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AN INVESTIGATION OF THE POSTERIOR COMPONENT OF OCCLUSAL FORCE

by

John Joseph Conroy

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Orthodontics in the Graduate College of The University of Iowa

May 1994

Thesis supervisor: Associate Professor Thomas Southard

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

John Joseph Conroy

has been approved by the Examining Committee for the thesis requirement for the Master of Science degree in Orthodontics at the May 1994 graduation.

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To Jennifer, my wife and best friend, and to the life we are creating through our love.

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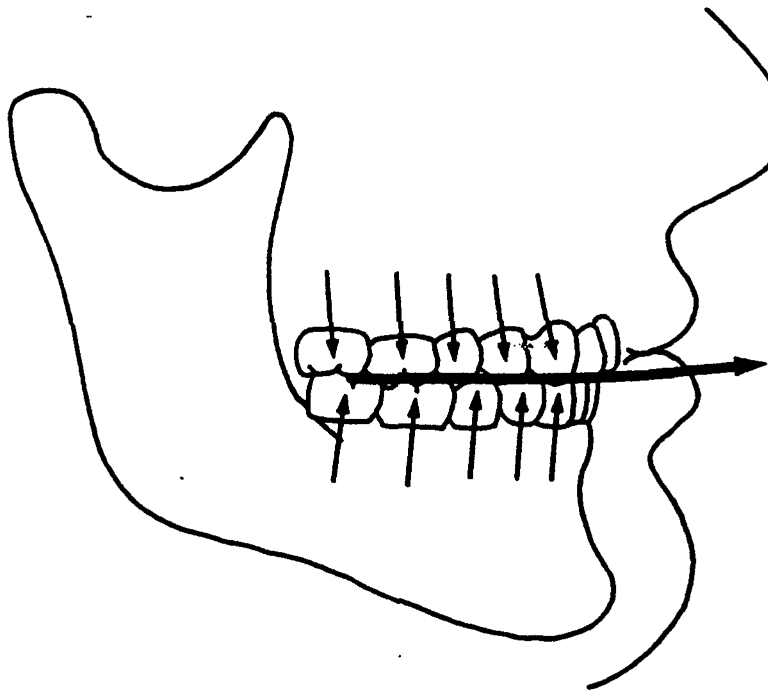
CHAPTER I

INTRODUCTION

Most authors acknowledge that movement of teeth, beyond that caused intentionally through application of fixed or removable orthodontic appliances, can be attributed to multifactorial components of force. Proffit (1978) noted that four primary factors influence the equilibrium position of the dentition: 1. intrinsic forces by the tongue and lips, 2. extrinsic forces such as habits or orthodontic appliances, 3. dental occlusion forces, and 4. periodontal membrane forces. A stable occlusion would purportedly result when balance in terms of the magnitude, duration, and direction of forces is achieved between those factors.

The possible role of occlusion in precipitating dental movements has been reported upon extensively in the literature, beginning with Edward Angle. While many bite force studies have focused on vertical occlusal forces during maximal effort, normal chewing, and/or swallowing, other studies have examined other aspects of bite force.
Trauner (1912) suggested that the causes of progressive movements of the teeth toward the front were related to the center of gravity of mandibular molars being located anterior to, rather than axially above, their roots. Stallard (1923) suggested that anterior drift of the dentition was caused by an anterior component of masticatory force related to axial inclinations of mandibular and maxillary teeth. He hypothesized that the arc of mandibular closing motion into occlusion would result in an anterior component of occlusal force on mandibular posterior teeth. Osborn (1961) investigated interdental forces for subjects with their jaws relaxed and with their jaws clenched. He concluded that "it can be deduced that all the cheek teeth were subjected to a mesial force under the

Figure 1. The anterior component of occlusal force



(Southard et al 1989)

conditions of the experiment." Burdi and Mayers (1988) proposed that the magnitude of the anterior component of occlusal force was influenced by the steepness of the occlusal plane. Southard et al (1989) was the first to quantify the anterior component of occlusal force as had long been theorized. They developed a methodology to measure the distribution of the anterior component of occlusal force from frictional force measurements of interproximal contact tightness both at rest and with the axial loading of the mesiobuccal cusp of the mandibular left second molar. The existence of an anterior component of occlusal force was demonstrated to have a distribution and dissipation that approximated an exponential decay function and which increased at a wider gape. They suggested that the anterior component of force distribution and dissipation curves should shift to maintain similar shape distribution in cases where teeth are missing but contacts maintained or when teeth anterior to the second molar are axially loaded. Southard et al (1990a) correlated anterior component of occlusal forces with dental malalignment. Tighter contacts between molars and premolars, both at rest and when recorded after axial loading of the second molar, were generally associated with increased incisor irregularity.

The purpose of this investigation is to investigate the effects on interdental forces of sequentially loading each tooth in a mandibular arch quadrant with a known bite force. The distribution and magnitude of an anterior component of occlusal force will be determined and compared with the findings of Southard et al (1989) who described an anterior component of occlusal force based on loading only second molars. Examination of interproximal contact forces posterior to the bite force loaded teeth will provide an opportunity to establish and quantify a posterior component of occlusal force.

CHAPTER II

REVIEW OF THE LITERATURE

Bite Force Measurement

Human bite force has been the focus of extensive research, and increasingly sophisticated bite force measuring techniques and study designs have allowed factors involved in generation of bite force to become better understood. Fields et al (1986) noted that study of human interocclusal forces began over three hundred years ago. They noted that early experiments were conducted using bulky instrumentation which required large vertical opening and measured bite force b iechanical compression of spring or hydraulic meters. Ahlgren and Owall (1970) used recordings of masticatory loads recorded by a piezoelectric transducer mounted in a metal crown. This provided the advantage of not having to insert a bite force registration device between the dental arches and allowed for more physiologic bite force measurements. The disadvantages of such an approach included cost, the need for a second procedure to remove and replace the crown, and the fact that it would be impractical and unethical to measure bite forces at different dental arch locations with such instrumentation. With advancing electronic technology, quartz and foil transducers incorporated into lever type transducer instruments have been most commonly employed to measure bite force (Blamphin et al 1990). For example, Dechow and Carlson (1983) described their use of a bite force transducer with two 350 ohm single element strain gauges connected in a full bridge configuration, asserting that each steel beam could then function as a differential strain beam.

Bite force researchers have studied multiple aspects of bite force and have used diverse methodologies. Wide discrepancies in bite force measurements are attributable, at least in part, to different techniques employed (Bates 1975). Pruim et al (1978, 1980) conducted experiments on human males with bilateral static bite force loads using two transducers and covering the upper and lower dentitions with ac[illegible] splints in order to keep the transducers properly positioned. Their study was the fir[illegible]o measure bilateral instead of unilateral bite forces; they recorded higher bite force magnitudes than had been reported in earlier studies. Corrucini et al (1985), in their study of Punjabi Indians, used a bite force transducer consisting of two 120-ohm-foil strain gauges connected in series and bonded to opposite sides of a bite block to eliminate inaccuracies that might be caused if a subject were to bite nearer to an edge rather than the center of the bite block. Biting closer to an edge might have caused bending instead of straight compression of the bite block; the two strain gauges connected in series corrected for possible bending effects. Blamphin et al (1990) noted several characteristics desirable for a bite force measurement instrument: one that requires a small amount of jaw opening, is small enough to allow free access to all areas of the dentition, is simple to use, is comfortable for subjects, is easily cleaned, and is sterilizable. They developed a gnathodynamometer which incorporated all of the above features for measuring maximum occlusal forces. Van Eijden et al (1988 ,1990, 1991) developed a three-component force transducer which registered both the direction and magnitude of maximum bite force, allowing for measurement of human subjects bite force in seventeen precisely defined directions.

