.

The resistive force which the lip exerted on the flange was measured by the LVDT. The LVDT signal was measured as an electrical output which was subsequently displayed on a digital voltmeter. A voltmeter reading was included on each digitized frame of the video recording, and was included on the printout of each image.

A 25 cm by 18 cm grid was used to determine the scale of the video image. The grid was videotaped on 10 separate occasions. The image size:actual size ratio was 0.57. See Appendix C for details. All video data measurements were corrected for scale image reduction using this ratio.

3.7 Determination of the Stress:Strain Relationship:

Cephalometric and video data were entered into a computer program (Lotus®, Spreadsheet for Windows, Cambridge, MA). This allowed the organization of the data and the application of mathematical formulae to determine the stress and strain relationship of the upper lip under compression.

The stress on each flange was determined for each trial by dividing the resistance force of the upper lip by the calculated labial flange area, that is:

Stress = Force/Area (g/mm^2).

The area of each flange was determined by multiplying the average height by the average width for each flange, and then subtracting the area of the flange relieved for the labial frenum.

The compressive strain on the upper lip was determined using the following formula:

$$\text{Strain} = \Delta \text{ lip thickness/original lip thickness}$$

$$= \frac{(\text{Flange}^{H} \text{ displacement} - \text{Lip}^{H} \text{ displacement})}{(\text{radiographic vermilion lip thickness})}$$

The average thickness of the flanges was 2 mm. It was not factored into the determination of lip compression since it was equivalent for all subjects. The slope of the stress:strain relationship for the upper lip under compression determined the stiffness of the upper lip, E, which has the units g/mm^2.

3.8 Determination of Area of Tooth Retraction from Occlusograms:

Occlusograms were made for each subject from photocopies of the occlusal surfaces of the pre- and post-treatment casts. The technique used was similar to the method described by Marcotte (1976). The changes in the maxillary incisor positions were quantified by calculating the *Area of Tooth Retraction* (ATR) from the occlusograms. To do this, pre- and post-treatment occlusograms were superimposed on the palatal rugae. Then the width of each maxillary incisor and the amount that it was retracted were multiplied. The sum of these products gave the Area of Tooth Retraction for the individual subject (see Figure 3.12), that is:

$$ATR\ (mm^2) = \Sigma\ (\text{maxillary incisor width (mm)} \times \text{amount of retraction (mm)})$$

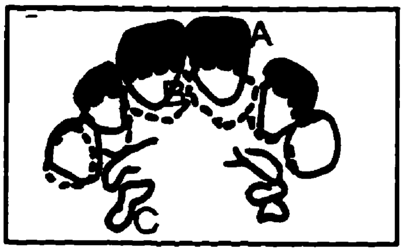


Figure 3.12 Area of Tooth Retraction. The area of tooth retraction is shown in black (shaded area) in the illustration.
A: Pre-treatment Incisor Positions
B: Post-treatment Incisor Positions
C: Palatal Rugae
(See text for details).

3.9 Prediction Models:

To give clinical relevance to the data gathered from the video and occlusogram studies, two models were presented to predict the movement and decompression of the upper lip in response to upper incisor retraction. These models were based on the physical characteristics of the upper lip as determined from the video data, and the changes in tooth position, as determined from the occlusogram data collected for each subject. The predicted lip changes were then compared to the cephalometric lip changes that were seen for each subject.

3.9.1 Prediction of Anteroposterior Lip Movement:

The theoretical lip movement in response to tooth retraction was determined as follows:

Theoretical Lip Movement (mm) = $(M_{F/L})$ $(1/W)$ (ATR)

Where:

$M_{F/L}$ = the slope of the flange^H:lip^H relationship

W = the transverse distance at the lateral incisors (mm)

ATR = the Area of Tooth Retraction (mm^2).

The slope, $M_{F/L}$, was a measure of the displacement of the upper lip in response to displacement of the flange. The slope associated with the wide flange was used because these data have the largest correlation coefficients (see section 3.11.3). The transverse distance at the lateral incisors was the linear distance as measured on the post-treatment occlusogram, from the distolabial surface of the right lateral incisor to the distolabial of the left lateral incisor (mm). The Area of Tooth Retraction was the sum of the tooth width multiplied by the amount of retraction for all four maxillary incisors, as measured on superimposed pre- and post-treatment occlusograms (mm^2).

3.9.2 Prediction of Anteroposterior Lip Decompression (Lip Product):

The decompression of the upper lip during orthodontic therapy has been described as a thickening of the upper lip after retraction of the upper incisors. A theoretical model was developed to predict the amount of decompression of the lip due to movement of the anterior teeth. The equation below calculates the theoretical Lip Product, which is the predicted decompression of the upper lip as a product of the Area of

Tooth Retraction (determined from occlusograms and described in section 3.8) and the lip stiffness, E (described in section 3.7); that is:

Lip Product (g) = (ATR) (E)

Where:

ATR = the Area of Tooth Retraction (mm^2)

E = the slope of the stress:strain relationship (g/mm^2)

3.10 Statistical Analysis of Data:

Multiple linear regression analysis was performed on the video data for each subject and all three flanges, using a computer software program (Lotus®, Spreadsheet for Windows, Cambridge, MA). Plots of the wide flange stress:strain and the horizontal displacement of the flange to the horizontal displacement of the lip ($flange^H:lip^H$) data for sessions 1 and 2 were made, with linear regression lines for each session (presented in Appendix D). The linear regression equations were determined for the stress:strain and the $flange^H:lip^H$ data, with the strain not exceeding 0.65 (for stress:strain data) and the flange having had no greater than 15 mm of anterior displacement (for $flange^H:lip^H$ data). As well, vertical lip movement could not exceed 3 mm.

Statistical differences between the slopes of the linear regression lines for the two sessions, three flanges and seven subjects were assessed using a computer software program (SPSS®, Version V6.1, Chicago, IL.). An one-way Analysis of Variance (ANOVA) was used to determine any statistically significant differences.

3.11 Error Analysis:

3.11.1 Introduction:

The main sources of error in this study were the identification of and measurement between landmarks on the cephalograph tracings, the identification of and measurement between landmarks on the video printouts, the lip-pressure recording apparatus, and the superimposition of and measurement from the occlusograms.

3.11.2 Cephalometric Error:

Errors in cephalometric tracing and landmark identification were assessed by multiple tracings of a good and a poor quality radiograph. Each radiograph was traced five times, each at separate sittings, and measured as previously described in section 3.5.1. The results of this are shown in Appendix E. The method error was similar to that found in other studies (Looi & Mills, 1986; Talass *et al.*, 1987), and was at maximum, ± 0.8 mm.

3.11.3 Video Error:

The effect of head rotation during recording sessions was assessed for three subjects. For each flange width, five image frames from each trial session were superimposed using the orthogonal axes system (a total of thirty images for each subject). The overlap of the three dots on the removable stickers was assessed by a best fit method and the differences were measured. See Appendix F for details. The vertical variability is most important, as this would affect the construction of the axes. The effect of head rotation was judged to be within the error of measurement, at maximum, ± 0.5 mm for the vertical position of the cheek sticker.

To compare the repositioning error of the removable dots on the tragus and infra-orbital rim, three images were randomly selected from each recording session and superimposed using the upper and midfacial structures and the ear. The horizontal and vertical positions of the stickers were determined relative to an orthogonal axes system. Vertical variations in placement would affect construction of the axes system. The average difference between vertical heights of the stickers between sessions was 2.0 ± 1.0 mm for the sticker at the tragus, and 1.5 ± 1.5mm for the sticker on the infra-orbital notch. These results are shown in Appendix G.

Errors in landmark identification and analysis of printed video images were quantified by selecting an image and remeasuring the distance between selected landmarks and the coordinate axes system five times. The error in landmark identification and analysis of printed video images was within the error of measurement, with a maximum range of ± 0.5 mm. See Appendix H for details.

The LVDT spring was calibrated using five trials. As the LVDT housing was displaced, it was gently tapped to disrupt the static friction. The total displacement of the large calibrated spring and LVDT housing was measured using a micrometer. The friction between the LVDT pin and housing was recorded as being between -4.5 and -1.5 voltmeter units, which was estimated to be ± 15 grams (see Appendix I, top diagram). This error was in the region of LVDT pin displacement which did compress the LVDT spring. Once the LVDT spring was compressed (between -1.5 and 3.0 voltmeter units), the standard error of the lip force estimate was ± 20 grams (see Appendix I, bottom diagram).

For the wide flange (average area = 1007 mm^2) the stress:strain regression line intercepted the Y-axis at 0.1 g/mm^2 on average. The error due to friction (± 20 g/1007 mm^2) was ± 0.02 g/mm^2, which represented, on average, 20 % of the stress recording at the average Y-intercept of the regression line. For the medium flange (average area = 713 mm^2) the error due to friction was ± 0.034 g/mm^2, which represented, on average, 47 % of the stress recording at the average Y-intercept of 0.06 g/mm^2. For the small flange (average area = 428 mm^2) the error due to friction was ± 0.05 g/mm^2, which represented, on average, 100 % of the stress recording at the average Y-intercept of .04 g/mm^2. Since the wide flange generated larger stress levels, the magnitude of the friction compared to these stress levels, was proportionately less than the two smaller flanges. Thus the wide flange recordings have less error due to friction associated with them.

3.11.4 Occlusogram Error:

The error associated with superimposing pre- and post-treatment occlusograms and measuring the changes in anterior tooth position was determined by repeating the Area of Tooth Retraction (ATR) measurement five times for each subject. The standard deviation (SD) and percent variation in the ATR are shown in Table 4.1. Where the percent variation was:

$$\frac{SD}{ATR} \times 100$$

The standard deviation was between 2 and 15 mm^2, and the percent variation was between 4 and 15 %.

The magnification and distortion associated with photocopying the patients' casts was determined by photocopying a calibrated ruler at the top, middle, bottom and sides of a photocopied page. The image was found to have been reduced 0.5 % at all positions and it was concluded that correction for this reduction was not necessary.

Another unmeasured source of error was the possibility for a change in the occlusal plane orientation in pre- as compared to post-treatment casts. This could have resulted in projection discrepancies between the pre- and post-treatment occlusograms that were compared. It was expected, however, that any gross discrepancies would have been easily identified through the superimposition technique.

CHAPTER 4
RESULTS

RESULTS

4.0 Introduction:

From pre- and post-treatment clinical orthodontic records of seven subjects, the area of tooth retraction and change in lip tissue dimensions were calculated. In addition, data was collected for these seven subjects, with analyses conducted on five trials for each flange at each of two recording sessions. The physical properties of the upper lip in each of the subjects were quantified by determining the slopes of the stress:strain and flange^H:lip^H regression lines. The slope of the stress:strain relationship was expected to be a measure of the lip tissue characteristics for a given individual. The slope of the flange^H:lip^H relationship was expected to reflect the tooth and lip displacement characteristics experienced by an individual as a result of orthodontic treatment. These results were compared using a one-way ANOVA and a multiple range test where significant findings occurred. Finally, theoretical models were derived that used the data obtained in this study to predict the upper lip position change and decompression with tooth movement.

4.1 Area of Tooth Retraction

The Area of Tooth Retraction (ATR) for the seven subjects is presented in Table 4.1. The pre- and post-treatment occlusograms were superimposed and measured five times for each subject. The standard deviation expressed for each subject reflects the varibility in the repeated measurements. The percentage variation was determined as the percent value of the standard deviation divided by the mean ATR for the repeated measurements.

The average ATR for the subjects was 68 ± 46 mm^2. This represents, on average, a 68 % variation in the ATR between subjects. This large variation in the ATR can be seen in figure 4.1. Subject PH had a far greater ATR than the other subjects, and subject CH had the least.

Table 4.1: Area of Tooth Retraction (ATR) as determined from the Pre- and Post-treatment Occlusograms of All Subjects. The mean values, standard deviations and percentage variations from five superimpositions and measurements for each subject, are shown. Also shown is the average ATR for all subjects, with the standard deviation (s.d.) about the overall average.

SUBJECT	**AREA OF TOOTH RETRACTION (mm^2)**	**STANDARD DEVIATION (mm^2)**	**PERCENTAGE VARIATION (%)**
KS	69	3	4
PH	163	15	9
DR	76	9	12
JC	64	5	8
CH	23	2	9
KC	48	4	8
JG	32	6	19
Average (± s.d.)	68 ± 46		

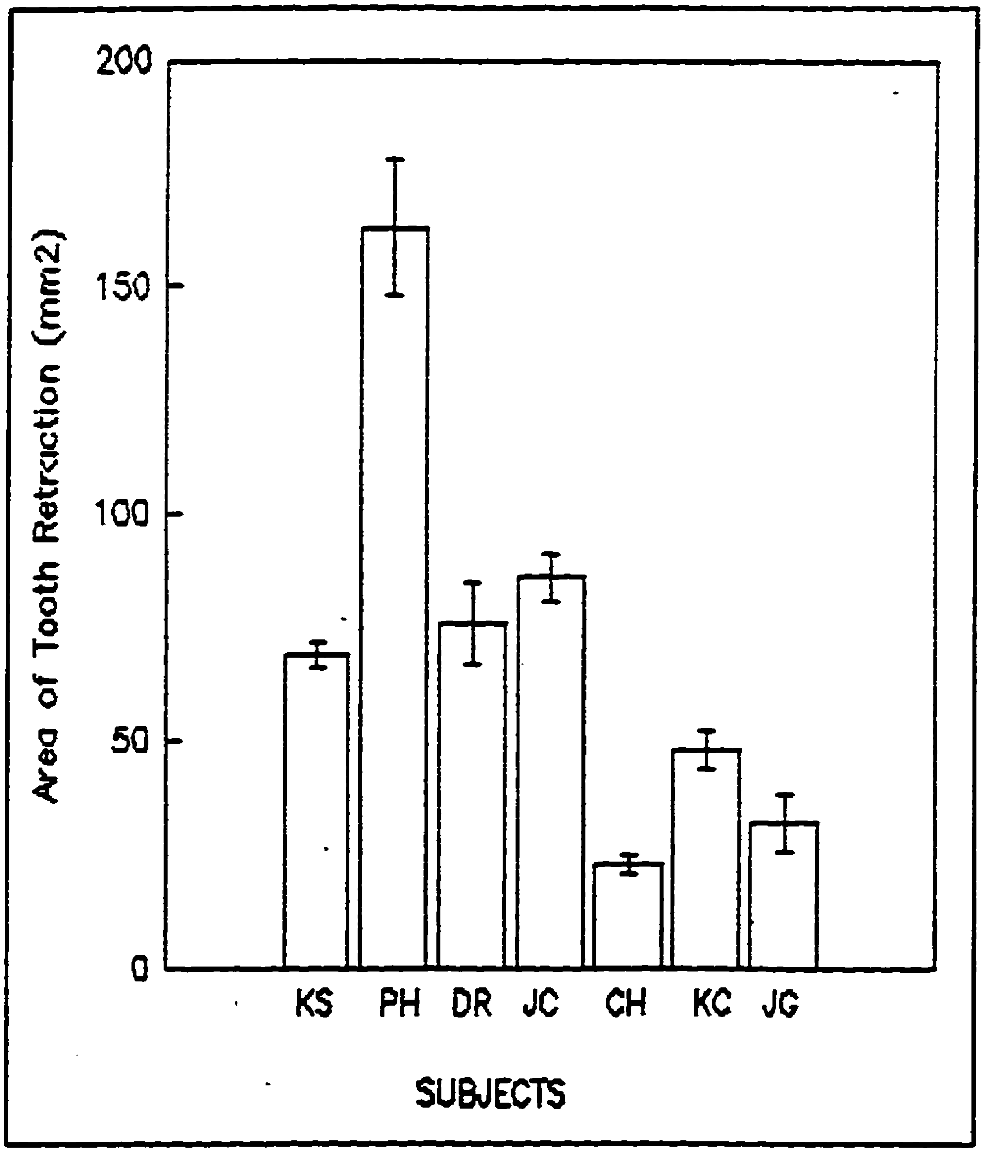


Figure 4.1 Area of Maxillary Tooth Retraction for the Seven Subjects. The standard deviation from the mean of five measurements is shown.

4.2 Cephalometric Data:

The individual and average changes in the cephalometric variables are shown in Appendix J. The average retraction of the UIP was 4.6 ± 2.4 mm, the UIE was 5.4 ± 3.3 mm. The average posterior movement of Ls was 1.7 ± 1.2 mm. The mean percentage of Ls movement to UIP retraction was 35 ± 13 %, and for Ls movement to UIE retraction it was 33 ± 11 %.

The pre- and post-treatment morphological features of the upper lip as measured from lateral cephalometric tracings are presented in Tables 4.2 and 4.3. The percentage change in lip thickness, shown in Table 4.2, was expressed as:

$$\frac{\text{Post-treatment thickness - Pre-treatment thickness}}{\text{Post-treatment thickness}} \times 100,$$

where a decrease in lip thickness post-retraction gave a negative result. The lip thickness values in Table 4.2 were used to determine the lip taper values in Table 4.3, as defined by Holdaway (1983):

Lip Taper = Basic Lip Thickness - Vermilion Lip Thickness

The correlations between the pre-treatment Lip Taper and the change in Lip Taper (Table 4.3) to the percentage of Ls movement/UIP retraction and Ls movement/UIE retraction (from Appendix J) are shown in Table 4.4. It can be seen that the relationship between Lip Taper and the lip movement in response to incisor retraction was poor.

Table 4.2: Upper Lip Thickness Dimensions. The pre- and post-treatment Vermilion and Basic Lip Thicknesses are shown for all subjects. Also presented are the percentage change in these thicknesses.

UPPER LIP THICKNESS (mm)						
	Vermilion Lip Thickness			Basic Lip Thickness		
Subject	Pre-Treatment	Post-Treatment	% Change in Thickness	Pre-Treatment	Post-Treatment	% Change in Thickness
KS	11.2	12.6	11.1	16.7	15.8	-5.7
PH	7.9	12.1	34.7	15.3	14.0	-9.3
DR	13.5	16.0	15.6	13.5	16.2	16.7
JC	11.0	11.7	6.0	14.4	14.4	0.0
CH	10.0	10.0	0.0	13.5	12.6	-7.1
KC	15.3	16.8	8.9	17.1	17.1	0.0
JG	11.2	11.7	4.3	15.3	16.2	5.5

Table 4.3: Upper Lip Taper. The pre- and post-treatment Lip Taper (Basic Lip Thickness - Vermilion Lip Thickness) are shown for all subjects. Also presented is the change in Lip Taper (pre-treatment Lip Taper - post-treatment Lip Taper).

UPPER LIP TAPER (mm)			
Subject	Pre-Treatment	Post-Treatment	Change in Taper
KS	5.4	3.2	2.2
PH	7.4	1.9	5.5
DR	0.0	0.0	0.0
JC	3.4	2.7	0.7
CH	3.4	2.7	0.7
KC	1.8	0.4	1.4
JG	4.1	4.5	-0.4

Table 4.4: Correlation of Lip Taper to Lip Movement/Upper Incisor Retraction Ratios.

	Pre-Treatment Lip Taper	**Change in Lip Taper**
Ls_Δ/UIP_Δ	r = 0.52	r = 0.50
Ls_Δ/UIE_Δ	r = 0.44	r = 0.37

Where: Ls_Δ = Ls movement
UIP_Δ = UIP retraction
UIE_Δ = UIE retraction

4.3 Video Data:

4.3.1 Combined Sessions 1 and 2 (Overall) Data:

The overall results presented in Appendix K are a combination of sessions 1 and 2 for both the stress:strain and $flange^H:lip^H$ data. For the stress:strain data, all regression lines showed high statistical significance at the $p<.001$ level for confidence limits of the slope, except for the medium flange data of subject JC ($p<.05$). All regression lines for the $flange^H:lip^H$ data showed high statistical significance at the $p<.001$ level for confidence limits of the slope.

While Appendix K reports the average slopes and the standard deviations, Appendix L reports the ranks of the slopes for the stress:strain and $flange^H:lip^H$ data. For the stress:strain data associated with the wide flange, the range of values for the slope of the regression analyses was from 0.18 to 0.38 g/mm^2 with an average of 0.25 $\pm$ 0.08 g/mm^2. The average values for the medium and narrow flanges were smaller than for the wide flange, at 0.19 ± 0.06 g/mm^2 and 0.19 ± 0.07 g/mm^2, respectively. For the flange^H:lip^H data the average slope associated with the wide flange (0.60 ± 0.06) is larger than the average slopes associated with the medium and narrow flanges (0.50 ± 0.08 and 0.50 ± 0.07 respectively).

4.3.1.1 Comparison of Subjects:

The mean stress:strain slopes for each subject were compared (Figure 4.2), and the mean flange^H:lip^H slopes for each subject were compared (Figure 4.3) to examine differences between the seven subjects. The data for the wide flange were used for the analyses since these data had the highest correlation coefficients of the three flanges (see Appendix K). The slopes of the 10 trials for each subject were used for the ANOVA. Significant differences for both the stress:strain and flange^H:lip^H slopes were found ($p<0.00001$ and 0.0001 respectively).

Further differences were investigated using a multiple range test (Scheffe Test) at the 0.05 significance level. The results of the statistical analysis are presented in Appendix M. Two subgroups were identified for both types of data, in which the lowest and highest means were not significantly different. For the stress:strain data, subset one included subjects CH, JG, PH, JC, KC, DR. Subset two had larger mean slope values and included subjects KC, DR and KS. For the flange^H:lip^H data, subset one included subjects KS, DR, JG, PH, CH and JC. Subset two had larger mean slope values and included subjects PH, CH, JC and KC. For the stress:strain data, subjects KC and DR were found in both subgroups, and for the flange^H:lip^H data, subjects PH, CH and JC were found in both subgroups. These subjects could be considered as having as intermediate level of lip stiffness and lip displacement in response to flange displacement.

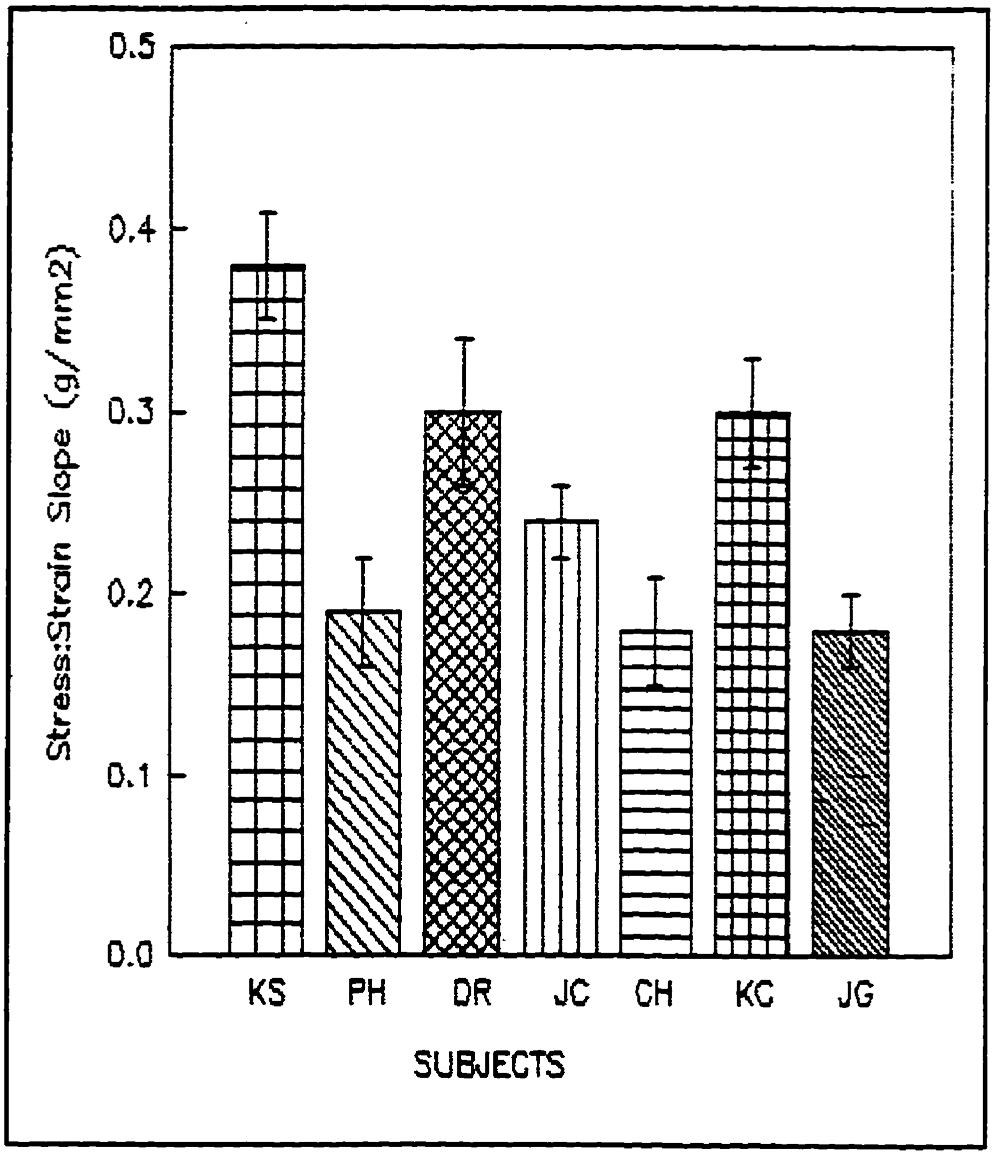


Figure 4.2 Mean Stress:Strain Slopes for the Wide Flange for All Subjects. The mean and standard deviation for 10 trials are indicated.

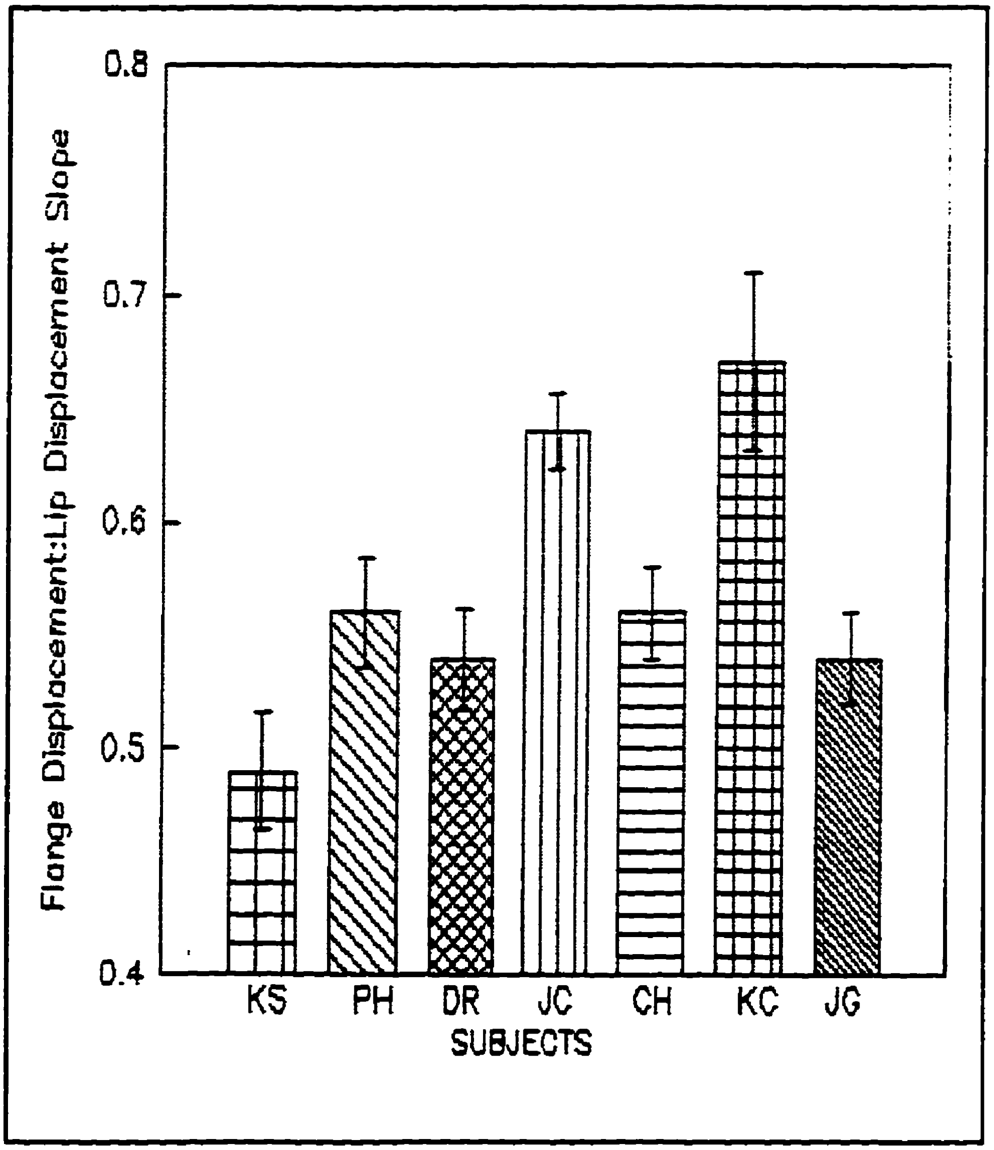


Figure 4.3 Mean Flange Displacement:Lip Displacement Slopes for the Wide Flange. The mean and standard deviation for 10 trials are indicated.

4.3.1.2 Comparison of Flanges:

The one-way ANOVA was used to compare the stress:strain and flange^H:lip^H slopes for the wide, medium and narrow flanges, using the combined data of sessions 1 and 2 (see Appendix N). For the slopes of the stress:strain and the flange^H:lip^H data, there were no statistically significant differences between the three flanges. Figures 4.4 and 4.5 show that overall, the wide flange tended to have a larger slope than the medium and narrow flanges, for both types of data, although this difference was not statistically significant. Figure 4.6 shows a comparison of the slopes of the stress:strain data for each of the three flanges for all seven subjects. Figure 4.7 shows a comparison of the slopes of the flange^H:lip^H data for each of the three flanges for all seven subjects. On a subject by subject basis, there were trends in the slopes of both types of data for the three flanges. These trends were not strictly consistent but most subjects showed larger slopes associated with the widest flange (particularly subjects KS, PH and JC).

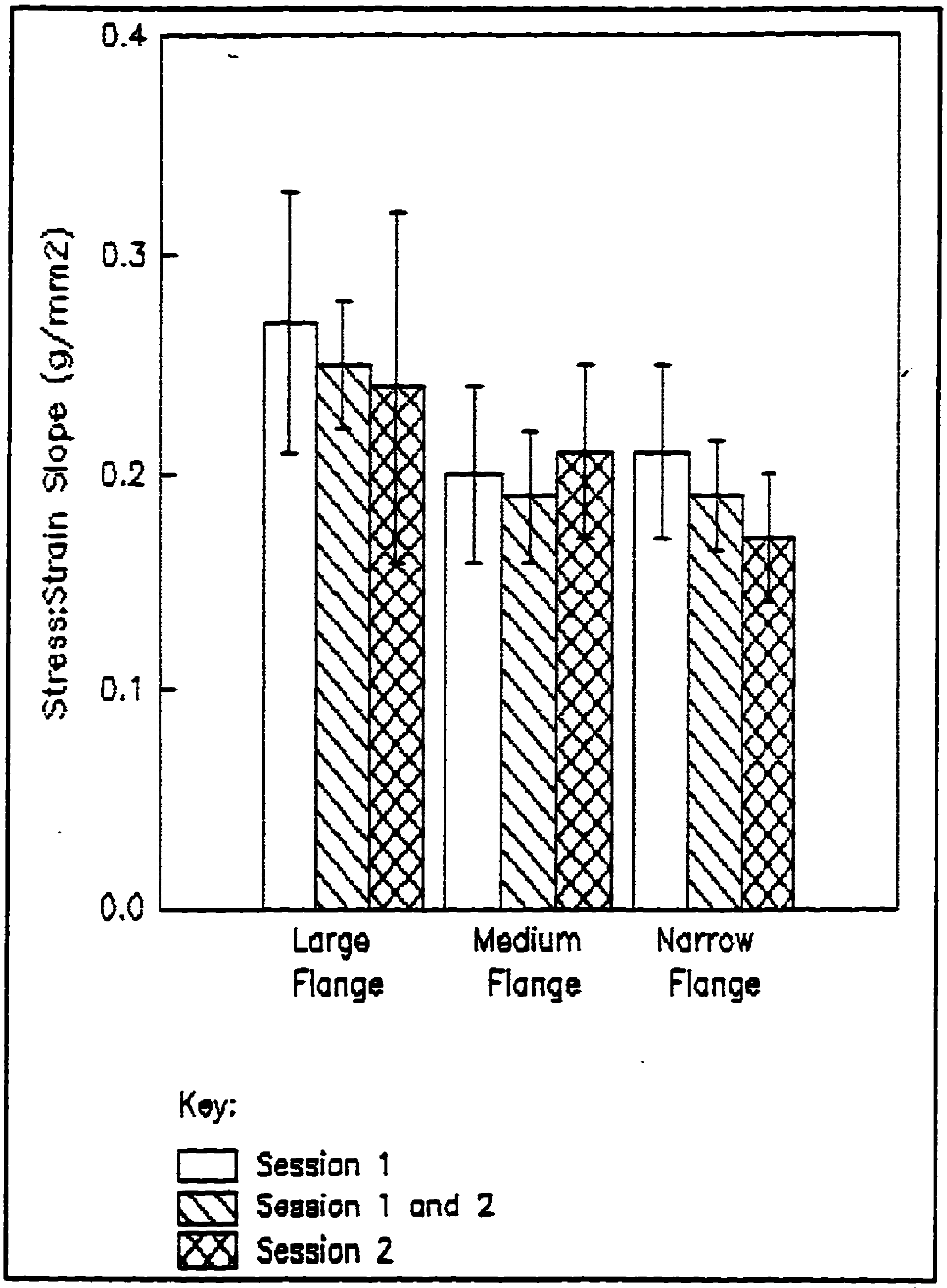


Figure 4.4 Comparison of Flanges and Sessions for the Stress:Strain Slopes (all subjects combined). The mean slopes and standard deviations are illustrated for data from 5 trials per session for each subject.

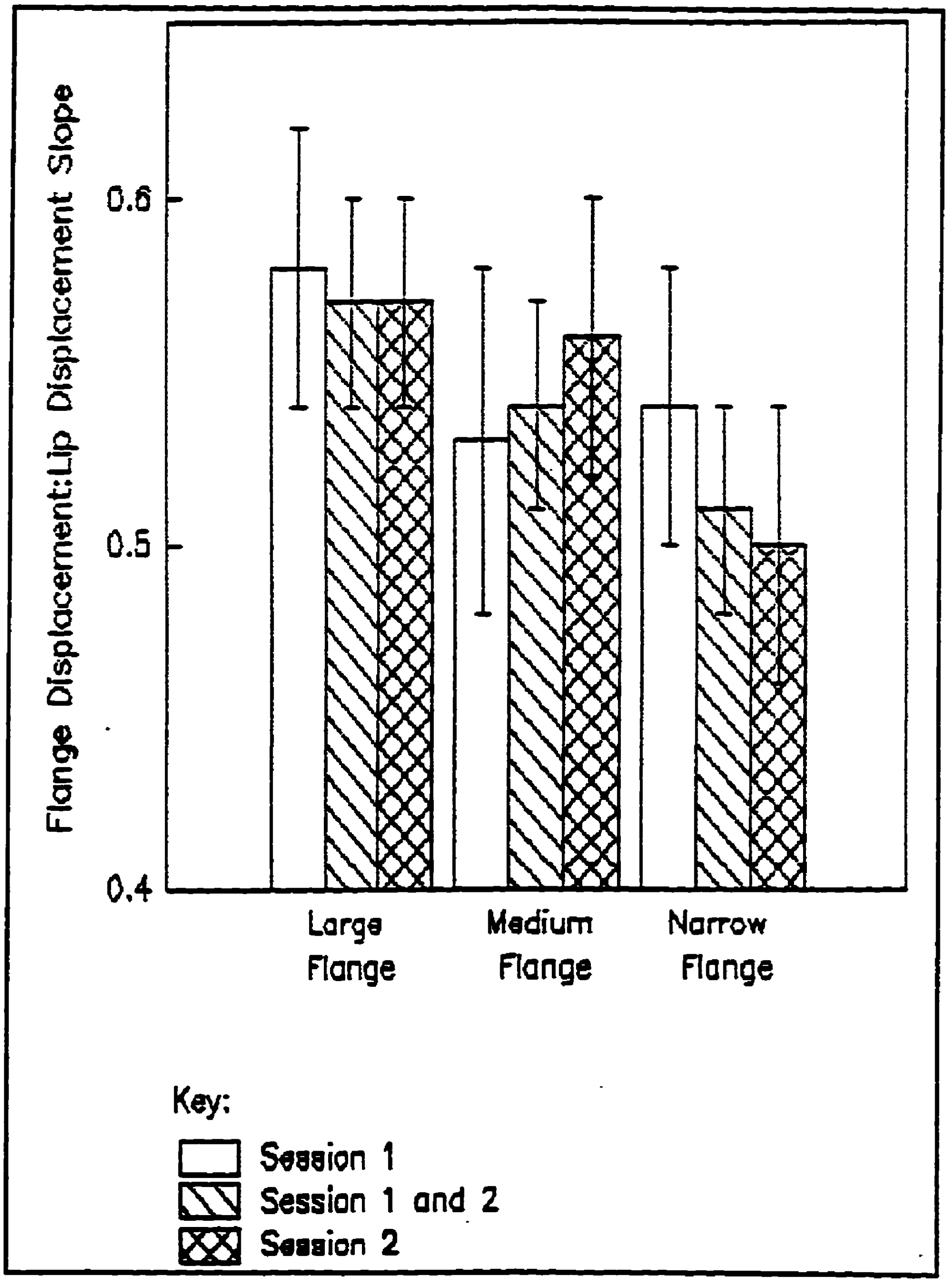


Figure 4.5 Comparison of Flanges and Sessions for the Flange Displacement:Lip Displacement Slopes (all subjects combined). The mean slopes and standard deviations are illustrated for data from 5 trials per session for each subject.