Bite Force Studies

Research methodologies employed in evaluating bite forces have applied forces to different teeth in different ways. Factors such as the tooth or teeth loaded, the duration of loading time, dimensions of the measuring instrument, and types of biting have been investigated. Corrucini et al (1985) measured normal chewing forces and maximum bite forces of three seconds duration centered on the mandibular right first molar and accomplished between 9:00 am and 12:30 pm. They found that replicate measurements on a different day on a subsample of their subjects yielded a good correlation ($r = 0.81$) for maximum bite force but a poor correlation ($r = 0.33$) for normal chewing forces. Ahlgren and Owall (1970) measured chewing cycle forces in 3 subjects masticating both homogenous boluses (chewing gum) and non homogenous boluses (peanuts) as well as the time interval between the chewing cycle phases with the transducer mounted in a metal crown on the upper right second premolar. They concluded that maximum bite force occurred in the intercuspal position and noted that chewing a non homogenous bolus such as peanuts into progressively smaller pieces made it impossible to reliably measure masticatory force. Proffit et al (1983) noted that thin occlusal force transducers with 30 micron thick polyvinylidine fluoride piezoelectric foil incorporated into a 0.5 mm thick transducer had problems with damage under maximum biting force and inaccurate data due to directional deformations. Their laboratory developed 2.5 mm and 6.0 mm quartz transducers to record occlusal forces during swallowing, simulated chewing, and maximum effort by loading the distobuccal cusp of the mandibular right or left first molar. Dechow and Carlson (1983, 1990) stimulated unilateral twitch and tetanic masticatory muscles contractions in 132 anesthetized rhesus monkeys and recorded maximal bite forces at central incisors, first premolars, and the most posterior occluding molar cusps with a 9 mm distance between the occluding teeth being measured. They demonstrated that a force plateau could be achieved which allowed approximate unilateral maximal firing of all masticatory muscles without activating contralateral muscles thus allowing maximal unilateral bite force to be recorded. The potential confounding influence of a psychological or voluntary inhibition of maximum bite force was eliminated by their subject selection and methodology. Fields et al (1986) examined unilateral vertical occlusal forces for groups of children, adolescents, and young adults during swallowing and normal chewing as well as maximal unilateral biting forces using 2.5 mm and 6.0 mm transducers. They reported on the effects of 5 mm incremental increases in interocclusal distances between 10 mm and 40 mm on maximal bite force in eight young adult males in order to document the effects of changes in gape upon maximum bite force. They also investigated the effects on maximal bite force of supporting the contralateral occlusion and changes in head posture. Table 1 summarizes different research methodologies employed in past bite force studies.

Factors Influencing Bite Force Magnitude

The results of research studies which employed differing technologies and methodologies to measure bite force have yielded insight into factors which can contribute to and/or modify bite force. Bite force has been reported to be influenced by physiologic factors, morphologic factors, environmental factors, and genetic factors.

Physiologic Factors

The influence on bite force generation of physiologic factors such as mode of respiration, pattern of mastication, masticatory muscle strength, and loading of the temporomandibular joint have been investigated. The results of those studies yield insight into factors which can contribute to and/or modify bite force. Corrucini et al (1985) reported differences between mouth breathers (diagnosed on history plus and one of a list of clinical criterion) and normal breathers; although no consistent difference was noted, greater bite-force variation was seen in the "mouth breather" groups. Ingervall et al (1989) established that no association existed between bite force and mouth breathing; they showed both of those factors to be associated with facial morphology. Ingervall et al diagnosed mouth breathing based upon history, rhinomanometrically determined nasal airflow and cephalometric measurements of the airway. The more accurate methodology used by Ingervall et al to diagnose mouth breathing suggests that their conclusions may be more valid.

The orthodontic literature had debated whether or not the temporomandibular joint was actually load bearing. Boyd et al (1990) proved that the temporomandibular joints of monkeys were load bearing of significant forces during function. Incisal biting resulted in measured temporomandibular joint loads of 28.5 lbs (13.0 kg) which were less than the loads measured for chewing 34.5 lbs (15.7 kg) and for "feisty vocal aggression" 39.0 lbs (17.7 kg). The authors noted that incisal biting causes slight superior and anterior condylar movements as well as loading of the condylar head. Katona (1989) discussed the significance of direction of bite force in affecting the force vectors acting on the occlusion and the temporomandibular joint. He noted that, under very specific loading conditions, forces on teeth could be expected to increase posteriorly. His mathematical model purportedly could be employed to explain experimental observations of the teeth and TMJ to bite force transducer application.

Morphologic Factors

Orthodontic researchers have for decades attempted to correlate morphologic factors with in vivo observations. Studies of bite force have focused on the influence of gape, anterior face height and other facial dimensions, cephalometric angles, tooth loaded, and amount of occlusion.

Gape in bite force studies has been determined by the dimensions of the transducers used. A synopsis of transducer widths employed can be seen in Table 1. Improvements in technology have allowed interocclusal forces to be registered for physiologic occlusion, such as swallowing and chewing, in addition to studies of maximum occlusal bite force. Proffit et al (1983) found no significant differences in bite force between 2.5 mm and 6.0 mm intercuspal separations. Dechow and Carlson (1983, 1990) reported that increases in gape had resulted in no significant change in bite force, contrasting with expected results. Fields et al (1986) noted that increasing the vertical opening from 10 mm to 40 mm at 5 mm increments for a sample of eight young adult males yielded higher mean maximum bite forces at 20 mm opening and at 40 mm opening. The authors suggested that orientation and function of masticatory muscles and facial soft tissues may have been responsible for the data collected. A combination of condylar rotation and translation in adapting to increased gapes for production of given bite forces may also have contributed to the biphasic data collected. The role of gape beyond normal physiologic functional limits producing characteristic maximum bite force patterns may be considered reflective of experimental methodology rather than of orofacial physiology. The trend of researchers employing newly developed transducers of progressively smaller dimensions demonstrates an interest in understanding physiologic responses of masticatory functions rather than responses to artificially created