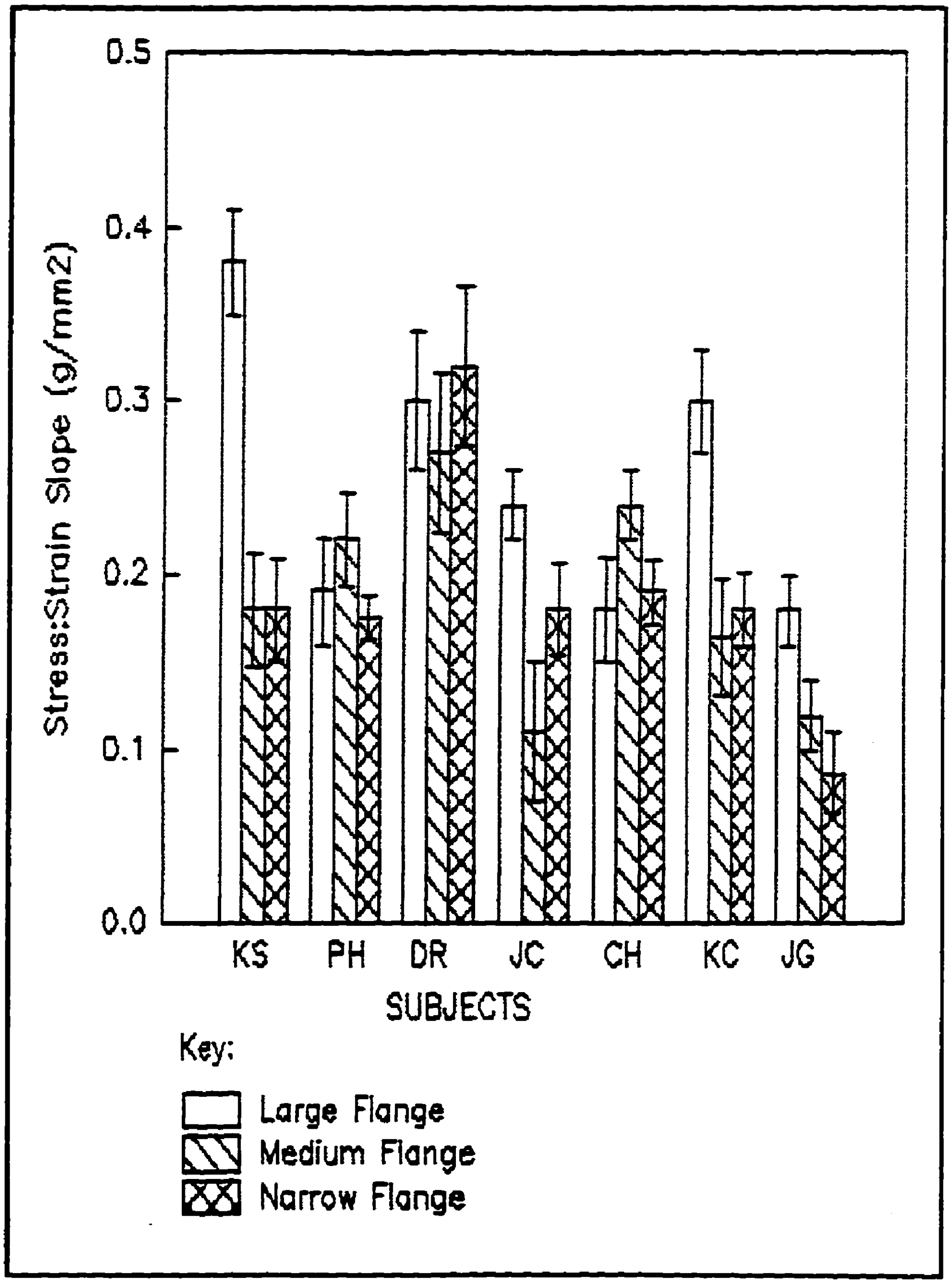


Figure 4.6 Stress:Strain Slopes for the Three Flanges for each of the Subjects. The mean slopes and standard deviations are illustrated for 10 trials from 2 recording sessions (5 trials/session).

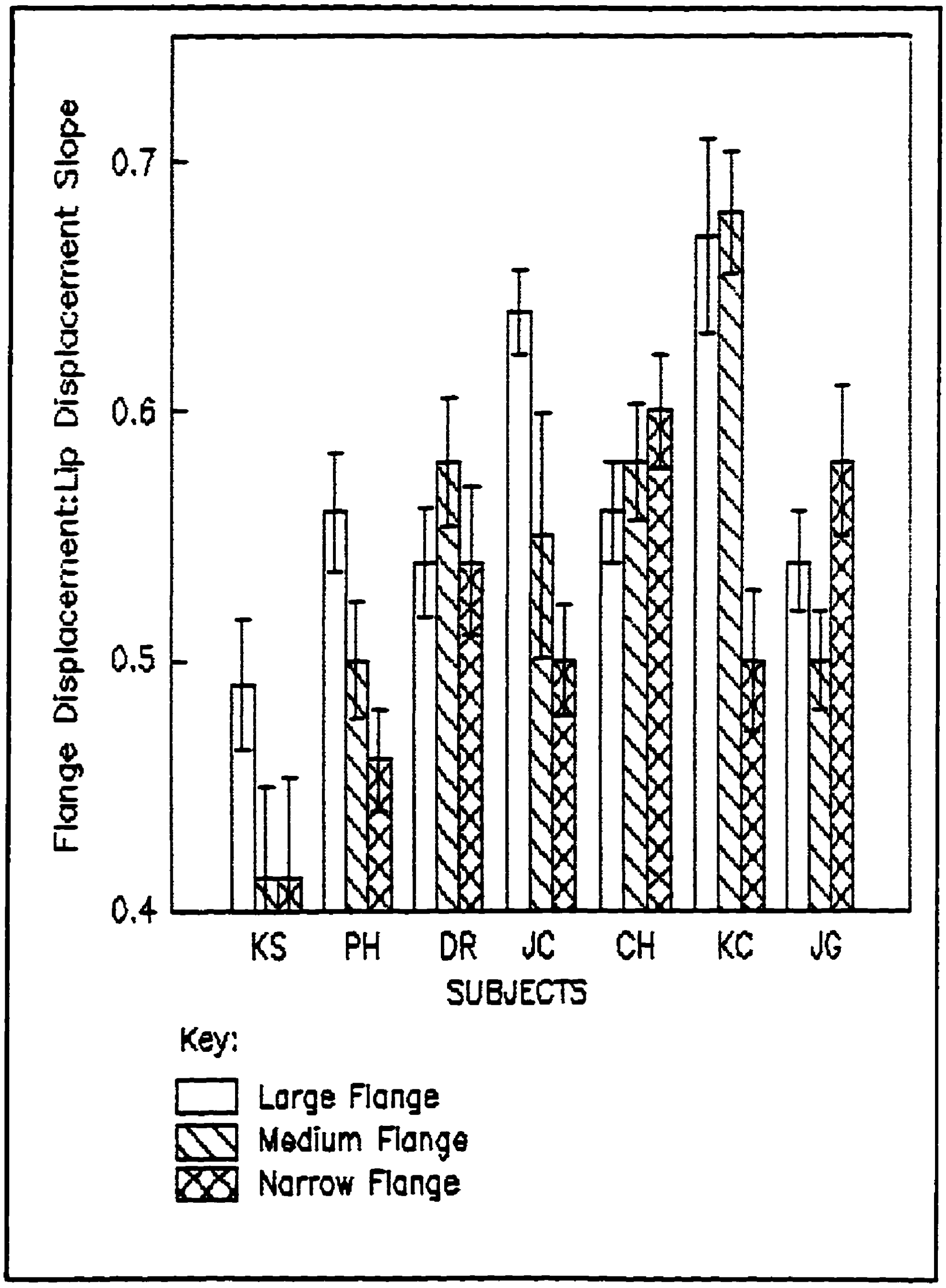


Figure 4.7 Flange Displacement:lip Displacement Slopes for the Three Flanges for Each of the Subjects. The mean slopes and standard deviations are illustrated for 10 trials from 2 recording sessions (5 trials/session).

4.3.1.3 Relationship of Stress:Strain and Flange^H:Lip^H Data:

Possible relationships between the slopes of the stress:strain and flange^H:lip^H data for each flange type were investigated using a linear regression analysis and pooled subject data. The correlation analyses showed that there were no relationships between the two types of data (see Appendix O for a summary of the results).

4.3.2 Individual Session 1 and 2 Data:

In recognition of the potential for differences in lip tonicity associated with temporal factors, the recording sessions were separated by one to four weeks. Comparing the results from the two recording sessions for each of the subjects tested the reproducibility of the recording apparatus as well as the temporal effects of lip tonicity.

The regression line characteristics for the stress:strain data and the results of statistical tests of these data for sessions 1 and 2 for each flange size are shown in Appendix P. The regression line characteristics for the flange^H:lip^H data and the results of statistical tests of these data for sessions 1 and 2 for each flange size are shown in Appendix Q. In general the correlation coefficients were high (average r 0.67 and 0.80, respectively) and significant at the $p<0.001$ level. Only the stress:strain relationship data from subject JG for session 2, narrow flange, tested statistically non-significant ($r=0.37$). During the first session with subject

PH, the narrow flange did not produce force levels larger than the force of friction, therefore no data is provided for this session.

4.3.2.1 Comparison of Session 1 and Session 2:

The results from the two recording sessions were compared using the wide flange data. In Appendix R the subjects are presented in a ranked order from smallest to largest slope. The average slope values and standard deviations for both sessions are reported in Appendices P and Q. The range of slope values was similar for both sessions for both relationships, however the ranking of subjects differed between the two sessions. This was likely due to a narrow range of slope values and small differences between the two sessions for each subject for both the stress:strain and flange^H:lip^H relationships.

Differences between the results from the two recording sessions were assessed using a one-way ANOVA. Appendix S shows that no statistically significant differences between the slopes of the two sessions were found for either the stress:strain or flange^H:lip^H data.

4.4 Prediction Models:

4.4.1 Prediction of Anteroposterior Lip Movement:

The lip properties determined from the cephalometric and video data were used to compare theoretical and measured lip movements (see Appendix T for details). Figure 4.8 shows the accuracy of this model by plotting the predicted and the actual amount of lip movement that was measured from the pre- and post-treatment cephalographs (Ls Δ). The dashed line illustrates the ideal prediction relationship, where the predicted and actual lip movement are equal. The symbols represent the measured lip movement versus predicted lip movement for each subject. For three of the seven subjects (PH, JC, CH), the theoretical and predicted lip movement values were the same and therefore these data fit the linear regression line in figure 4.8. In the four other subjects, the difference between the theoretical and predicted lip movement values was 0.5 mm. For KS, DR, and JG the theoretical prediction was 0.5 mm less than the measured lip movement, while for KC the theoretical prediction was 0.5 mm higher. For all seven subjects, there was a strong correlation between the predicted and measured lip movement ($r = 0.95$).

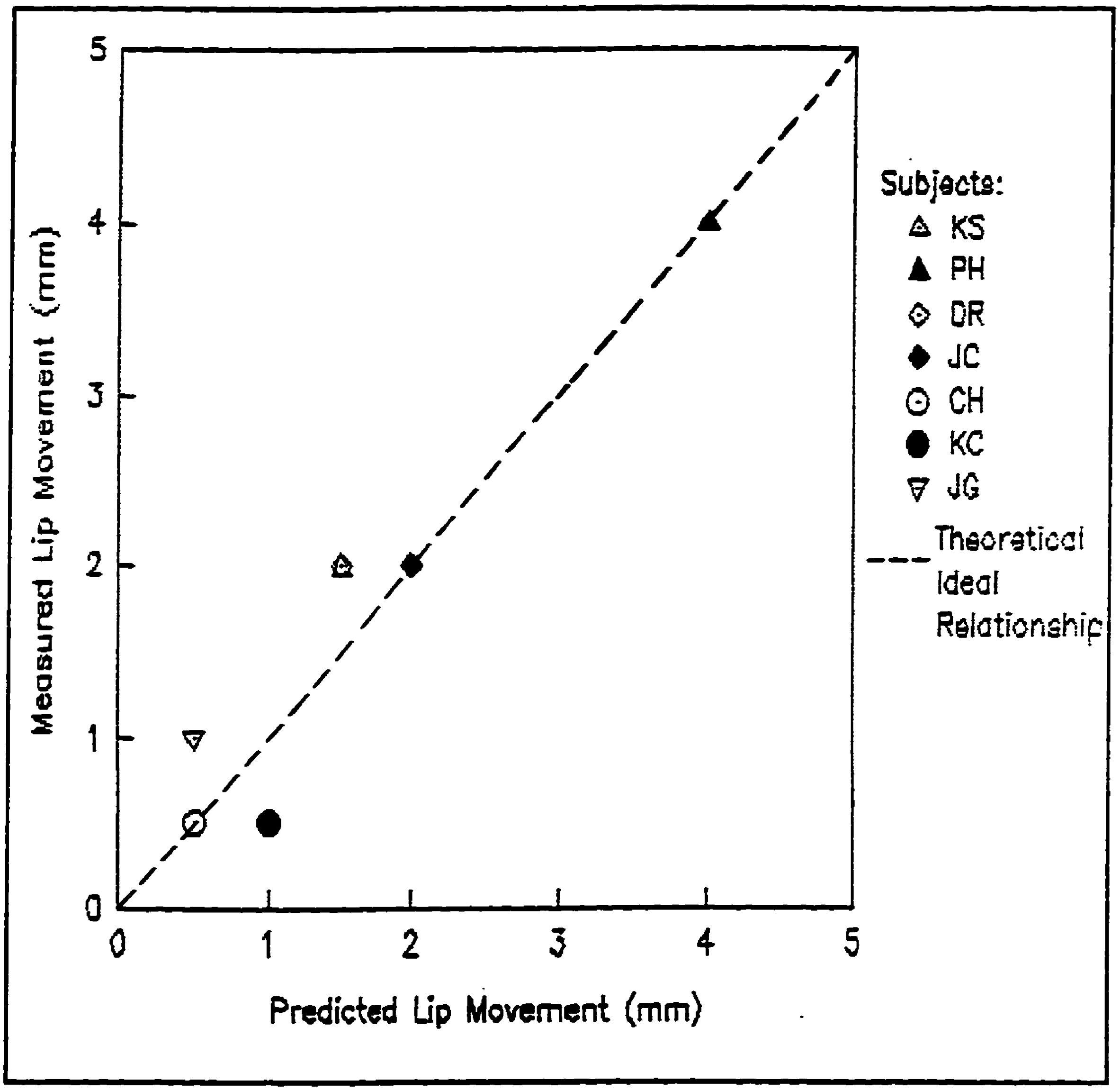


Figure 4.8 Measured versus Predicted Lip Movements for All Subjects. The symbols represent results from individual subjects. The dashed line is the theoretical ideal where predicted and measured lip movements are equal. (See text for details).

4.4.2 Prediction of Anteroposterior Lip Decompression:

The decompression of the upper lip from the pre- to post-treatment cephalographs was correlated to the Lip Product. The Lip Product as described in section 3.9.2, is the result of multiplying the Area of Tooth Retraction (as determined with occlusograms) and the lip stiffness (E, as determined from the slopes of the wide flange overall data). As is shown in Appendix U and Figure 4.9, there was a strong relationship between Lip Decompression at the vermilion border and the Lip Product ($r = 0.95$).

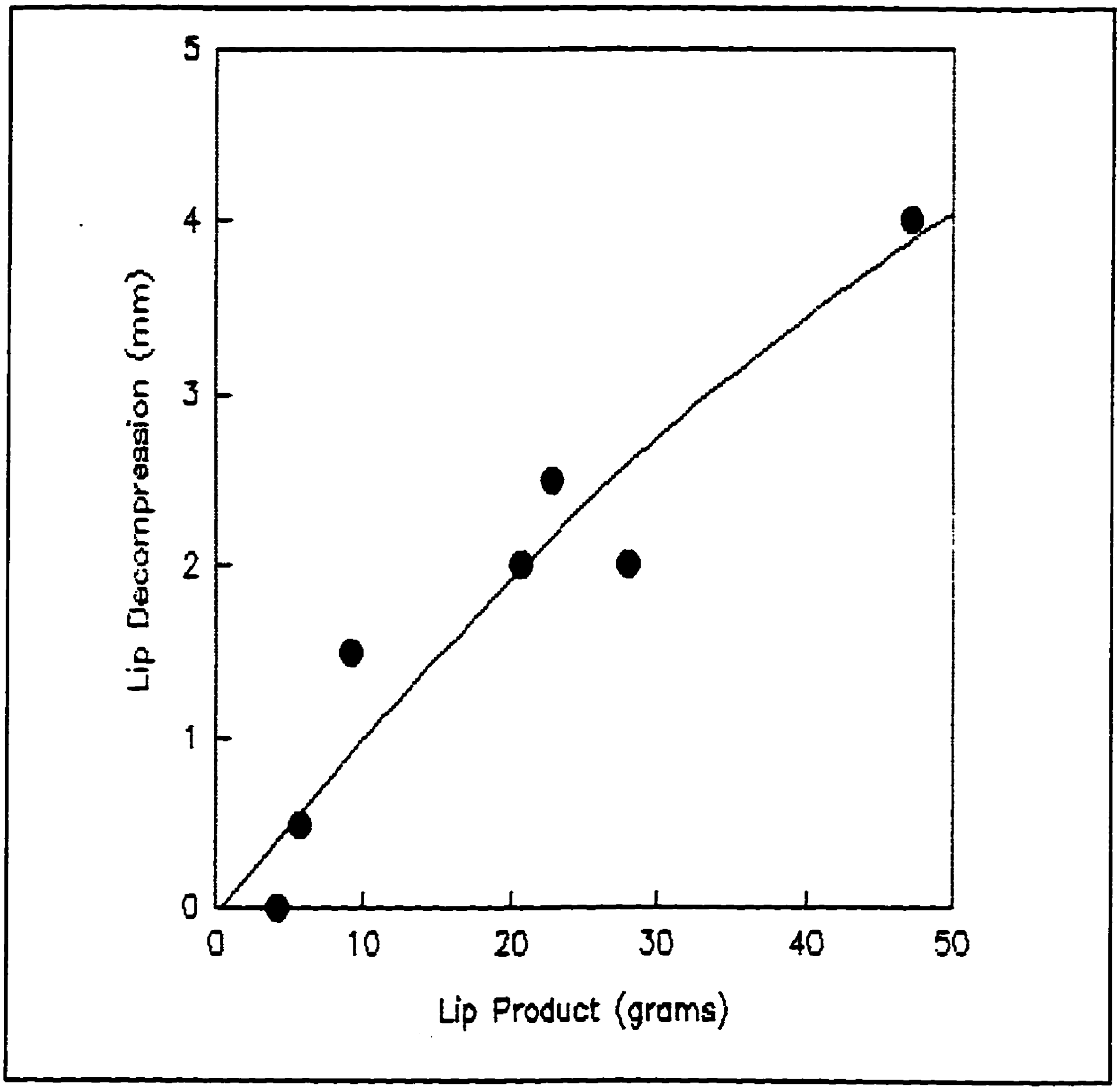


Figure 4.9 Lip Decompression versus Lip Product.
Lip Decompression is determined by measuring the change in Vermilion Lip Thickness from the pre- to the post-treatment cephalographs. The Lip Product is determined by multiplying the Lip Stiffness (E) and the Area of Tooth Retraction (ATR). (See text for details).