Table 1. Bite Force Study Methodologies

Researchers	Subjects	Experimental versus controls	Teeth Loaded	Transducer Width	Measured
Ahlgren & Owall (1970)	3 adult	No	# 4	mounted in tooth	Maximal bite force chewing peanuts, gum
Garner & Kotwal (1973)	150 10-25 year old	Sex, Age	# 8		Maximum incisal bite force
Pruim et al (1980)	7 male dental students	No	#18, 19, 21, 28 30, 31		Maximum bite force
Proffit et al (1983)	40 young adults	Normal versus long anterior face height	distobuccal cusp # 19 or 30	2.5 mm 6.0 mm	Swallow bite f. Chew bite f. Maximum b. f.
Dechow & Carlson (1983, 1990)	132 rhesus monkeys	Sex, Age	incisors first premolars distal molars	9.0 mm	Maximal bite force
Corrucini et al (1985)	255 adolescents	Rural versus Urban, Sex, +/- Mouthbreather	# 30	13.0 mm	Chew bite f. Maximum b. f.
Fields et al (1986)	17 children 10 adolescents 21 young adults	Sex Age	right first molars	2.5 mm 6.0 mm	Swallow bite f. Chew bite f. Maximum b. f.
" " "	8 adult males	change vertical opening	right first molars	from 10.0 mm to 40.0 mm in 5.0 mm increments	Maximum bite force
" " "	10 adolescents	+/- bilateral support	right first molars	2.5 mm 6.0 mm	Swallow bite f. Chew bite f. Maximum b. f.
" " "	10 adolescents	change head posture	right first molars	2.5 mm 6.0 mm	Swallow bite f. Chew bite f. Maximum b. f.
Blamphin et al (1990)	26 adults	Sex Dentate versus edentulous	Maxillary first molars R + L Maxillary first premolars R+L Maxillary central incisor	4.0 mm	Maximum bite force
Dean (1992)	141 adults	Controls versus Orthognathic surgery patients	Central incisors R + L first molars	15.0 mm	Maximum bite force

experimental conditions. While biphasic data have been produced for experimental changes in gape, little information of clinical significance can be inferred from those findings.

Facial morphology and concomitant correlations of masticatory muscle strength and bite force generation has been reported. Proffit et al (1983) had shown that differences in bite force magnitude existed between long anterior face height subjects and subjects of normal facial vertical dimensions and concluded that the differences could be explained by differences in masticatory muscle strength. Investigators have also impugned respiratory functional requirements in the development of long anterior vertical face height dimensions with subsequent masticatory muscle weakness. For long face adults, bite forces were significantly less. Ingervall and Helkimo (1978) characterized differences between the 25 strongest (mean maximum bite force 728N) and the 25 weakest (mean maximum bite force 380N) bite force subjects from an original population of 100 young adult males. They noted more variance in facial form in the weak group. The strong group was found to have shorter anterior face height, greater posterior face height, flatter mandibular plane angle, smaller gonial angle, and a broader maxilla. The authors hypothesized that facial form, particularly face height and mandibular inclination, may be developed in response to muscle strength and function. Orthognathic surgery patients differ morphologically from normal control subjects. Dean et al (1992) showed that patients scheduled for orthognathic surgery had significantly lower maximum bite forces compared with controls of the same sex. The magnitude of bite force is related to the strength of masticatory muscles and their efficiency in producing a closing movement. Differences reported in the literature in magnitude of bite force generated by morphologically different facial types are consistent with expected results.

Although the findings of studies of bite force which loaded different teeth cannot be directly compared due to methodologic differences, an understanding of some general concepts can be appreciated. Pruim et al (1980) recorded bilateral static maximum bite forces on different teeth and they found the highest mean bite force on first molars (965N) followed by second molars (756N) and first premolars (633N). The authors noted that with a static bite force, there can be only one optimum maximum bite position. They determined that position is at or near to the first molar. Corrucini et al (1985) noted a range of maximal bite forces from 22.35 kg (urban females) to 37.18 kg (rural males) and a range of normal chewing forces of 6.74 kg (urban females) to 12.35 kg (mouth breather rural males). Proffit et al (1983) reported mean normal swallow occlusal force at 2.5 mm opening to be 2.9 kg, chewing force to be 13.5 kg, and maximum bite force to be 31.0 kg. For normal-face adults at 6.0 mm opening, bite forces were slightly, but not significantly, larger. Garner and Kotwal (1973) documented a mean maximum incisive biting force for their sample of 150 subjects to be 35 pounds. Dechow and Carlson (1983, 1990) noted that maximal molar bite forces were two to two and one half times greater than maximal forces measured at incisors. Blamphin et al (1990) demonstrated that, for young male subjects, mean maximal maxillary left first molar biting force (495 N) was greater than mean maximal maxillary first premolar biting force (404 N) and mean maximal maxillary central incisor biting force (222 N). Van Eijden (1991), in his study of bite force magnitude in three dimensions, noted that vertical forces generally generated the largest bite force moments. His findings indicated greater mean maximal bite force for second molars (range 475-749 N) versus second premolars (range 424-583 N) and canines (range 323-485 N). He noted that, for any given bite location and direction measurement, the maximum bite force displayed a wide variation between individual subjects. His results demonstrated that the total moment of the bite force is dependent on both the bite-point location and bite-force direction. The bite-force moment was found to be largest in a vertical direction, of smaller magnitude in an anterior direction, and smallest in a posterior direction. This was noted despite greater bite forces being recorded in a posterior direction versus an anterior direction. Van Eijden explained the apparent contradiction by noting the much smaller muscular resistance arm of the posteriorly directed bite force. The range of mean maximal bite forces reported reflects the differences in methodologies employed. First molars consistently were reported to produce the largest maximal bite force, supporting Pruim's assertion of one optimum maximum bite position. Significant differences between swallowing, chewing, and maximum bite forces were observed as expected. Maximum molar bite force was consistently greater than twice the magnitude of maximum incisor bite force as observed in multiple studies. The observation of wide variation between individual subjects is consistent with the range of variation for morphological characteristics. The importance of not only the bite point location but also the bite force direction in understanding the mechanism of bite generation is now better appreciated.

The amount of occlusal contact may be related to the maximum amount of bite force produced by a given tooth. Garner and Kotwal (1973) correlated maximum incisive biting forces with the amount of linear anterior occlusion showing that greater linear contact of the incisor edges yielded greater bite forces. Fields et al (1986) found no significant differences for bite forces recorded with and without contralateral support. The maximum bite force findings of Pruim et al (1980) were higher than others reported with the explanation suggested that bilateral biting had contributed to the higher results. First molars have the largest occlusal table surface area as well as the largest maximum bite force. Future studies may be able to correlate bite force with occlusal contact area which intuitively would be expected.

Environmental Factors

Cross sectional studies of selected populations has revealed possible environmental influences on orofacial function. Corrucini et al (1985) demonstrated higher maximal bite forces and chewing forces for his rural Punjabi adolescent sample versus a matched urban sample. Similar results were observed in a study of rural Kentuckians (Corrucini et al 1978). The role of the consistency of diet in developing efficient masticatory function has been suggested based on the results of these and similar studies. The study of Blamphin et al (1990) demonstrated greater mean maximal biting forces for dentate subjects versus denture wearing subjects. Similar studies have found identical results in the prosthodontic literature.