CHAPTER 5
DISCUSSION

DISCUSSION

5.0 Introduction:

A specially designed apparatus was used in this study to test the hypothesis that lip profile changes in response to orthodontic tooth movement are not predictably associated with the physical properties of the upper lip as measured during simulated tooth movement.

The lip pressure recording apparatus provided a reliable method of measuring lip pressures with the wide and medium flanges. It was unreliable for the narrow flange (which had smaller force readings) as a result of the relatively high measurement error associated with the friction generated when sliding the LVDT pin through its housing (± 20 grams).

The video data were collected at two recording sessions, with five simulated tooth movement trials being analyzed from each session. Ten to fifteen images were selected per trial and used for the calculation of the linear regression line characteristics for each trial. Therefore, approximately 100-150 images were printed and analyzed for each flange for each subject. Combining the three flanges, thus, the data for each subject were comprised of information from between 300-450 images.

Multiple regression analysis of the stress:strain and $flange^H$:lip^H measurements allowed the determination of constitutive equations and correlation coefficients for all seven subjects.

The findings from the experiments permitted rejection of the null hypothesis. That is, in this study, the lip profile changes in response to orthodontic tooth movement were predictably associated with the physical properties of the upper lip as measured during simulated tooth movement. The lip profile changes were also found to be significantly influenced by the area of tooth retraction, as determined by measurements from superimposed pre- and post-treatment occlusograms. These measurements provided a more complete two-dimensional evaluation of the tooth position changes for an individual. This is in contrast to the assessment of change afforded by a lateral cephalograph, which generally only accounts for the linear retraction of the most protrusive incisor.

5.1 Cephalometric Data:

5.1.1 Changes in Upper Incisor and Upper Lip Position:

The results of the lateral cephalograph superimpositions must be compared to similar nongrowing subjects. In all subjects investigated the horizontal position changes for the upper lip and teeth occurred in the same direction. The mean percentage of horizontal position change in Ls compared to UIP was 35 $\pm$ 13 % and for horizontal position change in Ls compared to UIE it was 33 $\pm$ 11 %. In comparing these results with results reported from similar studies in the literature, the described changes in lip position were less. Lew (1992) found a percentage of horizontal position change in Ls compared to the UI of 47.6 % and Yogosawa (1990) found a percentage of 40 %. Both of these studies, however, involved Asian female subjects with bimaxillary protrusion malocclusions. Rains and Nanda (1982) and Talass *et al.* (1987) found higher percentages of horizontal position change in Ls compared to UI (63 and 64% respectively). Both of these studies controlled for growth effects. Differences between the Lew (1992), Yogosawa (1990), Rains and Nanda (1982), and Talass *et al.* (1987) studies may relate to the fact that the latter two studies involved samples of Cl II Division 1 subjects, which might be expected to show greater upper lip retraction than bimaxillary protrusion patients. It is plausible that the lips in a bimaxillary protrusion malocclusion are more "self-supporting", therefore, even though the anterior teeth are retracted, the lips may move posteriorly to a lesser degree.

5.1.2 Changes in Anteroposterior Upper Lip Thickness:

Changes in lip thickness pre- and post-treatment, differed at the vermilion and subnasale areas. The largest percentage change in AP lip thickness was 34.7 % at the vermilion area, for subject PH. In this case the lip got thicker exhibiting "decompression" with tooth retraction. For the other subjects the amount of lip decompression at the vermilion area was smaller (0.0 to 15.6 %). Daly and Odland (1979) have shown that for human skin, strain levels below 60 % cause an initial deformation of the elastin fibers, and are generally considered quite low for biologic materials. According to this scale, the upper lip tissues at the vermilion area do not appear to have been under even moderate strain levels in any of the subjects.

Generally, basic lip thickness did not change significantly, except for subject DR who had a 16.7 % decompression of this lip area with tooth retraction. Two subjects had no change (JC, KC), whereas three subjects had a decrease in thickness (KS, PH, CH). This may be related to remodelling changes in the alveolus at A-point in response to tooth movement. This differential change in vermilion and basic lip thicknesses resulted in a reduction in lip taper for all subjects except JG and DR.

Holdaway (1983) had suggested that patients with excessive lip taper will not experience lip retraction until the taper is "normalized" at 1 mm. This study did not find a strong relationship between the amount of change in lip taper and the lip movement to tooth retraction ratios (Table 4.4). However, Holdaway also stated that in adults, this normalization of lip taper does not always occur as the lips move in response to tooth movement. This qualification is supported by the results from this study. However Holdaway's observations (1983) cannot really be assessed since he did not provide data to support them. It is plausible that the differences that he observed between adults and adolescents could also be accounted for by growth effects on lip thickness during adolescence, rather than differences in lip response.

5.2 Video Data:

5.2.1 Introduction:

The cutoff value of 65 % for the strain values was appropriate considering the maximal percentage change in lip thickness with orthodontic treatment was 34.7 % for the seven subjects investigated. As the flange moved forward it eventually reached a point at which the lip moved upwards vertically relative to the flange. To limit this effect, no greater than 3 mm of vertical lip movement was allowed.

The correlation coefficients and **p** values for the linear regression lines were highly significant. This supports the use of first order constitutive equations and the pseudo-constant "E" for finite element methods (FEM), since the upper lip appears to act in a linear manner with limited compressive loads (i.e. this study involved no greater than 65 % strain of the upper lip). This low strain level represents the initial deformation of the elastin fibers in the dermis, and might be expected to be linear in nature.

No studies have been performed to investigate the viscoelastic properties of the upper lip. Studies of this type would require a significantly more accurate recording apparatus with the ability to measure the rate of strain (the velocity at which the load is applied).

5.2.2 Combined Session 1 and 2 (Overall) Data:

The correlation coefficients were largest for the wide flange data. This may be because larger force levels were generated by this flange size, and thus, the relative influence of the frictional error in the recording apparatus was less. The smaller flanges produced lower force levels and the ± 20 grams of error inherent to the apparatus had a relatively large effect.

Statistically, the flanges did not differ for either the stress:strain or the $flange^{H}$:lip^{H} data. To be able to show differences between the flanges would require a higher level of apparatus accuracy. The data associated with the wider flange did tend to have a larger slope. This would be expected since it would be less likely to slip out from under the upper lip, and would therefore transmit more of its force to the compression and displacement of the lip.

For the stress:strain data the average slope of the wide flange was generally larger than the medium and narrow flanges. The latter were more similar to one another (Appendix K). This may represent differences in lip compression between the orbicularis oris area of the lip, and the modiolar area, as suggested by Thüer *et al.* (1985) and Lindner and Hellsing

(1991). Weinstein *et al.* (1988) found that an increase in the size of the small acrylic balls used in their experiments did not change the vertical lip pressure. The areas of these acrylic balls were significantly less than the size of the flanges used in the study reported herein, and the acrylic balls had a maximal displacement of 12 mm. Only the orbicularis oris muscle would have been vertically compressed with the study by Weinstein and associates.

For the flange^H:lip^H data, the average slope was greater for the wide versus the medium versus the narrow flange. This would support the concept of greater lip displacement with a larger area of tooth protrusion (or retrusion) as measured from the cephalometric and occlusogram data.

Two statistically different subgroups were identified from the stress:strain and flange^H:lip^H data (Appendix M). More subjects were in the smaller slope value subset than the higher slope value subset for both types of data. Although the variation in the stiffness of the upper lip was not large in the seven subjects studied, these data do suggest that the physical properties of the upper lip can vary in different individuals.

5.2.3 Individual Session 1 and 2 Data:

The difference between the average slope values for the subjects for session 1 as compared to session 2 was greater for the stress:strain data (0.27 g/mm^2 and 0.24 g/mm^2, respectively). However, the average slope values for the flange^{H}:lip^{H} data were almost equal (0.58 and 0.57, respectively). This may have been due to the greater error potential in the lip pressure recording apparatus.

Although the ranking of subjects was different between the two recording sessions, statistical differences were not evident for either the stress:strain or flange^{H}:lip^{H} data. Any temporal differences in lip tone would be expected to be small and a high degree of technical accuracy would be required in order to detect these differences. Before the first trial the subject was instructed to relax her/his lips during the recording session, and then a number of practice trials were performed to make the subject comfortable with the flange movement. The use of multiple trials within each session was important in reducing the effect of active muscle tension on lip tonicity during flange movement.

When a cephalograph of a patient is made, it is possible for the patient to feel uncomfortable in the apparatus and to show abnormal lip posture. This is particularly so for an inexperienced patient, with a malocclusion that results in lip incompetence at rest. A normal reaction for such patients is to close the lips together, and present a lip position and morphology that is distorted from the relaxed, natural situation. For many patients, it can be difficult to attain relaxed perioral musculature in an unfamiliar clinical setting. It is possible that a number of the cephalographs used in past lateral cephalometric studies represented lip-postures which were not relaxed lip-postures. In such cases, the radiographic images produced would not have reflected a relaxed soft-tissue morphology. The amount of soft-tissue distortion could have been great, or even greater, than the "expected" changes in soft-tissue position associated with tooth movement.

Studies that have evaluated soft-tissue "repositioning" (Hillesund *et al.*, 1978, Wisth and Bõe, 1975) have used very controlled conditions not normally employed in an orthodontic office, where the subjects were given detailed explanations of the experimental apparatus and proper lip positioning was strictly evaluated before exposing the radiograph. Thus the repositioning error reported by these studies was probably significantly less than would be encountered in a clinical setting where such special controls are rarely employed.

5.3 Prediction of Anteroposterior Lip Changes:

The model presented to predict the movement of Ls in response to tooth movement (figure 4.8) is based on the product of three values. The percent variation is the standard deviation divided by the average value, expressed as a percentage. It is a measure of the relative amount of variation of the values used to predict the amount of lip movement. The percentage variation of each value was, from

Appendix T:

Flange^H:Lip^H Slope	10 %
$\frac{1}{\text{Transverse distance at the lateral incisors}}$	18 %
Area of Tooth Retraction	68%

It can be seen that the area of tooth retraction had the greatest variation in the values used to calculate the theoretical lip movement. There was little variation in the values of the flange^H:lip^H slopes or the transverse distance from the distolabial surface of one maxillary lateral incisor to the distolabial surface of the other in the seven subjects.

The average difference between the theoretical (TLM) and measured (CLR) lip movement was 0.3 ± 0.3 mm. This amount of error is within the error of tracing a cephalograph film or video image. The largest difference was 0.5 mm.

The model presented to predict decompression of the upper lip is based on the product of two values (figure 4.9). The percentage variation of each value is, from Appendix U:

Area of Tooth Retraction	68%
Stress:Strain Slope	25.5%

The values from the Area of Tooth Retraction were almost three times as variable as the values representing the overall stress:stain slope, for the wide flange (E(1,2)).

A greater amount of lip decompression was found with the stiffer lips. If elastic materials were examined, a stiffer material would be expected to be less compressible, and presumably, less "decompressible", than a more flexible material (Hooke's law). The measure of lip stiffness in this study was a combination of the compressibility of the lip tissue and the resistance of the lip to a hinge-like movement centered near the Subnasale region. A lip determined to be "stiff" may therefore show greater compression as a result of protraction of the teeth, and concomitantly, greater decompression as a result of retraction of the teeth, because of a greater resistance to movement at the base of the lip.

Both prediction models have shown the importance of the area of tooth retraction to predicted changes in lip position and thickness. This supports the model presented by Weinstein *et al.* (1983) for the cheek. These authors modelled the deformation of the internal cheek surface as a closed fluid-filled system bounded by parallel thin elastic membranes. Similar to a balloon, if one finger was pressed 4 mm into the surface, there was little expansion of the opposite surface. However, if four fingers were pressed 4 mm into the surface, then a significant expansion of the opposite surface was expected.

This analogy may explain why lateral cephalograph studies have shown such variable results. The retraction of the upper lip would be expected to differ depending on whether one or all four incisors are retracted. In this vein, the ATR could be taken one step further by combining vertical changes in lip support with the occlusogram. For instance, using pre- and post-treatment frontal photographs (1 to 1 magnification) of the relaxed lip position, the length of the incisors inferior to the inferior edge of the upper lip could be measured. This information could be used to calculate the *volume* of lip support change, and the derived volume change tested as a predictor of upper lip response. For subjects with an extremely high smile line, the incisor crown may actually provide little support for the lip. For such individuals, changes in the alveolar base might be expected to have a greater influence on lip position. These types of alveolar lip support changes would be difficult to measure from occlusograms. One possible solution to this and to the potential projection errors associated with the occlusogram may be to use a three-dimensional digitization system to quantify shape and volume changes in the support structures of the lip.

A natural self-supporting "rest" position of the lips with no tooth support has been shown in edentulous subjects (Burstone, 1967). If a subject's anterior teeth are retracted posteriorly past this natural rest position, then further retraction of the lips would not occur. Theoretically a void should exist between the teeth and the internal surface of the lip on a lateral cephalograph. Only one subject, DR, had a significant void between the lip and upper incisors. This may explain why, that although this subject had 8 mm of retraction of the incisal edge of the upper incisor and 6.5 mm of retraction of the labial surface of the upper incisor, only 2 mm of lip movement was demonstrated.

5.4 Clinical Significance:

The ability to accurately predict changes in the soft-tissue lip position with orthodontic treatment has obvious benefits to both patient and orthodontist. Much of the ambiguity found in the literature on the topic of soft-tissue response to tooth movement relates to the fact that growing, adolescent subjects were selected for study and the change in lip position was incorrectly assumed to be only treatment-induced. The inability to distinguish and accurately quantify growth versus treatment changes has clouded the prospect of formulating reliable treatment predictions. Less than strict control of measurement conditions has been another important problem associated with research in this area.

The best approach to studying soft-tissue changes associated with treatment is to first understand the changes that occur in a population where the variable of growth is somewhat controlled. It is known that soft-tissue changes occur during adult life, however, these are relatively small in magnitude over the short term (Behrents, 1985, 1989).

Capturing lip posture in a relaxed state is a large limitation of cephalometrics. Unless controlled for, this can create an unwanted variable when lip measurements are made from cephalographs. For ethical reasons, repeated radiographs cannot be made in order to address this problem. This is of particular concern since many treatment decisions are made from an analysis of the radiographic soft-tissue image (including plans for orthognathic surgical procedures). However, as an alternative, multiple photographs can be made. The integration of cephalometric and digital photographic images would allow an enhanced computer generated image to be produced. The possibility of scanning the pre-treatment casts and determining the proposed area of tooth retraction could be used in a prediction model. Estimation of the vertical changes in tooth position could also allow a determination of tooth retraction volume.

The data from this study has shown that the stiffness of the lip varies over a range for each of the individuals, as does the response of the upper lip to simulate tooth movement. The use of two or three constants contained within the range measured in this study, may help to identify either high, moderate or low upper lip stiffness subjects and may be useful in increasing prediction accuracy. Any differences between the predicted and measured lip movements were small and within the error of the video and cephalometric technique. Thus, the model prediction for lip movement was in good agreement with the measured lip movement for all the subjects investigated.

A significant amount of prediction error results from the uncertainty of growth changes in adolescent patients.

Cangialosi *et al.* (1995) compared growth predictions using a commercial computer program and a manual method, and found no significant differences in accuracy. Growth prediction is also limited by the accuracy of the cephalometric technique. Sinclair (1992) has previously stated that "it becomes clear that our ability to predict future growth in a clinically meaningful manner must remain low. Growth prediction is not a simple matter. Adding a mean increment of growth derived from a similar group of patients to an individual's measurements is unlikely to produce an accurate individual growth prediction." Therefore, even if soft-tissue changes with treatment could be accurately predicted, changes due to growth would also have to be predicted accurately. Currently there is no way to predict exactly how the soft-tissues will change with growth.

The comparison of this study to other research projects is difficult. The studies by Ho *et al.* (1982) and Weinstein *et al.* (1988) measured vertical lip stiffness and they did not include an optical method that might allow determination of strain levels produced. Their results showed differences between the upper and lower lips, between male and female subjects and between Black and Caucasian lips. These results also support the idea that physical lip properties vary from individual to individual, and there may be differences between races and sexes.

Orthodontists must be acutely aware of how difficult it can be to reproduce a relaxed lip posture when making cephalographs or when performing a clinical exam. Incorrect conclusions regarding soft-tissue morphology can lead to improper diagnosis and treatment decisions.

5.5 Limitations of the Project:

A single investigator designed and manufactured the apparatus and performed all testing. Analyses of both video and cephalometric data were also performed by the principal investigator. This eliminated the possibility of a blind investigation, and allowed for the possibility of subjective measurement bias.

This project restricted examination to the physical properties and changes in upper lip position. The lower lip, lower incisors and changes in vertical face height may also influence the position of the upper lip. The effect of the natural rest position was not evaluated, but presumably subjects with minimal lip thickness changes would be closer to this "rest" position.

The effect of strain rate and stress relaxation were not evaluated. The viscoelastic properties of the lip may not be important clinically. The high statistical significance of the linear regression analysis validates treating the upper lip as an elastic material when placed under moderate compressive loads. Changes in lip position were noted after the retention period, however long-term adaptation to tooth position changes were not evaluated.

The protrusion of the flange was obviously not an exact reversal of the tooth movement situation occurred through orthodontic treatment. Tipping and bodily tooth movement may cause different changes in lip support. Any change in vertical tooth position may also change the area of support for the lip.

Vertical displacement of the flange due to the pendulum arm was ignored. The pendulum arm was made as long as possible to minimize vertical movement of the flange. Over a 10 mm AP arc of the flange, the vertical movement of the flange was approximately 0.8 mm.

Technical factors that may have affected the experimental results included potential variability in constructing flanges and drilling holes for the connector rod, plus lip dryness effects on the friction between the flange and the lip.

Although a large amount of statistically significant data was collected for each subject, the small sample size and the small amount of tooth movement for some subjects limited the evaluation of the prediction models statistically. This was a retrospective study and the possible changes with time in the lip properties after tooth retraction or the possible changes due to aging were not evaluated.

CHAPTER 6
CONCLUSIONS
AND
RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusions:

The following conclusions were drawn from the study, based on the analysis of the collected data:

1) The lip pressure and position recording apparatus used in this investigation provided a reliable method of recording the stress:strain and flange^H:lip^H relationships of the upper lip.

2) The accuracy of the recordings were generally greater for the wider flanges than for the smaller flanges because the larger forces and pressures associated with the wide flanges were relatively less affected by the frictional resistance in the apparatus.

3) Multiple linear regression analysis of the stress:strain and the flange^H:lip^H data showed a high level of statistical significance. Viscoelastic properties of the upper lip appear to be insignificant at lower strain levels (<65%).

4) Changes in anteroposterior lip thickness due to tooth retraction were different at the vermilion and the subnasale regions (vermilion versus basic lip thicknesses). In general, the vermilion lip thickness changes were small, between 0.0 and 15.6 %, except in one case where the increase in the vermilion lip thickness was 34.7 %. The amount of lip compression and

decompression with orthodontic tooth movement was generally quite small.

5) Initial lip taper and changes in lip taper were not related to the amount of lip retraction.

6) Two statistically different subgroups were identified for both types of data.

7) There were no statistical differences between the wide, medium and narrow flanges, although the wide flange tended to have a larger regression slope for both types of data.

8) There were no significant differences between sessions one and two for all the subjects.

9) The slope of the stress:strain data was not related to the slope of the flange^H:lip^H data.

10) For the theoretical models presented to predict upper lip movement and upper lip decompression, the area of tooth retraction was the most important variable.

11) Any differences between the theoretical lip movement and the measured lip movement for the seven subjects were within the error of both the cephalometric and video techniques.

12) The results of this study suggest that the upper lip behaves in a similar fashion to the cheek, where the cheek is a closed fluid-filled system bounded by parallel thin elastic membranes, as presented by Weinstein *et al.* (1983).

6.2 Recommendations for Future Research:

Based upon the results obtained from this investigation, recommendations for future studies of the physical properties of the lips and changes in lip position with orthodontic treatment include:

1) The measurement of lip pressure and positional changes using an apparatus which employs a load cell to measure forces should be considered. This would eliminate the errors in force measurement produced by friction between the LVDT housing and pin, as well as the friction between the lip and flange. Placement of highly accurate pressure transducers in several flanges of known thickness would significantly increase the experimental accuracy.
2) The prediction models of lip movement and changes in lip taper presented in this study should be tested further. Ideally this would be through a prospective study involving a large number of nongrowing subjects for whom large amounts of anterior tooth movement are planned.
3) The use of multiple photographic images to assess the facial profile could reduce the chance of a distorted lip posture being represented in pre- and post-treatment lateral cephalometric radiographic records.
4) The development of computer software to allow integration of cephalometric hard-tissue, photographic

soft-tissue and occlusogram images would allow a large number of subjects to be easily and systematically investigated.

5) The results of ultrasonic investigations into the physical properties of the lips and facial structures should be tested by comparison with the results derived from an investigation using the technique described. If verified and calibrated, sonic and ultrasonic investigations could provide a relatively quick and easy method of determining the physical properties of the upper lip. Such techniques could possibly be incorporated into commercially-available computerized clinical data-collecting systems (e.g. Dolphin Imaging System®, Los Angeles, CA).
6) The completion of similar experiments to evaluate possible differences in the physical properties of adolescent and adult lips, could help to establish possible age-related changes.
7) Experiments involving a gross dissection with detailed morphological description and a histological evaluation of the lips and related structures would be beneficial. Ideally, this would be in combination with an evaluation of the physical properties of the same soft-tissue structures.
8) The development of a computer-based superimposition technique for occlusograms to help predict and

calculate the area and possibly the volume of tooth retraction. The desired Area of Tooth Retraction could be derived by employing occlusograms as part of the orthodontic treatment planning. As a result, more definitive treatment goals would be established. This could be a clinical asset as well as a means of testing clinical outcomes in a way that is not currently common practice.

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APPENDIX A:

A Review of Human Lip Structure/Anatomy:

Research associated with the structure and composition of the upper lip is limited. What follows, however, is an overview of the anatomic composition of the lips, differentiating where possible, the upper and lower lip tissues.

The lips are fleshy folds consisting of skin superficially and mucous membrane internally, with the orbicularis muscle, loose connective tissue and the labial nerves and blood vessels contained between (Johnson and Moore, 1989). They consist of four principal layers - skin, muscle, glandular tissue and mucosa (Liebgott, 1986). Generally, there is a lack of fat in lip tissue since delicate muscle movements need to be transferred directly to the overlying skin for facial expression (Cordoso *et al.*, 1995).

The skin covering the lips has a keratinized stratified squamous epithelium. It is called thin skin (hairy) because the dermal and epidermal layers are generally 75 to 150μm thick (Junqueira *et al.*, 1986). Moving inferiorly, the skin layer color changes at the vermilion border to red, as this transitional area between external skin and internal mucosa is very thin and hairless, allowing the redness of the underlying capillary bed to show through.

The muscle layer consists primarily of the orbicularis oris and contributing circumoral muscles. The musculature of the upper lip is deep to the fascial layer (Pensler *et al.*, 1985) with the superficial musculoaponeurotic (SMAS) system bridging the gap between the orbicularis oris muscle and the dermis. Contractions of the facial musculature are transmitted to the dermis by the SMAS by means of its dermal connections.

There are conflicting opinions as to the relative contribution of muscle to the structure of the upper lip. Delaire (1978) stated that muscle tissue is the major constituent of the lips, with the horizontal and oblique fibers/bands being the most prominent, based on his work with dissected cadavers.

Vinkka-Puhakka *et al.* (1989) examined the circumoral musculature of 11 healthy females with a mean age of 22.8 ± 2 years using ultrasound techniques. Transverse and sagittal ultrasonic scans were made with the lips both relaxed and contracted. Prior to imaging the lip stiffness was assessed by a palpation technique. Frontal and lateral photographs were used to observe changes in the external contours of the lips, and to compare these changes with those seen ultrasonically. From selected ultrasound images they described the muscle of the lower lip as being close to the mucosa, while that of the upper lip appeared sandwiched between connective tissue layers. These muscle layers became thicker on contraction. Ultrasonic images showed that the muscle tissue made up only a part of the total thickness of the lip (less than one third) and varied amongst the individuals in shape, transonicity (clearness) and thickness. The muscle image tended to be clearer and thicker in individuals with lips regarded clinically as "stiff" than in subjects whose lips were less firm, however, thickness of the muscle image did not appear to be related to thickness of the lip.

The study by Delaire (1978) involved cadaver specimens, and it would be expected that the muscle tissue would represent a relatively thicker component of the specimen. The ultrasound investigation of Vinkka-Puhakka *et al.* (1989) suggested that in the living subject, with normally hydrated tissues, the thickness of muscle is relatively less and the stiffness of the lip (which was determined subjectively) may not be related to the thickness of muscle seen on ultrasound images. This supports the hypothesis herein, that the physical properties of the upper lip would not necessarily be expected to be related to the morphology of the lip as seen on a lateral cephalometric radiograph.

Nairn (1975) described the buccinator and orbicularis oris muscles as a continuous sheet of fibers from left to right pterygo-mandibular raphe. Based on an unknown number of dissections, Nairn described the orbicularis oris muscle as having a peripheral part lying close to, and parallel with, the inner mucosal surface of the lip and a marginal part lying beneath the red lip margin. The marginal fibers were thin and lay close to the skin. The marginal part curled outward, its form followed the mucosa of the lip as this everted on to the face and became the red lip margin (Figure A.1).

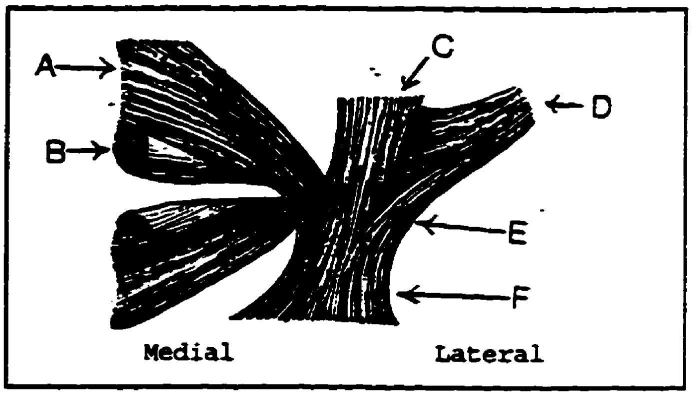

Figure A.1
Fibers of the Orbicularis Oris Muscle and Insertion of Fibers into the Modiolus.

A: Peripheral Fibers of the Orbicularis Oris M.
B: Marginal Fibers of the Orbicularis Oris M.
C: Levator Anguli Oris M.
D: Zygomaticus Major M.
E: Modiolus Area.
F: Depressor Anguli Oris M.
Where M. = muscle
(Modified from Nairn, 1975:Figure 10)

As the fibers of this marginal part passed laterally to the angle of the mouth they twisted over the border of the flat peripheral part and came to be deep to it. When the muscle contracted to close the lips, the fibers shortened and the curl flattened out. Contraction of the orbicularis oris muscle tightened the sheet across the anterior teeth, and with the tension so built up, uncurled the everted margin. In the absence of teeth, the tension would be less. This action pulled the red margins of the lips towards each other, made them smaller, and gave a thin hard line to the lips. The ultrasonic investigation by Vinkka-Puhakka *et al.* (1989) found the opposite, with the marginal hook or curl of muscle becoming more pronounced upon contraction. The length of this marginal hook was longer in the lower lip and was about twice as long in Australian aboriginals, suggesting racial differences in the muscular content of the lips.

According to Nairn (1975) the orbicularis oris and buccinator muscles can be regarded as forming an almost continuous muscular sheet, split anteriorly for the mouth. Their junction at the modiolus provides a point which can be fixed in a variety of positions by the modiolar stays (the zygomaticus major, levator anguli oris and depressor anguli oris muscles). The modiolus is a muscular or tendinous node with groups of converging muscles just lateral to and slightly above the corner of the mouth. The "stays" immobilize the modiolus in any position. Some fibers of one muscle pass into and through the modiolus into another muscle.

Three bands of muscles insert into the upper lip (Basmajian and Slonecker, 1989), the levator labii superioris alaeque nasi, levator labii superioris and zygomaticus minor muscles. The depressor labii inferioris, depressor anguli oris and mentalis muscles insert into the lower lip.

Cordoso *et al.* (1995) did a histologic study of the mentolabial sulcus of the lower lip and found that there were large numbers of elastic fibers throughout the lip. The intermuscular septa contained large numbers of elastic fibers in addition to collagen fibers. An extrapolation of this data to the upper lip may not be strictly appropriate since the lower lip is a "self-supporting" structure and as such, would be expected to have greater amounts of elastic fibers. A similar study of elastic fiber content in the upper lip has not be performed.

The glandular layer consists primarily of minor salivary glands which lie within the submucosa. Their ducts open at the mucosal surface. Sebaceous glands are present in the upper lip and buccal mucosa in about three quarters of adults (Ten Cate, 1985). The oral surface of the lip is lined by mucosa, which is a moist non-keratinized stratified squamous epithelium with no epidermal appendages. The underlying connective tissue layer is the lamina propria. In the lips and cheeks there is a layer of loose fatty or glandular connective tissue (submucosa) containing the major blood vessels and nerves supplying the mucosa. The minor salivary glands are located in or just beneath the lamina propria of the mucosa. Sebaceous glands, if present, are located in the lamina propria.

A Review of Mechanical Principles As Applied to the Soft-Tissues:

A quantitative analysis of the mechanical properties of soft tissue is best addressed through the application of engineering principles (Fung, 1981). These mechanical properties can be defined in terms of the deformation produced by a given force over time. Photographic and optical methods have been used for studying the deformation of soft tissues. The accuracy of the measurement technique is limited mainly by the ability to identify target points accurately and the reproducibly at the time of digitizing. This in turn depends upon a number of factors including the photographic technique, the lens quality and the inherent clarity of the target points (Stokes and Greenapple, 1985).

The force is "standardized" by expressing it as stress, the force per unit area. The basic unit of stress is the newton per square meter (N/m^2) or pascal (Pa). Stresses acting perpendicular to the surface of an object are termed "normal stresses", whereas all remaining stresses are called "shearing stresses" (Fung, 1981).

The deformation of a solid that can be related to various stresses is described by the strain of the solid material. Various dimensionless ratios can be used to define strain. The use of a dimensionless ratio eliminates the absolute length from the consideration. For example, if a material of initial length L is stretched to length Lo, the ratio L/Lo is called the "stretch ratio" (Larrabee, 1986).

Within the elastic limit of a material, a strain (e) is proportional to the stress (σ) producing it. This is known as Hooke's Law, and it applies to materials with a linear stress-strain relationship, i.e.:

$$\sigma = Ee$$

where material constant E = Young's Modulus (modulus of elasticity)

Hooke's Law can be applied only to materials with a linear stress-strain relationship and for small strains. The range of validity of Hooke's Law is bounded by "yield stresses" particular for that material (Fung, 1981). An *isotropic* material has the same elastic properties in all directions (equal stress produces equal displacement in any direction). An *anisotropic* material has elastic properties with a directional variation.

Liquids are traditionally modelled according to the theory of "hydrodynamics" which states that perfectly viscous liquids obey Newton's law:

$$\delta = \eta \ (d\epsilon/dt)$$

where η is viscosity, ϵ is strain, and t is time. Stress (σ) is directly proportional to the rate of strain but independent of the strain itself.

Many materials combine the characteristics of elastic solids and viscous liquids and therefore are termed *viscoelastic*. Some common properties of viscoelastic materials are hysteresis, stress relaxation and creep. Hysteresis implies that stress-strain relationships in cyclic loading and unloading are different, such that their curves will not superimpose. Stress relaxation describes the decreasing stress seen when a constant strain is placed on a viscoelastic material. Creep refers to the increasing strain or length of a material over time when placed at a constant stress.

Motoyoshi *et al.* (1992) used the finite element method (FEM) to predict facial deformation following orthognathic surgery of a mandibular prognathism case. FEM is effective for analysis of the transformation of various material bodies under pressure. The FEM was applied to develop a mathematical model that consisted of elements that represented the nasal cartilages, the facial muscles and other soft tissues. With the nonlinear biologic materials, Young's Modulus (E) was assumed to be a constant value in the FEM (Motoyoshi *et al.*, 1992). The calculation of E for nonlinear materials started by designating the pseudo-constant "E". The authors found that stresses on the skin were small (several g/mm^2) with the neighbouring tendinous tissue having the largest stress. The tendons at the anguli oris acted as pivots for facial muscles, and transmitted tension on a muscle to the other muscles, skin or bone. They found that their predicted results with FEM were comparable to lateral cephalometric studies involving similar surgical procedures. With FEM, the use of "pseudo" constants (E) for biological tissues is justified for small amounts of tissue compression and decompression. This is because at relatively low stress:strain levels, it is primarily the elastic fibers that would be compressed or decompressed (Daly and Odland, 1979).

Much of the stress:strain data that has been collected from biological tissues has involved significantly greater stress levels than that involved with tooth movement. For example, Holmes (1986) discussed uniaxial compression tests of tissue samples using as much as 1.6 to 2.0 MPa of stress. By comparison, for the study presented in this dissertation, most stress levels were in the magnitude of 10^{-3} MPa. At lower "physiologic" stresses, the major difference amongst the tissues tested was the degree of distensibility from the relaxed (unstressed) state (Fung, 1981).

The stress:strain relationship of the upper lip would depend to some extent on the constituent mechanical properties, but also on the anatomical relationships.

The ultrasonic modality has been used in estimating quantitatively the mechanical properties of tissue in the "deep range", known as tissue characterization. Sumi *et al.* (1995) used pure static and/or very low deformation to derive a set of linear equations in which unknowns were the spatial derivatives of the relative shear modulus and the coefficients were the strain and its spatial derivatives. This method can give the static stiffness of living tissue, and may offer orthodontists and researchers a way of differentiating lip stiffness from individual to individual with a relatively simple method. It would also allow the determination of Young's Modulus for the different soft tissues affected by orthodontic and orthognathic treatment modalities. The stiffness values determined ultrasonically could be compared to stiffness values determined through compression of the lip (similar to the study herein).

The major structural components of the skin which affect its mechanical behaviour are the elastin fibers, the collagen fibers and the ground substance. Collagen is the most important structure.

The majority of experimental investigations into the mechanical properties of skin have used *in vitro* uniaxial test procedures, in which a length of skin is deformed in one direction and the resulting stress:strain relationship determined. The accepted mechanism is presented in Figure A.2.

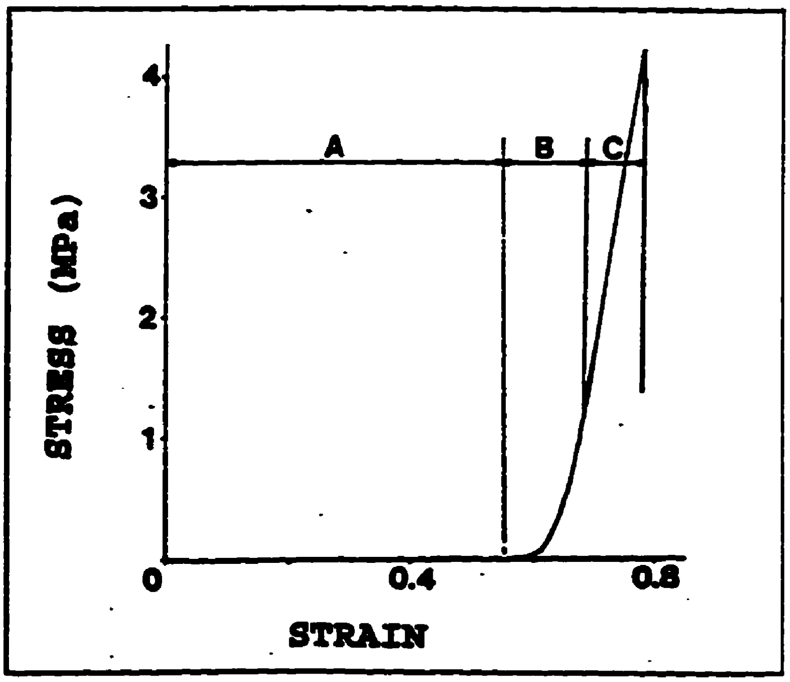

Figure A.2
Stress:Strain Curve For Human Skin Under Tension.

A: Initial Deformation of Elastin Fibers.
B: Gradual straightening of collagen fibers.
C: Collagen fibers stretched in stress direction.