Genetic and Growth Factors

Differences between maximal bite force generation and functional bite forces for different age and sex distributions have been reported. Dean et al (1992) noted that male controls had higher molar maximum bite forces (50 kp) and nearly equal maximum incisor bite forces (15 kp) as female controls. The authors defined their unit of bite force measurement, the kilopond (kp), as the unit of force equivalent to 1 kg of weight. Garner and Kotwal (1973) correlated maximum incisive biting forces with age and sex. With increased age, maximum incisive biting forces increased up to the highest mean value (50 pounds) recorded for the 25 year old males in the sample. Males tended to have higher maximum incisive bite forces. The study of Blamphin et al (1990) confirmed greater mean maximal biting forces for males versus females. Fields et al (1986) showed that adults had significantly greater bite forces (swallowing 2.9 kg, chewing 13.5 kg, maximum 31.0 kg) than those seen in adolescents (swallowing 1.8 kg, chewing 7.3 kg, maximum 14.5 kg) and children (swallowing 1.9 kg, chewing 7.2 kg, maximum 14.5 kg). Dechow and Carlson (1983,1990) indicated that adult monkeys generated twice the maximal incisor bite force (140 N) as did juvenile monkeys (70 N). Corrucini et al (1985) reported a sex difference, with male mean bite forces being greater than those recorded by environmentally similar female groups. Consistent findings of mean male greater than mean female bite force and adult greater than juvenile bite force have been noted. Morphologic differences may be expected to exist between those different groups. Thus, although the differences observed between sexes and ages of populations may be attributed to genetics and growth, morphologic features such as muscle mass or orientation and/or masticatory muscle lever functions may be related to bite force generation.

Factors Associated with the Anterior Component of Occlusal Force

A methodology to quantify the anterior component of occlusal force being so recently developed, few investigations have been conducted to explore and describe factors involved with anterior component of occlusal force generation. Southard et al (1990b) used regression and correlation analyses to investigate influences on the anterior component of occlusal force. Factors suggested by a review of the literature, ie, steepness of the occlusal plane angle, condylar axis height, and second molar root axial inclination were not found to significantly correlate with the anterior component of force measured between the mandibular left second premolar and first molar while loading the mandibular left second molar. They found that mandibular second molar root width, increased bite force, resting interproximal force, and increased gape did correlate with an anterior component of occlusal force. Increased second molar root width resulted in decreased anterior component of occlusal force. The investigators determined that the anterior component of occlusal force increases were proportional to bite force increases. This was important in that it demonstrated that the anterior component of occlusal force was a physiologic phenomenon which responded to changes in functional physiologic parameters rather than solely a function of morphologic factors.

Physiologic Interproximal Contact Tightness

The premise that interproximal dental forces could be measured, introduced by Osborn in 1961, was refined by Southard et al in their description of an anterior component of occlusal force. Their interest in the physiologic role of interdental forces lead to further studies. The effects of posture on interproximal resting (not biting) contact tightness were reported by Southard et al (1990c). They measured posterior interproximal contacts on subjects seated upright, then placed supine, and returned to upright seated position. Contacts were shown to decrease in tightness upon return to upright posture. The effects were more pronounced more distally in the dental arches. The myth that the presence of mandibular third molars caused increased interproximal contact tightness which would lead to mandibular incisor crowding was debunked by Southard et al (1991, 1992) utilizing the instrumentation developed to quantify the anterior component of force. They demonstrated that mandibular third molars do not cause an anterior component of occlusal force consistent with the amount of force that would be necessary to cause mandibular incisor crowding. Their findings again indicated that interproximal contact tightness varied with postural changes (1992). Interproximal contact tightness was thus demonstrated to exercise an active role in response to physiologic changes in posture.

The Significance of an Anterior Component of Occlusal Force

The significance of an anterior component of occlusal force - from both historical and contemporary perspectives - is that many orthodontists believe that an anterior component of occlusal force could contribute to increased incisor crowding over time. Little et al (1976) demonstrated that at 5, 10, and 20 years post-orthodontic retention, mandibular incisors tended to display increasing Irregularity Index scores. Orthodontists have long observed that a functional occlusion may, over time, exhibit incisor irregularity, as described by Little et al. Other authors looked for other explanations.

The role of gingival fibers and muscular soft tissue influences was championed by devotees of the functional matrix theory. Moss and Picton (1971) demonstrated mesial drift of teeth in adult monkeys when forces from the occlusion, cheeks and tongue had been eliminated. They interpreted their observations of mesial inclination of molars without occlusal contacts and interproximal contacts as being evidence that mesial drift would occur without an anterior component of occlusal force. A 1973 study by Picton and Moss did demonstrate that greater approximal migration of molars occurred when occlusal surfaces were substantially sloped to yield a horizontal component of occlusal force. However, they determined that traction of the transseptal fiber system played a more substantial role than occlusal forces. Subsequent studies by the same investigators (1974, 1978, 1980, 1981) implicated fibroblasts of gingival transseptal fibers in causing movement of molar teeth.

While Southard et al (1990a, 1990b) found a correlation between the anterior component of occlusal force and incisor irregularity, second molar root width, resting interproximal force, and increased gape no cause and effect relationships were established. The mechanism of distribution of interdental forces during loading of a single tooth or multiple teeth requires differential compression of periodontal ligament spaces and movement, bodily and/or tipping, of teeth. The significance of transient force applications, resulting in momentary movements and subsequent rebounds, has not been established. Parafunctional clenching or bruxing habits of increased force magnitude or duration may have more significant influences upon the force distribution effects on the dentition. Although the contribution of bite point location to the magnitude and direction of bite force has come to be appreciated (van Eijden 1990), no studies to date have sequentially loaded all of the teeth in a dental arch to observe potential changes in interproximal forces.

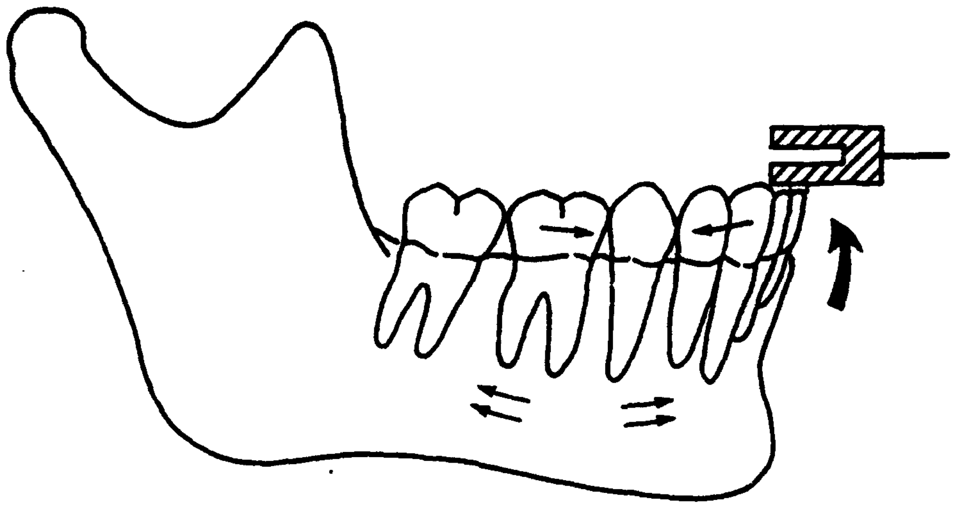
Mandibular Flexure

As a vital structure, the mandible has been shown to undergo deformation upon loading. Conceptually, bending of the mandible at its midsagittal position, near the first molar site, might be implicated in causing changes in dental interproximal contact tightnesses (Figure 2). Southard et al (1990b) assumed that the anterior component of occlusal force was transmitted to anterior teeth via interdental contacts and mesial tilting of the bite force loaded second molar. They dismissed the hypothesis that mandibular flexure could compress the dentition because they did not note increasing interproximal forces anterior to open dental contacts.