Modified from Daly and Odland, 1979, Figure 19.

Initial deformation is due to deformation of the delicate elastin network (A in Figure A.2). This is the area of tissue compression seen when the teeth are moved into or away from the lips; the second part of the curve (B in Figure A.2) is due to gradual straightening of the randomly oriented collagen fibers; and the final part of the curve (C in Figure A.2) results when the majority of the collagen fibers are elongated in the direction of the stress.

With the tensile tests, stress is applied in the plane of the skin. When a load is applied to the epidermis, the skin is compressed. The resulting deformation is largely a function of fluid interchange with the surrounding unstressed skin (Daly and Odland, 1979). Holmes (1986) and Bogen (1987) considered connective tissues as being multiphasic materials that are formed from a fibrous network of collagen and/or elastin.

With hydrated tissues (e.g. articular cartilage), the fluid and solid phases interact nonlinearly as they flow relative to one another. The biphasic model (Mow *et al.*, 1980) assumes the tissue is a porous elastic solid which is filled with fluid. It is assumed that the nonlinear viscoelastic response of tissue is due primarily to the viscous drag arising from the relative motion of the fluid and solid phases. Material properties commonly differ between individuals (Motoyoshi *et al.*, 1992), and it is difficult to determine the actual stress:strain relationship per unit mass in the human face.

The only previous attempts to measure the physical properties of the lips were by Ho *et al.* (1982), and Weinstein *et al.* (1983, 1988). Ho *et al.* (1982) and Weinstein *et al.* (1988) used the same apparatus to try to measure lip stiffness in the vertical plane of space. The experimental instrumentation involved 4 acrylic balls of increasing diameter attached to the end of a force-transducer bar. Displacement of the force-transducer bar was controlled by a three-dimensional micrometer, and the change in force with a unit change in the displacement of the transducer was measured. The bar was displaced vertically 12 mm (1.2 mm at a time).

Ho *et al.* (1982) used this apparatus to quantify lip stiffness in the vertical plane on a sample of ten Caucasian males and females between the ages of 18 and 26 years. All subjects had acceptable skeletal and soft-tissue profiles. The order of decreasing lip stiffness was male lower lip, female lower lip, male upper lip and female upper lip. With displacement of the transducer bar, the lip pressure was found to increase. The effect of lip contact area was evaluated using four acrylic buttons of increasing surface area. At a fixed transducer-bar displacement, the pressure remained constant with change in the contact area. At small lip displacements there was an approximate linear relationship between force and displacement (represented by a simple linear model), however with greater displacements, the relationship was non-linear, and approximated a second-order function.

Weinstein *et al.* (1988) used this experimental design to compare relaxed vertical lip stiffness on a group of white and black male and female subjects between the ages of 18 and 26 years, each exhibiting an acceptable skeletal and soft tissue profile. In this study the force-displacement relationship was linear at 1 mm transducer-bar displacements, but was a second-order polynomial for larger displacements. The same T-spring model as developed by Ho *et al.* (1982) was 96 % accurate for the Caucasian subjects. Again the lower lip had greater stiffness, as did male versus female lips, and Black versus Caucasian lips. Caucasian subjects tended to have less variation in lip morphology. With a given transducer-bar displacement, the lip pressure remained constant for changes in flange area, whereas the lip pressure increased with greater transducer-bar displacements. The general equation describing force versus displacement was:

$$f(x) = ax^2 + bx + c,$$

where $f(x)$ = applied force, x = displacement of the acrylic button and a,b and c were constants. The force magnitude was controlled by the first term (linear part) of the equation. The equation describing force versus area was:

$$f(Area) = kArea + d,$$

where $f(Area)$ = applied force, Area = area of the acrylic button and k and d were constants.

Weinstein *et al.* (1983) determined the force-displacement characteristics of the cheek in 10 adult subjects (in the maxillary premolar-molar area). They used a linear variable differential transformer (LVDT) and a pressure transducer and modelled the deformation pattern of the internal cheek surface to a closed fluid-filled system bounded by parallel thin elastic membranes. As a hydraulic bellow was pressed into the cheek, the fluid was displaced to a different elevation causing a shallow force displacement slope. Further insertion caused the incompressible fluid to exert pressure on the outer membrane, since the fluid could no longer be displaced. They suggested further study was needed to understand the relation between the area of the displacing button or tooth and the deformation patterns of both internal and external membranes. The resting lip forces were less than most other studies, primarily related to the fact that the plunger was inserted through the space of a missing tooth, and did not rest labial to the tooth surface like most lip or cheek force recording instrumentation.

These studies regarding the displacement of the lips have only been concerned with the force required to vertically displace the lips. Although mathematical models have been presented to describe this behavior, no research literature could be found to describe the relationship between the physical properties of the lips and clinical tooth and lip movements.

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APPENDIX B:

INFORMATION FOR PROSPECTIVE PARTICIPANTS IN A CLINICAL STUDY OF LIP PRESSURE AND POSITION:

Since the teeth support the lips, any movement of the front teeth in a forward or backward direction using "braces" will result in movement of the lips. Predicting how much the lips will move for any given person is still unreliable. The purpose of this study is to investigate the changes in lip pressure and lip position under simulated forward movements of the upper front teeth. The principal investigator is qualified as a general dentist and is a graduate student in the Master of Science and clinical orthodontic specialty program at the University of Manitoba.

To be eligible for the study, a person should:

i) have completed orthodontic treatment, where the removal of some teeth allowed the upper front teeth to be moved back,

ii) have been at least 16 years of age at the beginning of orthodontic treatment, (and therefore would have approximately reached adult height),

iii) have orthodontic records (specifically the x-rays that were taken before and after treatment) that are on file and maintained at the Graduate Orthodontic Clinic, University of Manitoba,

iv) have clean and healthy gums and teeth.

Participants in the study will have an initial appointment to have the study fully explained, to ask questions, and to have an impression of the upper teeth made. After this there will be two similar recording sessions approximately 2-4 weeks apart. A total of approximately 3-4 hours will be required. All sessions can be arranged for a mutually convenient time.

At each recording session a technique to measure the lip pressure will be used, that involves moving a small, thin plastic shield (like a "mouthguard" that covers only the front of the upper front teeth) forward approximately 1-2cm, while recording the change in lip position on video tape. A small (3-4mm diameter) rod will be used to pull the shield forward, and it will be attached at the other end to a pressure recorder. The impression of the upper teeth will allow a model to be made for the custom construction of a set of 3 plastic shields for each person. The same acrylic material that is used for orthodontic retainers will be used for these shields. The lip displacement tasks will be repeated a number of times for each shield.

The general health and well being of any participant should not be affected by any techniques applied in this study. The risks associated with this study are similar to the risks in wearing an orthodontic retainer and include: allergic reactions to materials used, accidental swallowing or inhaling of materials, irritation of the gum tissue in contact with the acrylic facings, and slight jaw tiredness at the completion of the recording session.

Immediate and obvious benefits to the participants as a result of taking part in this study are not expected. However, the information gained through this study is expected to add to the overall understanding and predictability of the changes to the lip profile that can result through orthodontic treatment.

Each subject will be compensated $15 per recording session. There is no obligation to participate. Anyone who does so may withdraw from the study at any time, without penalty. The information gathered from this study will be used solely for research purposes and the names of any participants will not be revealed.

If you wish to participate, or have further questions regarding this study, please contact Dr. Kent Goldade, at the Graduate Orthodontic Clinic (789-3545).

APPENDIX B (continued):

INFORMED CONSENT FOR LIP PRESSURE/POSITION CLINICAL STUDY

I,_______________ (please print name), have agreed to participate in a study concerned with lip pressure and lip position changes, to be conducted by Dr. Kent Goldade, Graduate Orthodontic Student. I have read the information sheet about the study and it has also been explained to me by Dr. Goldade. All questions regarding the Lip Pressure/Position Study have been answered to my satisfaction. I understand that this study will involve the use of 3 custom-constructed appliances to record the lip pressure, and that the changes in lip position will be recorded on video tape.

I understand that the study requires 3 separate sessions: an initial session where information about the study will be given and an impression of my upper teeth will be made, followed by two similar but separate recording sessions.

I understand that there are no specific, personal benefits to be realized as a result of my participation in this study, but that the results of the research are expected to contribute to a better understanding of the changes in lip position with orthodontic treatment. I understand that I will receive monetary compensation for taking part in this study ($15/recording session). The information from this study will become property of the University of Manitoba, and may appear in scientific publications and presentations, but the names and identities of the participants will be protected and will remain anonymous. All videotapes will be destroyed after the study is completed.

I have volunteered to take part in this study on my own, and I realize that I am able to withdraw from the study at any time, without penalty.

Signature of Participant: _____________________

Date: _____________________

Signature of Witness: _____________________

APPENDIX B (continued):

The University of Manitoba
Faculty of Dentistry

COMMITTEE ON RESEARCH INVOLVING HUMAN SUBJECTS

Date:	December 7, 1995
Committee Reference	EC 40/95P
Names of investigators:	Drs. Goldade, Iwasaki, Nickel and Smith
Your project entitled:	Lip Profile and Pressure Response to Changes in Lip Position,

has been approved by the Committee.

PLEASE NOTE

Any significant changes in the approved protocol must be reported to the Chair of the committee for the Committee's consideration and decision, prior to the implementation of the changes in the protocol.

Yours sincerely,

Colin Dawes

Colin Dawes B.Sc., B.D.S., Ph.D.
Chair, Committee on Research
Involving Human Subjects

APPENDIX C:

Video Image Reduction Factor:

A 25 by 18 cm grid was videotaped 10 times
and the printed images were measured to determine
the image reduction factor.

	Length (cm)	Width (cm)
Trial 1	13.8	9.4
Trial 2	13.3	9.4
Trial 3	14.8	10.4
Trial 4	14.6	10.3
Trial 5	14.8	10.9
Trial 6	14.7	10.6
Trial 7	14.6	10.4
Trial 8	14.7	10.6
Trial 9	13.8	9.9
Trial 10	14.2	9.8
Average	14.3	10.2
SD	0.7	0.5

Image Reduction Factor = video image distance/actual grid distance.

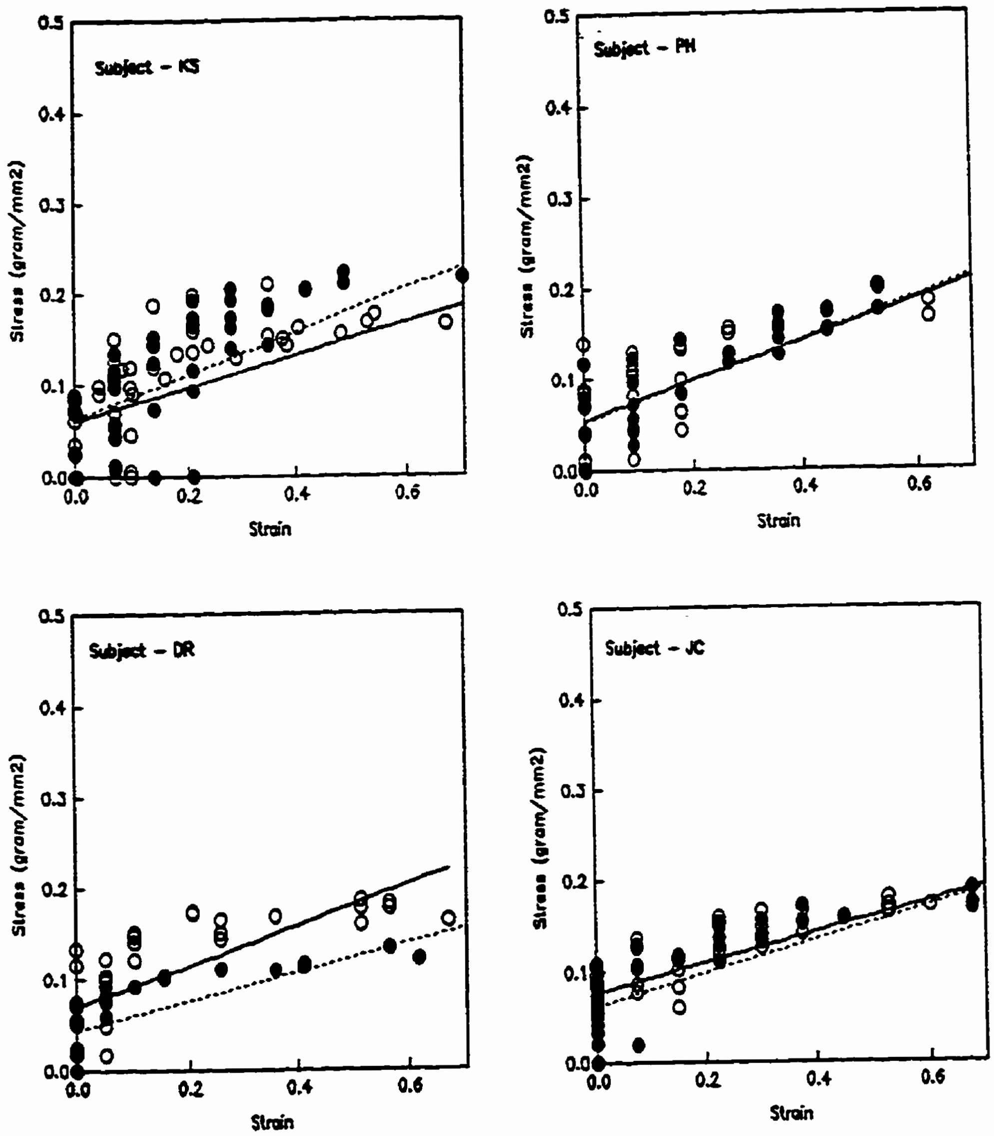
	Distance on Grid	Distance on Video Printout	Image Reduction Factor
Width	18	10.2	0.57
Length	25	14.3	0.57

Average Image Reduction Factor = 0.57

SD = standard deviation

APPENDIX D:

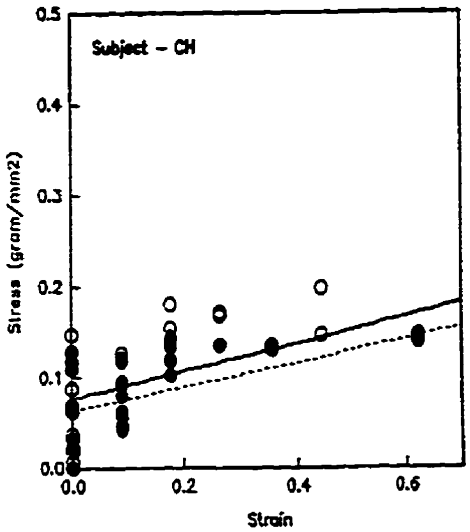
Plots of Stress:Strain Measurements (Wide Flange).

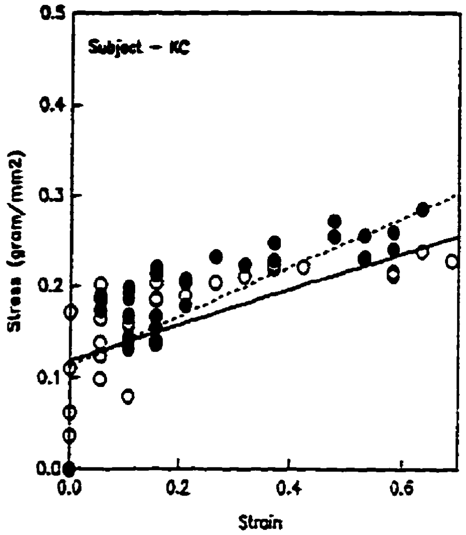


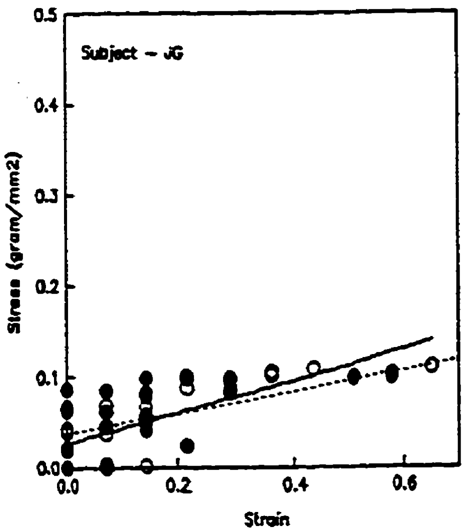
○ Session 1 (data point)
● Session 2 (data point)
—— Session 1 (linear regression line)
--- Session 2 (linear regression line)

APPENDIX D (continued):

Plots of Stress:Strain Measurements (Wide Flange).



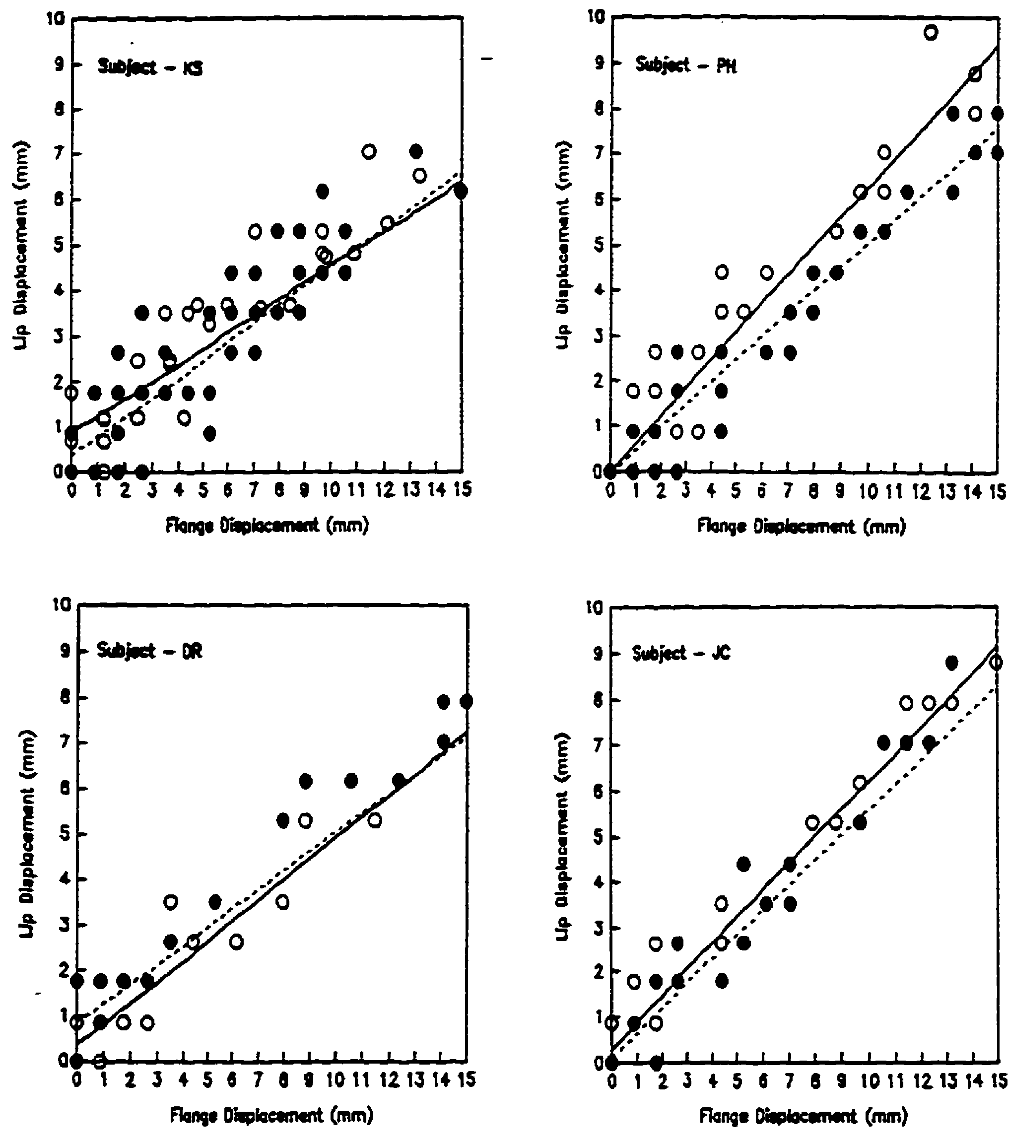




○ Session 1 (data point)
● Session 2 (data point)
—— Session 1 (linear regression line)
--- Session 2 (linear regression line)

APPENDIX D (continued):

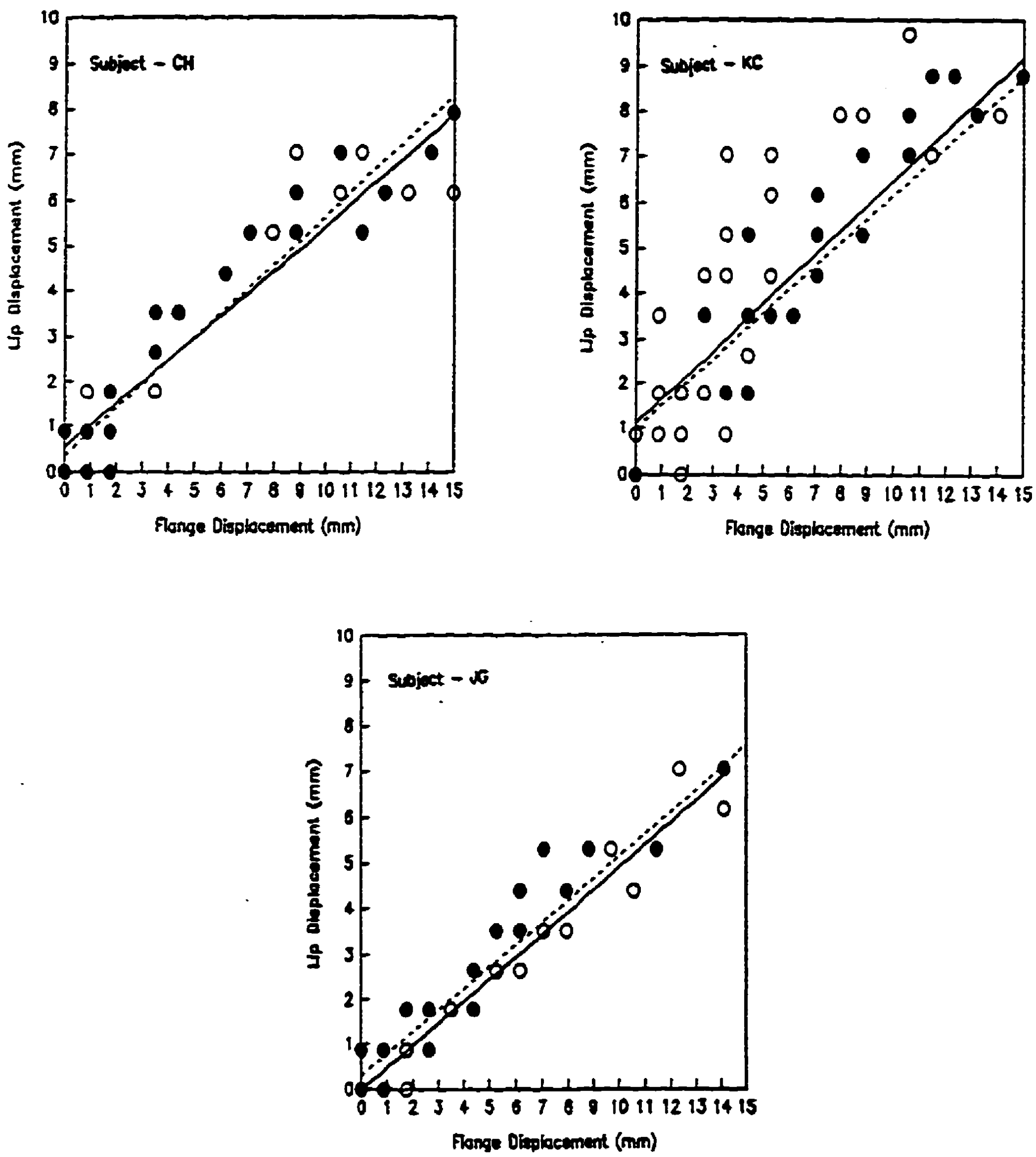
Plots of Flange Displacement:Lip Displacement Measurements (Wide Flange).



○ Session 1 (data point)
● Session 2 (data point)
—— Session 1 (linear regression line)
--- Session 2 (linear regression line)

APPENDIX D (continued):

Plots of Flange Displacement:Lip Displacement Measurements (Wide Flange).



○ Session 1 (data point)
● Session 2 (data point)
—— Session 1 (linear regression line)
--- Session 2 (linear regression line)

APPENDIX E:

Cephalometric Error:

The "A" and "D" record cephalographs from subject JG were retraced on five different occasions. The "A" record cephalograph was a good quality image, while the "D" record cephalograph was a poor quality image. What follows are the results of measurements of the horizontal distance, in millimeters, of the specified landmarks from the Y-axis. The average distances and standard deviations (SD) are shown, as well as the differences between the results for the two cephalographs. These measurements have not been adjusted for image magnification (9.8 %).

Landmark: * all measurements in mm.

Ls

		Ceph "A"	Ceph "D"	Difference
Tracing 1		116.0	112.5	3.5
Tracing 2		116.0	113.5	2.5
Tracing 3		115.5	113.0	2.5
Tracing 4		116.5	112.5	4.0
Tracing 5		116.5	113.5	3.0
	Average	116.1	113.0	3.1
	SD	0.4	0.5	0.7

UIP

		Ceph "A"	Ceph "D"	Difference
Tracing 1		104.5	100.0	4.5
Tracing 2		105.0	100.5	4.5
Tracing 3		104.0	100.0	4.0
Tracing 4		104.5	100.0	4.5
Tracing 5		105.0	101.0	4.0
	Average	104.6	100.3	4.3
	SD	0.4	0.5	0.3

UIE

		Ceph "A"	Ceph "D"	Difference
Tracing 1		103.0	98.0	5.0
Tracing 2		103.5	99.0	4.5
Tracing 3		102.5	98.0	4.5
Tracing 4		103.5	98.5	5.0
Tracing 5		104.0	100.0	4.0
	Average	103.3	98.7	4.6
	SD	0.6	0.8	0.4

SD = standard deviation

APPENDIX F:

Error Due to Head Rotation:

For three representative subjects, five images for each flange width were randomly selected for each session. The images were superimposed on the orthogonal axes system, registered at Orbitale. The horizontal and vertical distance of the three removable stickers was measured in relationship to the origin. The standard deviations (SD) of the horizontal and vertical measurements are shown. Horizontal displacement of the Tragal point is not shown since this does not affect axes orientation. All measurements are corrected for image reduction, and rounded to the nearest 0.5 mm.

Subject:		**Tragus (SD)**	**Cheek (SD)**	
		horizontal:	horizontal:	vertical:
CH	Session 1	1	0.5	0.5
	Session 2	0.5	0.5	0.5
KC	Session 1	0.5	1	0.5
	Session 2	0.5	0.5	0.5
JC	Session 1	2.5	1	0.5
	Session 2	1	0.5	0.5

SD = Standard deviation.

APPENDIX G:

Error in Repositioning Stickers:

The error in repositioning the tragus (Tr) and infra-orbital (I-O) stickers was assessed by randomly selecting and superimposing three images from each recording session, using the upper and midfacial structures and the ear. The average difference between the two recording sessions is shown, as well as the average standard deviation. The average difference and standard deviation between sessions, for all seven subjects, is also shown. All measurements are corrected for image reduction, and rounded to the nearest 0.5 mm.

Subject		Average difference between sessions (mm).	Average standard deviation between sessions (mm).
DR	Tr (vertical)	2.0	0.5
	I-O (vertical)	1.0	0.5
PH	Tr (vertical)	2.5	1.0
	I-O (vertical)	1.0	0.5
JG	Tr (vertical)	2.5	1.0
	I-O (vertical)	2.5	1.0
KS	Tr (vertical)	0.5	2.0
	I-O (vertical)	2.0	1.5
CH	Tr (vertical)	2.5	1.5
	I-O (vertical)	1.5	1.5
KC	Tr (vertical)	1.5	1.0
	I-O (vertical)	0.5	1.0
JC	Tr (vertical)	2.5	0.5
	I-O (vertical)	0.0	0.0
Overall:	Tr (vertical)	2.0	1.0
	I-O (vertical)	1.5	1.5

APPENDIX H:

Error due to Landmark Identification and Axes System Construction for the Video Images:

Image # 110 from subject KC, session 2, medium flange, was randomly selected and remeasured five times. The horizontal and vertical distance of the three landmarks to the axes system are shown, as well as the standard deviation (SD) of the measurements. All measurements are corrected for image reduction.

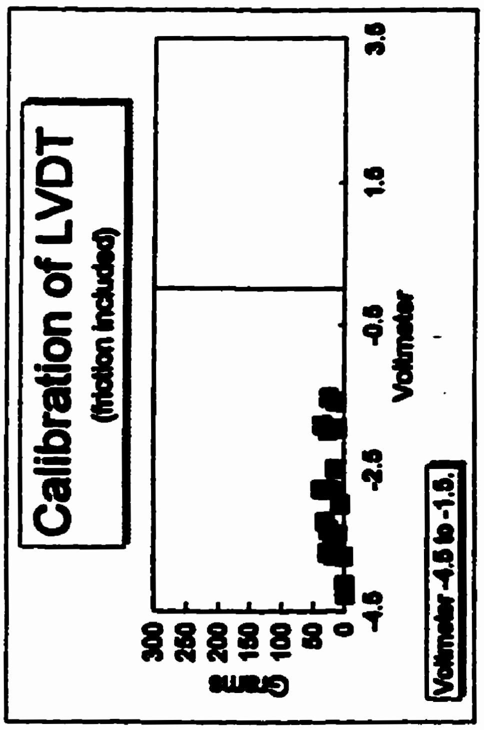
Landmark:

		Horizontal (mm)	Vertical (mm)
Ls	Average	23.9	26.4
	SD	0.4	0.0
Stm	Average	22.0	31.3
	SD	0.0	0.5
Flange	Average	107.0	
	SD	0.3	

SD = standard deviation

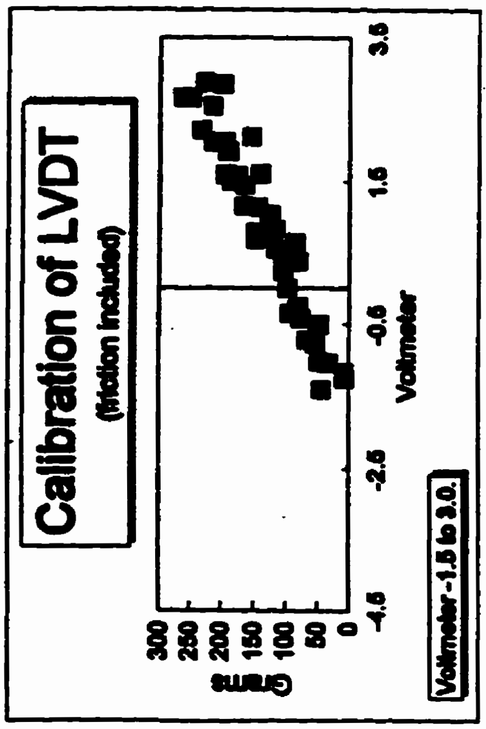
APPENDIX I:

Calibration of LVDT and Determination of Friction Associated with the Apparatus:



Regression line for friction (Voltmeter -4.5 to -1.5):

Regression Output:		
Constant		24.1
Std Err of Y Est		15.0
R Squared		0.1
No. of Observations		26.0
Degrees of Freedom		24.0
X Coefficient(s)	4.1	
Std Err of Coef.	3.4	



Regression line for friction: (Voltmeter -1.5 to 3.0)

Regression Output:		
Constant		90.2
Std Err of Y Est		20.0
R Squared		0.9
No. of Observations		49.0
Degrees of Freedom		47.0
X Coefficient(s)	49.4	
Std Err of Coef.	1.8	

APPENDIX J:

Cephalometric Data:

Pre- to Post-Treatment Horizontal Changes.

Measurements have been adjusted for magnification (9.8 %) and rounded to the nearest 0.5 mm.

Subject	UIP (mm)	UIE (mm)	Ls (mm)	Ls/UIP - %	Ls/UIE - %
KS	4.0	5.0	2.0	50	40
PH	8.5	10.5	4.0	47	38
DR	6.5	8.0	2.0	31	25
JC	4.0	6.0	2.0	50	33
CH	2.0	1.0	0.5	25	50
KC	2.0	2.0	0.5	25	25
JG	5.0	5.0	1.0	20	20
Average	4.6	5.4	1.7	35	33
SD	2.4	3.3	1.2	13	11

KEY:

UIP	Upper Incisor Point
UIE	Upper Incisor Edge
Ls	Labrale Superius
Ls/UIP - %	The percentage of Ls to UIP movement.
Ls/UIE - %	The percentage of Ls to UIE movement.
SD	Standard deviation

APPENDIX K:

Stress:Strain Regression Line Characteristics and Statistical Tests Results:

Overall (Combined Sessions 1 and 2) Data:

Wide Flange

Subject	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	0.04	0.38	0.04	0.03	0.62	0.78	108	p<.001
PH	0.04	0.19	0.03	0.03	0.53	0.70	49	p<.001
DR	0.05	0.30	0.04	0.04	0.47	0.68	65	p<.001
JC	0.06	0.24	0.03	0.02	0.60	0.77	75	p<.001
CH	0.06	0.18	0.04	0.03	0.35	0.59	66	p<.001
KC	0.15	0.30	0.04	0.03	0.84	0.92	69	p<.001
JG	0.30	0.18	0.03	0.02	0.50	0.71	59	p<.001
Average:	0.10	0.25	0.04	0.03	0.56	0.74	70	
SD	0.10	0.08	0.01	0.01	0.15	0.10	19	

Medium Flange

Subject	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	0.03	0.18	0.04	0.03	0.31	0.55	77	p<.001
PH	0.04	0.22	0.03	0.03	0.51	0.70	63	p<.001
DR	0.08	0.27	0.05	0.05	0.35	0.59	62	p<.001
JC	0.06	0.11	0.06	0.04	0.11	0.33	58	p<.05
CH	0.05	0.24	0.03	0.02	0.69	0.83	69	p<.001
KC	0.15	0.17	0.03	0.03	0.37	0.61	44	p<.001
JG	0.03	0.12	0.03	0.02	0.44	0.66	61	p<.001
Average	0.06	0.19	0.04	0.03	0.40	0.60	62	
SD	0.04	0.06	0.01	0.01	0.18	0.15	10	

Narrow Flange

Subject	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	0.01	0.18	0.03	0.03	0.33	0.57	77	p<.001
PH	0.01	0.18	0.02	0.01	0.78	0.89	55	p<.001
DR	0.09	0.32	0.07	0.05	0.45	0.67	56	p<.001
JC	0.03	0.18	0.03	0.03	0.63	0.79	29	p<.001
CH	0.04	0.19	0.03	0.02	0.61	0.78	70	p<.001
KC	0.09	0.18	0.02	0.02	0.60	0.77	53	p<.001
JG	0.01	0.09	0.03	0.02	0.27	0.52	36	p<.001
Average	0.04	0.19	0.03	0.03	0.50	0.70	54	
SD	0.04	0.07	0.02	0.01	0.20	0.13	17	

APPENDIX K (continued):

Flange Displacement:Lip Displacement Regression Line Characteristics and Statistical Tests Results:

Overall (Combined Sessions 1 and 2) Data:

Wide Flange

Subject	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	0.30	0.49	0.83	0.03	0.79	0.89	101	p<.001
PH	-0.04	0.56	0.78	0.02	0.89	0.94	72	p<.001
DR	0.31	0.54	0.64	0.02	0.90	0.95	63	p<.001
JC	-0.12	0.64	0.69	0.02	0.95	0.97	72	p<.001
CH	0.31	0.56	0.70	0.02	0.92	0.96	68	p<.001
KC	0.48	0.67	1.4	0.04	0.80	0.89	63	p<.001
JG	0.03	0.54	0.57	0.02	0.91	0.95	58	p<.001
Average	0.18	0.60	0.80	0.02	0.88	0.90	71	
SD	0.22	0.06	0.30	0.01	0.06	0.03	15	

Medium Flange

Subject	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	0.05	0.41	0.94	0.04	0.62	0.79	79	p<.001
PH	0.49	0.50	0.79	0.02	0.88	0.94	59	p<.001
DR	0.32	0.58	0.77	0.03	0.89	0.94	63	p<.001
JC	-0.06	0.55	1.3	0.05	0.68	0.83	59	p<.001
CH	0.03	0.56	0.88	0.02	0.90	0.95	68	p<.001
KC	0.23	0.68	0.84	0.02	0.90	0.96	63	p<.001
JG	0.21	0.50	0.76	0.02	0.92	0.96	61	p<.001
Average	0.20	0.50	0.90	0.03	0.83	0.91	65	
SD	0.20	0.06	0.20	0.01	0.10	0.07	7	

Narrow Flange

Subject	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	-0.21	0.41	0.94	0.04	0.60	0.78	78	p<.001
PH	0.13	0.46	0.60	0.02	0.90	0.96	51	p<.001
DR	0.45	0.54	0.77	0.03	0.89	0.90	55	p<.001
JC	0.11	0.50	0.50	0.02	0.94	0.97	29	p<.001
CH	0.14	0.60	0.90	0.02	0.91	0.96	68	p<.001
KC	0.50	0.50	1.7	0.02	0.80	0.90	82	p<.001
JG	0.02	0.56	0.65	0.03	0.92	0.96	29	p<.001
Average	0.16	0.50	0.90	0.03	0.85	0.90	55	
SD	0.20	0.07	0.40	0.01	0.10	0.07	21	