Recent studies have investigated the magnitudes and directions of forces associated with biting forces. Throckmorton et al (1980) discussed influences such as ramus height and relative mechanical advantages of temporalis and masseter muscles for skeletally different points in pointing out the bite force mechanical disadvantages of long anterior face height subjects. Mathematic modeling of mandibular function as a two-dimensional lever was reviewed by Hylander (1975) who suggested the mandible could be accurately modeled as a lever but not as a link between temporalis and masseter muscle groups. Andersen et al (1990) used a "multiple modeling technique" to generate geometrical finite element models of the mandible representing compact and trabecular bone parts. They found linearity in mandibular stress-strain response to varying moment/force ratio applications. Swallowing forces (5 N) produced little stress-strain mandibular response. Simulated low, constant orthodontic forces of one Newton produced mandibular stress levels much less than those created by intermittent chewing forces (50 N). Physiologic chewing function was shown to result in stresses in the mandible of ten times the magnitude of swallowing forces. Whether or not those increased stresses may contribute to mandibular alveolar deformation resulting in interdental contact tightness changes has not been determined.

In order for mandibular flexure upon biting to be considered as a possible explanation for changes in dental relationships upon biting, evidence of true loading of the temporomandibular joint with biting was needed. Boyd et al (1990) proved that the temporomandibular joints of monkeys bore loads during function that were highest for nonmasticatory activities. They noted the condyles were positioned slightly anterior and superior for incisal biting. Noting different loading of the condyle and condylar positions at incisal bite versus molar bite is consistent with the results of Fields et al (1986) whom

Figure 2. Mandibular flexure with bite force load



described multiphasic maximum bite forces for increasing gapes.

While studies of mandibular bending and mathematical modeling of that phenomenon had often focused on sagittal relationships, the mandible in vivo functions in three dimensions. Hobkirk et al (1991) recognized patterns of mandibular deformation described in the literature that included symphyseal bending, symphyseal shear, and symphyseal twisting. They noted that mandibular distortion can result in changes in the relationships of the dental arch across the midline and examined mandibular deformation in subjects with osseointegrated implants. The authors found that, with maximum opening, protrusion, and lateral excursions from rest positions, forces as high as 16 N were reached with relative displacement between implants of up to 420 um. Clinical factors believed to contribute to the magnitudes of forces observed included the physiologic mandibular dimensions and the inter-implant distance. Their results are consistent with Hylander's 1984 proposal that the lateral pterygoid muscles cause bending of the mandible upon opening. Daegling et al (1992) noted biomechanical differences between torsion and bending in their investigation of mandibular structural rigidity. While their research focused on determining the preferability of an open or closed section model for torsional resistance in the mandible, the authors noted that "the greater porosity of alveolar bone with respect to adjacent compact bone probably also means that as a material it will experience higher strains for a given load." The mandible, as a composite structure of compact and alveolar bone, thus can be expected to distribute forces in a non uniform manner with the tooth supporting alveolar bone being more likely to deform. This study, as well as the earlier discussed work of Andersen et al, emphasized the role of an intact, viscoelastic periodontal membrane and of teeth in distribution of forces loaded to the mandible either directly or via the dentition at different sites. Implicating mandibular flexure in causing changes in dental interproximal contact tightness must take into consideration the biomechanical characteristics of the different biomaterials comprising the mandible. A suitable model that can conclusively demonstrate such a role has yet to be developed.

Summary

Orthodontists have for decades sought to understand the factors involved in maintaining teeth in corrected positions following orthodontic treatment. Weinstein et al (1963) postulated that more than one stable equilibrium position may exist for elements of the dentition and that differential forces of small magnitude, even soft tissue forces, may over time lead to tooth movement. A series of investigations by Moss and Picton (1971, 1973, 1974, 1978, 1980, 1981) stressed the role of gingival fibers inducing tooth drift independent of occlusion. Edwards (1973) established the value of soft tissue procedures such as the circumferential supracrestal fiberotomy in enhancing stability. The role of occlusion contributing to instability of orthodontic treatment results had long been postulated prior to the quantification of the anterior component of occlusal force by Southard et al in 1989. Many studies have investigated bite forces and factors which influence bite force generation for normal function and maximum effort. Proffit (1978) "revisited" the concept of equilibrium theory and sagaciously noted that both malocclusions and the stability of treatment corrected occlusions are dependent upon both genetic and environmental influences. Balance between soft tissue forces, functional requirements, and parafunctional influences in both magnitude and duration of cumulative forces is necessary for an equilibrium state to be achieved and maintained.

The significance of a physiologic anterior component of occlusal force is that, unlike with morphologic characteristics, with changes in local physiologic conditions such as posture, bite force, and gape, changes in the anterior component of force can be registered. The quantification of the anterior component of occlusal force was achieved by unilaterally axially loading the distobuccal cusp of a mandibular second molar and noting increases in interproximal contact tightness mesial in the arch. It seems logical then to employ a similar methodology, ie, measuring interproximal contact tightness while axially loading premolars, canines, and incisors, to investigate whether or not a POSTERIOR component of occlusal force exists, and if so, to quantify its magnitude. Based upon a review of the literature, this has not previously been done. An experiment of this design should also reaffirm the presence of an anterior component of occlusal force.

The purpose of this investigation is to investigate the effects on interdental forces of sequentially loading each tooth in a mandibular arch quadrant with a known bite force. The distribution and magnitude of an anterior component of occlusal force will be determined and compared with the findings of Southard et al (1989) who described an anterior component of occlusal force based on loading only second molars. Examination of interproximal contact forces posterior to the bite force loaded teeth will provide an opportunity to establish and quantify a posterior component of occlusal force.

CHAPTER III

MATERIALS AND METHODS

Interproximal Force Measurement

According to Coulomb's Law, a force required to move two objects in contact must overcome the frictional resistance between the two; the force applied (f) to achieve movement is equal to the coefficient of dynamic friction (u) multiplied by the force holding the objects in contact (F), $f = u F$. In the case of a stainless steel matrix sliding between two tooth enamel surfaces, Osborn (1961) reasoned that interproximal force (IPF) would be related to the frictional force (f) by the equation $IPF = f / 2u$ due to two tooth surfaces being in contact with the steel strip. The coefficient of dynamic friction (u) between tooth enamel and the stainless steel matrix material had been calculated to be 0.145 (Southard 1989). Thus, the frictional force (f) recorded in this experiment by direct measurement can be converted into a measure of interproximal contact tightness by dividing by 0.29, that is, $IPF = f_{measured} / .29$.

Calculation of the Anterior (Posterior) Components of Force

As described previously, the anterior component of occlusal force results from mesial tipping at the loaded tooth which increases the interproximal force at all teeth anterior to the loaded tooth. For this reason, the anterior component of occlusal force at any mesial contact can be calculated as:

$$ACF = IPF_{biting} - IPF_{not\ biting}$$

where ACF represents the anterior component of force and IPF represents the interproximal force measured. The posterior component of force (PCF) would be calculated using the same equation for contacts posterior to the loaded tooth. In this experiment, $IPF_{\text{not biting}}$ for a given contact was measured initially and finally after biting. Therefore an average $IPF_{\text{not biting}}$ was used, as follows:

$$ACF\ (PCF) = (IPF_{\text{biting}}) - (IPF_{\text{initial not biting}} + IPF_{\text{final not biting}})/2.$$

The difference between the interproximal force biting and the average of the interproximal force $_{\text{initial not biting}}$ and the interproximal force $_{\text{final not biting}}$ is equal to the magnitude of the anterior component of occlusal force for contacts anterior to the given loaded tooth or is equal to the magnitude of the posterior component of occlusal force for contacts posterior to the given loaded tooth.