APPENDIX L:

Ranking of Subjects Using Slopes of Overall Data:

Ranking of Stress:Strain Slopes:

Wide Flange:

Subject	Slope
JG	0.18
CH	0.18
PH	0.19
JC	0.24
DR	0.30
KC	0.30
KS	0.38

Medium Flange:

Subject	Slope
JC	0.11
JG	0.12
KC	0.17
KS	0.18
PH	0.22
CH	0.24
DR	0.27

Narrow Flange:

Subject	Slope
JG	0.09
PH	0.18
JC	0.18
KC	0.18
KS	0.18
CH	0.19
DR	0.32

Ranking of Flange Displacement:Lip Displacement Slopes:

Wide Flange:

Subject	Slope
KS	0.49
JG	0.54
DR	0.54
PH	0.56
CH	0.56
JC	0.64
KC	0.67

Medium Flange:

Subject	Slope
KS	0.41
JG	0.50
PH	0.50
JC	0.55
DR	0.58
CH	0.58
KC	0.68

Narrow Flange:

Subject	Slope
KS	0.41
PH	0.46
JC	0.50
KC	0.50
DR	0.54
JG	0.58
CH	0.60

APPENDIX M:

Comparison of Subjects Using Wide Flange Data:

Stress:Strain

<u>One-Way Analysis of Variance:</u>

Source	DF	Sum of Squares	Mean Squares	F Ratio	F Prob.	
Between Groups	6	1.023	0.171	7.851	0.00001	S
Within Groups	63	1.368	0.022			
Total	69	2.391				

<u>Multiple Range Test: Scheffe Test with Significance Level 0.05:</u>

Homogenous Subjects (highest and lowest means are not significantly different):

SUBSET 1:						
Subject:	CH	JG	PH	JC	KC	DR
Mean:	0.18	0.18	0.19	0.24	0.30	0.30
SUBSET 2:						
Subject:	KC	DR	KS			
Mean:	0.30	0.30	0.38			

Flange Displacement:Lip Displacement

One-Way Analysis of Variance:

Source	DF	Sum of Squares	Mean Squares	F Ratio	F Prob.	
Between Groups	6	0.236	0.039	5.755	0.0001	S
Within Groups	63	0.431	0.007			
Total	69	0.668				

<u>Multiple Range Test: Scheffe Test with Significance Level 0.05:</u>

Homogenous Subjects (highest and lowest means are not significantly different):

SUBSET 1:						
Subject:	KS	DR	JG	PH	CH	JC
Mean:	0.49	0.54	0.54	0.56	0.58	0.64
SUBSET 2:						
Subject:	PH	CH	JC	KC		
Mean:	0.56	0.58	0.64	0.67		

APPENDIX N:

Comparison of Wide, Medium and Narrow Flange Results Using Overall Data:

Stress:Strain

One-Way Analysis of Variance:

Source	DF	Sum of Squares	Mean Squares	F Ratio	F Prob.	
Between Groups	2	0.021	0.010	2.240	0.135	NS
Within Groups	18	0.083	0.005			
Total	20	0.104				

Flange Displacement:Lip Displacement

One-Way Analysis of Variance:

Source	DF	Sum of Squares	Mean Squares	F Ratio	F Prob.	
Between Groups	2	0.028	0.014	0.070	0.933	NS
Within Groups	18	3.648	0.203			
Total	20	3.677				

APPENDIX O:

Correlation of Stress:Strain and Flange Displacement:Lip Displacement Slopes:

Overall combined data from sessions 1 and 2 for all subjects. i.e. 10 trials per flange (2 sessions with 5 trials per session).

Flange Type	r2	r
Wide	0.02	0.14
Medium	0.02	0.14
Narrow	0.003	0.05

APPENDIX P:

Stress:Strain Regression Line Characteristics and Statistical Tests Results:

Sessions 1 and 2 - Wide Flange Data:

SESSION 1

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p-value
KS	1	0.04	0.35	0.04	0.04	0.58	0.76	50	p<.001
DR	1	0.06	0.35	0.04	0.08	0.52	0.72	37	p<.001
CH	1	0.07	0.33	0.05	0.06	0.45	0.67	31	p<.001
PH	1	0.04	0.32	0.04	0.08	0.59	0.67	35	p<.001
JC	1	0.07	0.22	0.03	0.03	0.49	0.77	39	p<.001
KC	1	0.15	0.14	0.03	0.14	0.49	0.70	26	p<.001
JG	1	0.03	0.19	0.03	0.03	0.60	0.77	29	p<.001
	Average:	0.06	0.27	0.04	0.06	0.52	0.72	35	
	SD	0.04	0.09	0.01	0.04	0.06	0.04	8	

SESSION 2

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p-value
KS	2	0.04	0.41	0.04	0.04	0.66	0.80	56	p<.001
DR	2	0.04	0.24	0.03	0.24	0.55	0.74	26	p<.001
CH	2	0.06	0.15	0.04	0.03	0.43	0.65	33	p<.001
PH	2	0.04	0.29	0.03	0.03	0.77	0.88	32	p<.001
JC	2	0.06	0.25	0.04	0.04	0.60	0.77	34	p<.001
KC	2	0.16	0.19	0.02	0.03	0.65	0.81	25	p<.001
JG	2	0.03	0.16	0.03	0.20	0.39	0.60	28	p<.001
	Average:	0.06	0.24	0.03	0.08	0.58	0.76	33	
	SD	0.04	0.09	0.01	0.08	0.13	0.09	11	

APPENDIX P (continued):

Stress:Strain Regression Line Characteristics and Statistical Tests Results:

Sessions 1 and 2 - Medium Flange Data:

SESSION 1

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	1	0.04	0.23	0.03	0.04	0.44	0.66	39	p<.001
DR	1	0.05	0.25	0.03	0.04	0.55	0.89	29	p<.001
CH	1	0.07	0.29	0.06	0.08	0.30	0.79	31	p<.001
PH	1	0.02	0.14	0.03	0.03	0.40	0.79	32	p<.001
JC	1	0.04	0.23	0.02	0.02	0.74	0.90	34	p<.001
KC	1	0.14	0.13	0.03	0.04	0.37	0.75	20	p<.001
JG	1	0.03	0.11	0.03	0.02	0.49	0.70	29	p<.001
	Average:	0.06	0.20	0.03	0.04	0.47	0.78	31	
	SD	0.04	0.07	0.01	0.02	0.14	0.09	6	

SESSION 2

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	2	0.01	0.21	0.04	0.04	0.37	0.61	39	p<.001
DR	2	0.03	0.21	0.03	0.03	0.62	0.79	29	p<.001
CH	2	0.08	0.25	0.05	0.08	0.40	0.63	31	p<.001
PH	2	0.07	0.29	0.05	0.06	0.40	0.63	32	p<.001
JC	2	0.05	0.25	0.03	0.03	0.66	0.81	34	p<.001
KC	2	0.16	0.12	0.02	0.04	0.32	0.56	20	p<.01
JG	2	0.04	0.14	0.03	0.03	0.43	0.65	29	p<.001
	Average:	0.06	0.21	0.03	0.04	0.46	0.67	31	
	SD	0.05	0.06	0.01	0.01	0.13	0.09	6	

APPENDIX P (continued):

Stress:Strain Regression Line Characteristics and Statistical Tests Results:

Sessions 1 and 2 - Narrow Flange Data:

SESSION 1

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	1	0.01	0.21	0.04	0.04	0.39	0.62	41	p<.001
DR	1	0.01	0.17	0.02	0.01	0.80	0.90	28	p<.001
CH	1	0.06	0.41	0.07	0.07	0.50	0.70	27	p<.001
PH	1	*	*	*	*	*	*	*	*
JC	1	0.04	0.15	0.03	0.03	0.40	0.63	31	p<.001
KC	1	0.09	0.18	0.03	0.03	0.54	0.73	28	p<.001
JG	1	0.01	0.12	0.03	0.03	0.41	0.64	22	p<.005
	Average:	0.04	0.21	0.04	0.04	0.50	0.70	29	
	SD	0.04	0.11	0.02	0.02	0.15	0.10	7	

* No data for subject PH because lip force was not larger than the frictional force of the recording apparatus.

SESSION 2

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	2	0.01	0.12	0.03	0.04	0.24	0.49	34	p<.005
DR	2	0.01	0.19	0.02	0.02	0.76	0.88	27	p<.001
CH	2	0.09	0.25	0.06	0.05	0.46	0.68	27	p<.001
PH	2	0.03	0.18	0.03	0.03	0.63	0.80	29	p<.001
JC	2	0.04	0.21	0.03	0.02	0.73	0.85	37	p<.001
KC	2	0.07	0.24	0.03	0.03	0.69	0.83	25	p<.001
JG	2	0.01	0.04	0.02	0.03	0.14	0.37	12	NS
	Average:	0.04	0.17	0.03	0.03	0.52	0.70	27	
	SD	0.03	0.07	0.01	0.01	0.25	0.20	6	

APPENDIX Q:

Flange Displacement:Lip Displacement Regression Line Characteristics and Statistical Tests Results:

Sessions 1 and 2 - Wide Flange Data:

SESSION 1

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	1	0.55	0.46	0.66	0.03	0.84	0.92	46	p<.001
PH	1	0.10	0.55	0.65	0.03	0.90	0.95	36	p<.001
DR	1	0.40	0.55	0.63	0.02	0.94	0.97	33	p<.001
JC	1	-0.15	0.67	0.82	0.05	0.86	0.93	36	p<.001
CH	1	0.11	0.64	0.77	0.03	0.95	0.98	37	p<.001
KC	1	0.56	0.69	1.60	0.06	0.78	0.88	37	p<.001
JG	1	-0.06	0.50	0.47	0.02	0.94	0.97	28	p<.001
	Average:	0.22	0.58	0.72	0.04	0.92	0.96	32	
	SD	0.26	0.50	0.34	0.02	0.06	0.03	5	

SESSION 2

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	2	0.08	0.52	0.94	0.04	0.77	0.88	53	p<.001
PH	2	0.63	0.50	0.56	0.03	0.94	0.97	25	p<.001
DR	2	0.19	0.58	0.82	0.03	0.90	0.95	33	p<.001
JC	2	-0.10	0.52	0.57	0.02	0.94	0.97	34	p<.001
CH	2	-0.12	0.63	0.57	0.02	0.96	0.98	33	p<.001
KC	2	0.26	0.66	0.92	0.04	0.92	0.96	26	p<.001
JG	2	0.01	0.62	0.53	0.04	0.92	0.96	28	p<.001
	Average:	0.14	0.57	0.70	0.03	0.91	0.95	33	
	SD	0.25	0.36	0.17	0.02	0.06	0.03	10	

APPENDIX Q (continued):

Flange Displacement:Lip Displacement Regression Line Characteristics and Statistical Tests Results:

Sessions 1 and 2 - Medium Flange Data:

SESSION 1

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	1	0.37	0.45	1.00	0.05	0.68	0.82	37	p<.001
PH	1	0.60	0.48	0.90	0.04	0.84	0.92	31	p<.001
DR	1	0.28	0.63	0.70	0.05	0.84	0.92	28	p<.001
JC	1	-0.45	0.42	0.66	0.05	0.75	0.87	25	p<.001
CH	1	0.14	0.60	1.1	0.04	0.87	0.93	33	p<.001
KC	1	0.00	0.66	0.77	0.03	0.93	0.96	33	p<.001
JG	1	0.18	0.47	0.71	0.02	0.93	0.96	30	p<.001
	Average:	0.16	0.53	0.97	0.05	0.83	0.91	31	
	SD	0.34	0.58	0.27	0.02	0.09	0.05	4	

SESSION 2

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	2	-0.27	0.39	0.65	0.04	0.71	0.84	40	p<.001
PH	2	0.32	0.52	0.60	0.03	0.93	0.96	26	p<.001
DR	2	0.33	0.57	0.83	0.03	0.90	0.95	33	p<.001
JC	2	0.20	0.69	0.99	0.05	0.86	0.93	32	p<.001
CH	2	-0.07	0.58	0.62	0.03	0.94	0.97	33	p<.001
KC	2	0.73	0.63	0.83	0.04	0.92	0.96	28	p<.001
JG	2	0.26	0.54	0.75	0.03	0.93	0.96	29	p<.001
	Average:	0.21	0.56	0.83	0.04	0.88	0.94	32	
	SD	0.35	0.45	0.26	0.03	0.08	0.04	5	

APPENDIX Q (continued):

Flange Displacement:Lip Displacement Regression Line Characteristics and Statistical Tests Results:

Sessions 1 and 2 - Narrow Flange Data:

SESSION 1

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	1	-0.38	0.44	0.69	0.04	0.77	0.88	40	p<.001
DR	1	0.22	0.42	0.74	0.03	0.87	0.93	23	p<.001
CH	1	0.28	0.62	0.65	0.03	0.92	0.96	25	p<.001
PH	1	*	*	*	*	*	*	*	*
JC	1	0.15	0.65	1.24	0.06	0.84	0.92	29	p<.001
KC	1	1.10	0.50	1.90	0.05	0.74	0.86	42	p<.001
JG	1	0.00	0.60	0.72	0.05	0.91	0.95	18	p<.001
	Average:	0.23	0.54	1.10	0.04	0.84	0.80	25	
	SD	0.48	0.40	0.48	0.03	0.07	0.35	10	

* No data for subject PH because lip force was not larger than the frictional force of the recording apparatus.

SESSION 2

Subject	Session	Y-int.	Slope	SE-Y	SE-X	r2	r	df	p value
KS	2	-0.02	0.38	1.20	0.06	0.39	0.62	34	p<.001
PH	2	0.06	0.48	0.48	0.02	0.96	0.98	26	p<.001
DR	2	0.47	0.49	0.79	0.03	0.89	0.94	28	p<.001
JC	2	0.11	0.50	0.51	0.02	0.94	0.97	29	p<.001
CH	2	0.05	0.58	0.35	0.01	0.99	0.99	35	p<.001
KC	2	-0.08	0.52	1.07	0.03	0.91	0.95	38	p<.001
JG	2	-0.01	0.56	0.54	0.04	0.96	0.98	9	p<.001
	Average:	0.08	0.50	0.76	0.04	0.86	0.92	28	
	SD	0.18	0.48	0.30	0.03	0.20	0.10	10	

APPENDIX R:

Ranking of Subjects Using Stress:Strain Slopes for Session 1 and 2 Data:

Ranking of Stress:Strain Slopes For Sessions 1 and 2:
(Wide Flange)

Subject	Session	Slope	Subject	Session	Slope
KC	1	0.14	CH	2	0.15
JG	1	0.19	JG	2	0.16
JC	1	0.22	KC	2	0.19
PH	1	0.31	DR	2	0.24
CH	1	0.33	JC	2	0.25
DR	1	0.35	PH	2	0.29
KS	1	0.35	KS	2	0.41

Ranking of Flange Displacement:Lip Displacement Slopes for Sessions 1 & 2:
(Wide Flange)

Subject	Session	Slope	Subject	Session	Slope
KS	1	0.46	DR	2	0.50
JG	1	0.50	KS	2	0.52
CH	1	0.55	PH	2	0.52
DR	1	0.55	CH	2	0.56
JC	1	0.64	JG	2	0.62
PH	1	0.67	JC	2	0.63
KC	1	0.69	KC	2	0.66

APPENDIX S:

Comparison of Session 1 versus 2 Results Using Wide Flange Data:

Stress:Strain

One-Way Analysis of Variance:

Source	DF	Sum of Squares	Mean Squares	F Ratio	F Prob.	
Between Groups	1	0.003	0.003	0.445	0.517	NS
Within Groups	12	0.092	0.008			
Total	13	0.095				

Flange Displacement:Lip Displacement

One-Way Analysis of Variance:

Source	DF	Sum of Squares	Mean Squares	F Ratio	F Prob.	
Between Groups	1	0.023	0.023	0.123	0.732	NS
Within Groups	12	2.273	0.189			
Total	13	2.297				

APPENDIX T:

Lip Properties for Comparison of Predicted and Measured Anteroposterior Lip Movement:

Subject	CLR	Trans.	{1/Trans.}	F:L Slope	F/L Ratio	ATR	TLM	DIFF.
KS	2.0	27.5	0.036	0.49	0.018	69	1.5	0.5
PH	4.0	28.0	0.036	0.56	0.020	163	4.0	0.0
DR	2.0	28.0	0.036	0.54	0.019	76	1.5	0.5
JC	2.0	21.0	0.048	0.64	0.031	64	2.0	0.0
CH	0.5	27.0	0.037	0.56	0.021	23	0.5	0.0
KC	0.5	24.0	0.042	0.67	0.028	48	1.0	0.5
JG	1.0	38.0	0.026	0.54	0.014	32	0.5	0.5
Average	1.5	27.6	0.040	0.60	0.03	68	1.3	0.3
SD	1.2	5.2	0.007	0.06	0.01	46	0.8	0.3
% Var.	80	19	18	10	33	68	57	100

KEY:

CLR	Ls movement from the pre- to post-treatment cephalograms (mm).
Trans	Transverse distance between distolabial surfaces of right and left lateral incisors (mm).
F:L Slope	Overall flange displacement:lip displacement regression line slope for the wide flange.
F/L Ratio	Product of flange displacement:lip displacement slope and 1/Trans (1/mm).
ATR	Area of tooth retraction as measured on pre- and post-treatment occlusograms (mm2).
TLM	Theoretical lip movement = product of F/L ratio and ATR (rounded to nearest 0.5 mm).
DIFF.	Absolute value (theoretical - measured lip movement) = TLM - CLR.
SD	Standard deviation.
% Var.	Percent variation (SD/Average).

Correlation of TLM and CLR:

$r = 0.95$

APPENDIX U:

Lip Properties for Comparison of Predicted and Measured Anteroposterior Lip Decompression:

Subject	E (1,2)	ATR	LP	Decomp.
KS	0.38	69	26.2	1.4
PH	0.19	163	31.0	4.2
DR	0.30	76	22.8	2.5
JC	0.24	64	15.4	0.7
CH	0.18	23	4.1	-0.2
KC	0.30	48	14.4	1.5
JG	0.18	32	5.8	0.5
Average	0.25	68	17.1	1.5
SD	0.08	46	10.1	1.5
% Var.	32	68	59	100

KEY:

E (1,2)	Slope for overall wide flange stress:strain regression line (g/mm2).
ATR	Area of tooth retraction as measured on pre- and post-treatment occlusograms (mm2).
LP	Lip Product (E (1,2) multiplied by ATR) (g). [This represents compressibility of the upper lip]
Decomp.	Change in vermilion lip thickness from pre- to post-treatment cephalogram (mm).
SD	Standard deviation.
% Var.	Percent variation (SD/Average).

Correlation of Lip Decompression to LP:

$r = 0.95$