Selection of Subjects

Ten healthy young adult Caucasian volunteers participated, nine males and one female. Mean age was 25.4 years, standard deviation 1.6 years. Subjects were required to have an unrestored mandibular left quadrant dentition with intact interproximal contacts and minimal incisor irregularity. Minimal incisor irregularity was required in order to be able to apply Coulomb's Law of friction which required flat surfaces, not irregular ones. Subjects all had complete dentitions from second molar to second molar in the mandibular arch; potential subjects with missing premolars, interproximal restorations, open contacts, excessive incisor irregularity, or fixed lingual retainers were excluded. Maxillary and mandibular alginate impressions were made of all subjects in order to calculate their respective irregularity index. Some subjects provided a copy of a recent panoramic radiograph. A panoramic radiograph was produced for subjects who did not have a copy of a recent film available and who agreed to have a radiograph exposed.

Guidelines for Instrumentation

Bite Force Transducer Design

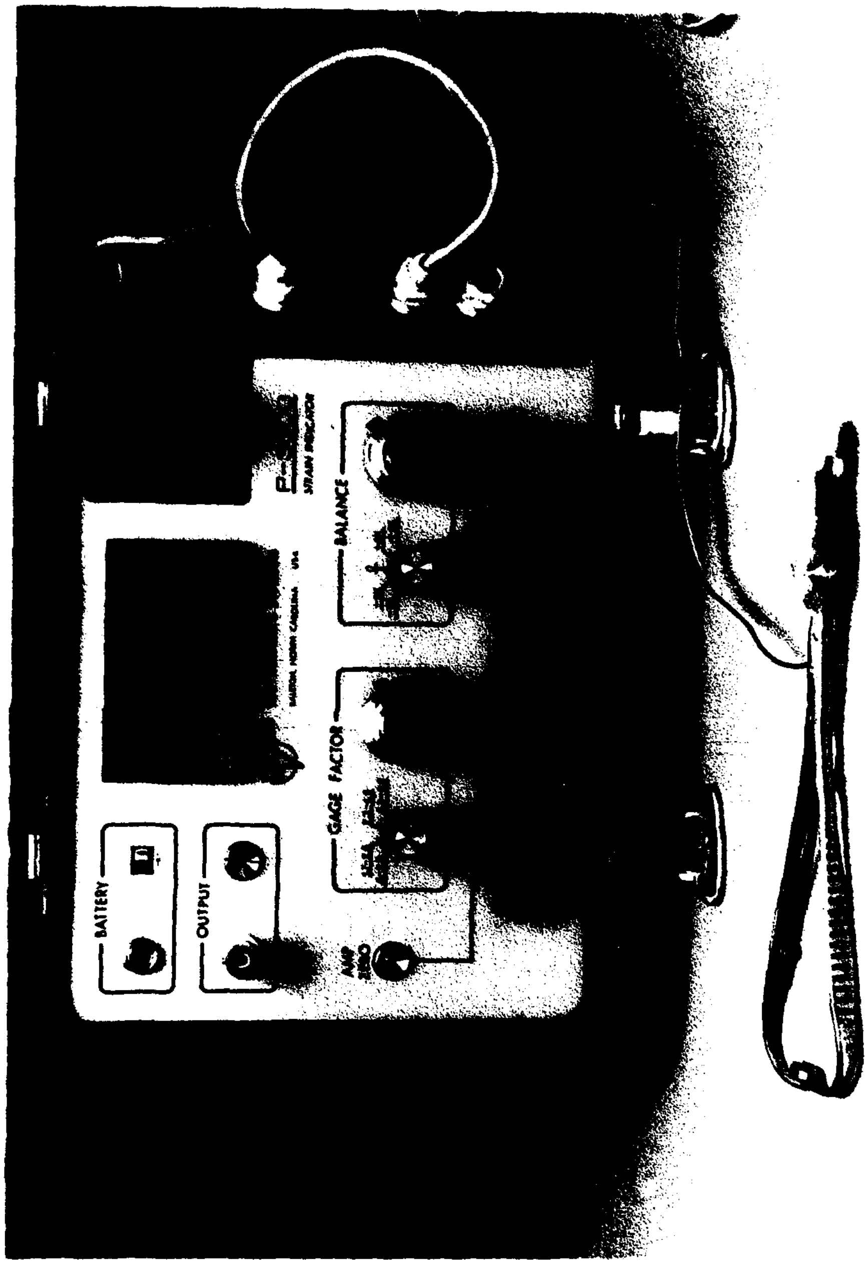
The design of a bite force transducer for this study needed to be simplified in order to realize the goal of measuring interproximal force changes for six different individually loaded teeth, from incisors to the first molar. The incisal edges and buccal cusps of the mandibular dentition from central incisor to first molar presented a complex variety of surfaces; for this investigation subjects were directed to produce an axially directed force consistent for eight consecutive loadings of a given tooth.

A custom bite force transducer was fabricated and connected to a strain indicator (Model P-3500 Strain Indicator, Measurements Group Instruments Division, Raleigh, North Carolina) as illustrated in figure 3. The gauge consisted of two stainless steel bars with one 120 ohm resistance strain gauge (Model EA-06-062AP-120, Measurements Group Instruments Division, Raleigh, North Carolina) bonded to the upper bar with cyanoacrylate cement. The gauge was connected as one arm of a Wheatstone bridge to the strain indicator. When bite force was applied to the transducer, the gauge was strained and the resulting voltage signal magnitude was displayed digitally on the strain indicator. To calibrate the strain indicator, known loads of different magnitude were applied to the transducer. The goal was to achieve a reproducible bite force that could be comfortably generated individually by all teeth in the mandibular left quadrant in order to produce comparable results for incisor, canine, premolar, and first molar loadings. The desired bite force also needed to be of sufficient magnitude to minimize the effects of gauge dimensional changes due to intraoral temperature changes during respiration. Pilot studies were performed with a bite force magnitude of approximately 4.0 kilograms. Subjects reported that incisive biting forces of that magnitude were uncomfortable and two subjects experienced small incisal enamel fractures. Two modifications were then implemented. First, the end of the stainless steel upper arm of the transducer was covered on its superior surface by a thin layer of restorative composite material to reduce the risk of enamel fracture of maxillary teeth during biting. Second, bite force needed to produce 50 microstrain on the digital display of the strain indicator was accepted as the standard bite force for the experiment. This was found to be the equivalent of 2.0 kilograms. The transducer had a Mathieu hemostat affixed to one end with acrylic; the dimensions of the hemostat allowed subjects to consistently orient the bite force transducer parallel to the occlusal plane, thus allowing the bite force to be applied perpendicular to the bite force transducer. A slight divot was placed in composite on the inferior arm of the transducer in order to allow secure loading of a single point or cusp on a mandibular tooth. The distance between the superior and inferior aspects of the bite force transducer was 10.4 millimeters. The resultant interincisal gape was dependent upon the positioning of the bite force transducer; a larger interincisal gape was noted for mesiobuccal cusp of the mandibular left first molar loading versus for left mandibular lateral and central incisor loading.

Interproximal Matrix Strips

Stainless steel universal matrix strips of 0.015 inch (.038 mm) width (Teledyne Getz, Elk Grove Village, IL) were prepared prior to data collection. Wearing gloves in order to prevent epidermal oils or other secretions from lubricating the stainless steel surface, .011 inch ligature loops were tack welded to one end of the strip to serve as a handle for pulling.

Figure 3. Bite force transducer


BATTERY
OUTPUT
AMP ZERO
GAGE FACTOR
BALANCE
STRAIN INDICATOR

Tension Force Transducer

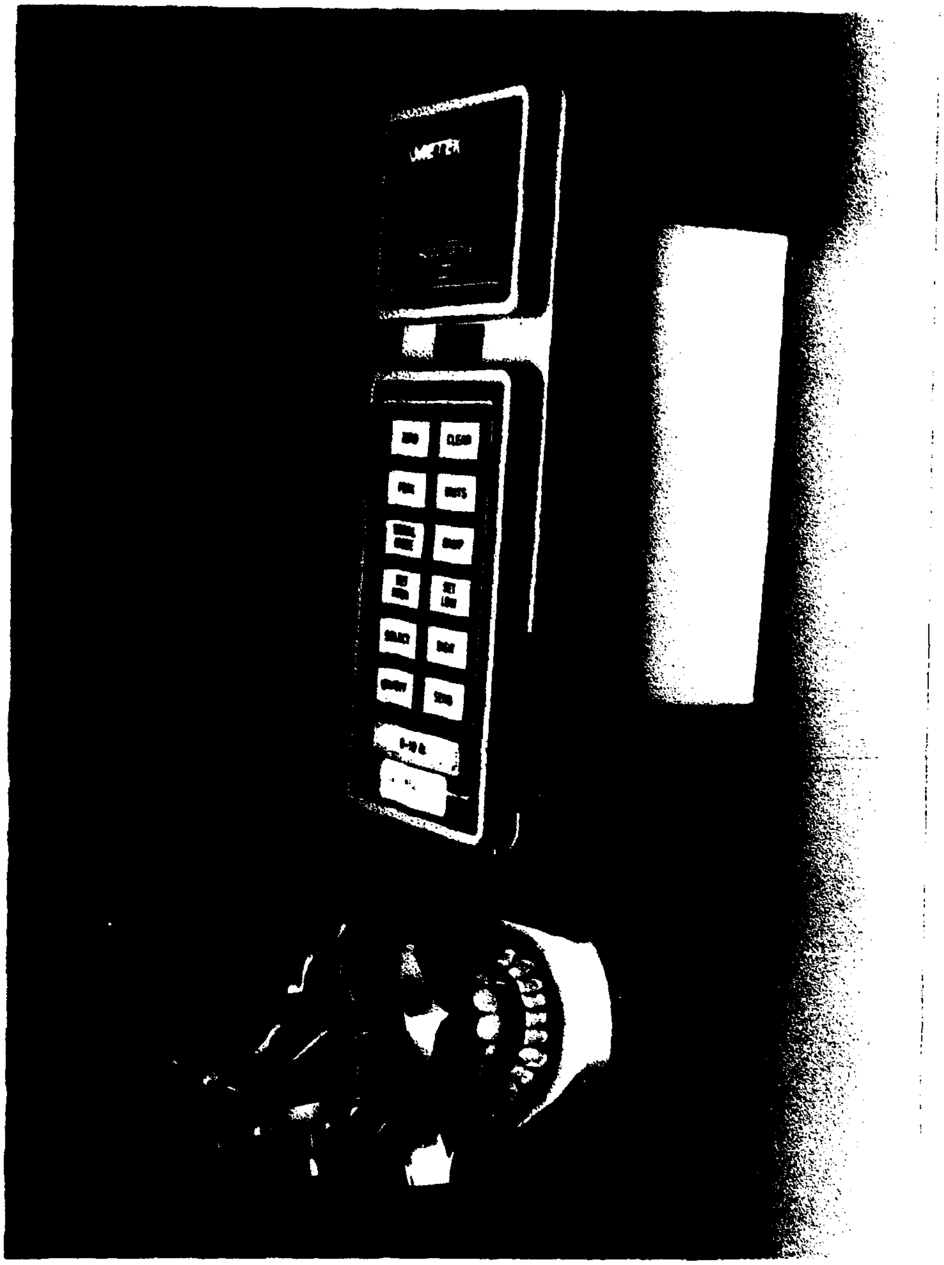
An electrical, self calibrating tension force gauge as seen in figure 4 (Accuforce III digital force gauge, Ametek Corporation, Largo, FL) was used to measure the frictional resistance to movement of a prepared stainless steel matrix band placed between two teeth. The interproximal force between the teeth could then be calculated. Measurements recorded with the subject initially not biting, biting, and finally not biting could subsequently be used to calculate the magnitude of an anterior or posterior component of occlusal force.

Experimental Procedure

In order to faithfully compare posterior component of occlusal force data with anterior component of occlusal force results previously published (Southard et al 1989, 1990) a similar measurement technique and experimental procedure was followed.

The subject was instructed to produce a bite force that measured 50 microstrain on a digital display on the instrument placed in front of him. Subjects were easily trained to achieve a reproducible bite force of this magnitude that could be comfortably generated by all the teeth in the mandibular left quadrant. The subject was further instructed to keep the bite force transducer in his mouth when not biting in order to avoid thermally-induced dimensional alterations of the transducer arms. Subjects became proficient at consistently orienting the hemostat parallel to the occlusal plane, thus insuring loading of the bite force transducer perpendicular to the occlusal plane while loading the mandibular left dentition as follows: mesiobuccal cusp of the first molar, buccal cusps of the second and first premolars, cusp tip of the canine, and incisal edge of the lateral and central incisors. The subject was allowed to practice and become comfortable with generating

Figure 4. Tension force transducer



the light bite forces requested on molars, premolars, canines, and incisors prior to initiation of data recording.

The subject was seated upright facing the digital display which registered the magnitude of bite force produced. Left cheek retraction was accomplished with a standard cheek retractor, thus avoiding possible soft tissue interference. A prepared matrix strip was inserted into the interproximal contact between the mandibular left first molar and second premolar. Tension was then placed onto the loop handle on the strip with the tensile strain indicator with enough force to just overcome the coefficient of friction and slide the strip buccally approximately 1 mm. The magnitude of the force needed to slide the matrix strip, an indicator of interproximal contact tightness, was recorded. The subject was then instructed to bite on the transducer with sufficient force to measure 50 microstrain on the digital gauge while maintaining the hemostat parallel to the occlusal plane. A research assistant and the subject both indicated when the desired bite force was achieved and, at that moment, tension was again applied to the matrix strip of magnitude to slide the strip approximately 1 mm buccally. The subject was then instructed to stop biting and tension was applied again to the matrix strip to record a second "no bite" reading of interproximal contact tightness. The investigator and the research assistant both repeated the three tension data readings which were promptly recorded by the assistant. In cases of disagreement over noted values, the sequence of readings was repeated. In cases where the weld of the .011 inch loop failed after one or more readings, the entire sequence was repeated with a new matrix strip. Each sequence of "initial no bite - bite - final no bite" readings was performed with a new strip.

The subject was instructed to keep the bite force transducer in his mouth. A new matrix strip was inserted between the mandibular left first and second premolars.

Following the "initial no bite - bite - final no bite" sequence as noted above, recordings of interproximal contact tightness were made, again with the mesiobuccal cusp of the mandibular left first molar being loaded. Matrix strips were drawn through all of the interproximal contacts until the mandibular right lateral incisor - right canine contact had undergone the same sequence. Interproximal contact designations are seen in figure 5.

The entire procedure was then repeated, again starting with the interproximal contact between the second premolar and first molar, with the second premolar being loaded at the same bite force. The procedure was, in due course, repeated loading the mandibular left first premolar, canine, lateral incisor, and central incisor. Contacts both anterior to and posterior to the bite force loaded tooth were measured.

CHAPTER IV

RESULTS

Three objectives were addressed during this investigation: 1) to ascertain the effects on interdental forces of sequentially loading each tooth in the mandibular arch from the first molar forward, 2) to determine the distribution and magnitude of an anterior component of occlusal force generated by loading each tooth in the mandibular arch from the first molar forward, and 3) to investigate and quantify the existence of a posterior component of occlusal force.

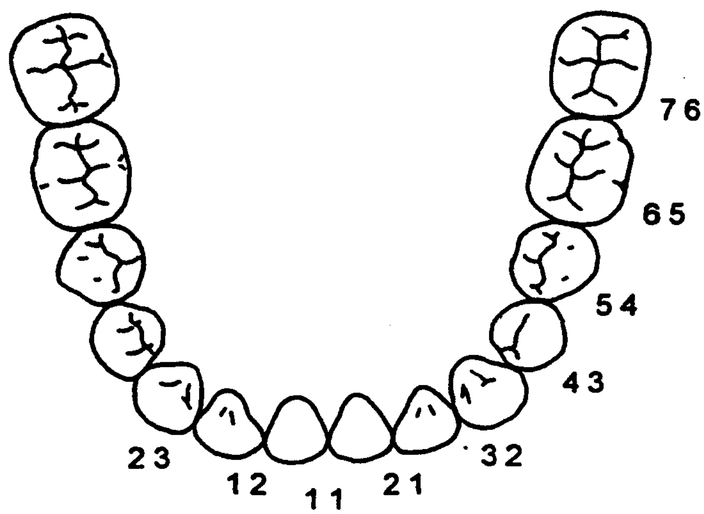
The Effects on Interdental Forces

Consistent effects of axial bite force loading upon contacts both anterior and posterior to the loaded tooth were observed. Figure 5 shows the contact designations for the mandibular arch which were used. Mean data for all ten subjects are presented in figures 6 - 11. For each interproximal contact in every figure, the first bar (black) represents the mean value of the "initial no bite" recordings. The second bar (white) represents the mean value of the "bite" recordings of interproximal contact tightness made while the subjects were loading the indicated tooth. The third bar (gray) represents the mean value of the "final no bite" recordings made shortly after the occlusal load was removed. Changes in interdental forces with the axial loading of a given tooth are calculated as the difference between the average of the "initial no bite" and "final no bite" interproximal force levels (black and gray bars) and the "bite" (white bar) interproximal force level. An increase in interproximal contact tightness caused by axial loading of a tooth is charted by having the center (white) bar of greater magnitude than the black and gray bars adjacent to it. The label on each graph and the arrow indicate which tooth was loaded with the known bite force. The interproximal contacts measured are labeled. An increase in interproximal contact tightness at a contact anterior to the loaded tooth is evidence of an anterior component of occlusal force. An increase in interproximal contact tightness at a contact posterior to the loaded tooth is evidence of a posterior component of occlusal force.

Axial loading of the mandibular first molar resulted in mean changes in interproximal forces as illustrated in figure 6. Contacts anterior to the loaded tooth (all the contacts measured) experienced increases associated with the axial bite force load. The magnitude of the mean changes associated with the bite force decreased with increased distance from the loaded tooth. "Final no bite" recordings of interproximal force were consistently smaller than "initial no bite" recordings of interproximal force for the same contacts. The mean data displayed results that formed a smooth curve. Mean interproximal forces were larger for posterior teeth (premolars and molar) than for anterior teeth (incisors).

When the mandibular left second premolar was loaded (figure 7), contacts anterior and posterior to the loaded tooth were measured. Contacts anterior to the loaded tooth demonstrated increased tightness, as seen by the greater magnitude of interproximal forces for the "bite" (white bar) data versus the "initial no bite" and "final no bite" data. The contact between the left lateral and central incisor showed a slightly greater mean magnitude of interproximal force change than seen between the lateral incisor and canine. This was not expected and may be attributable to random measurement error or to variation found in the sample studied. The contact posterior to the loaded tooth had a mean increase in tightness. As was observed above, "final no bite" interproximal forces

Figure 5. Interproximal contact designations


76
65
54
43
32
21
11
12
23

levels consistently, but to a small degree, were smaller than "initial no bite" interproximal force levels.

Loading the mandibular left first premolar yielded similar results as seen in figure 8. Contacts anterior to the loaded tooth increased in tightness. As noted with the second premolar loading sequence, the contact tightness increase between the lateral and central incisor was slightly greater than that seen between the lateral incisor and canine. This indicates consistency for the results for the small sample size of the study. The contacts posterior to the loaded tooth had a small mean increase in tightness. The magnitude of the interdental force changes observed were largest for the three contacts anterior to the loaded tooth and decreased with increased distance from the tooth. A relationship similar to that noted above between the initial and final no bite interproximal forces was observed.

Axial loading of the canine yielded data, seen in figure 9, that differed from the trends heretofore noted. Interproximal contacts anterior to the loaded tooth increased in tightness with a decreasing magnitude moving away from the loaded tooth. The magnitude of the changes observed was less than that found when the first molar or premolars were loaded. Posterior to the loaded tooth, in contrast to what was observed loading premolars, the mean interproximal contact tightness decreased in magnitude, with the largest decrease in contact tightness between the canine and first premolar. A consistent difference between initial and final no bite interproximal forces was again observed.

The results observed when the mandibular left lateral incisor was bite force loaded (figure 10) demonstrated that the contacts immediately mesial and distal to the loaded tooth experienced the greatest magnitude of contact tightness increase. Distal to the loaded tooth, a small increase in contact tightness was noted between the first premolar and canine. The contacts between the premolars and molars decreased in tightness upon bite force loading of the lateral incisor. The contacts anterior and to the right of the loaded lateral incisor showed variable results of small magnitude. The initial and final no bite interproximal forces demonstrated a relationship consistent with that previously mentioned.

Axial loading of the mandibular left central incisor showed (figure 11) dramatic increases in interproximal contact tightness immediately mesial and distal to the loaded tooth. The contacts between the right lateral and central incisors and between the left lateral incisor and canine displayed moderate increases in tightness. The magnitude of interproximal contact tightness increases dissipated further away from the loaded tooth; a slight mean increase in tightness at the left canine - first premolar contact was followed by no mean change at the first premolar - second premolar contact and a mean lightening of contact tightness between the second premolar and first molar.

Existence and Measurement of the Anterior and Posterior Components of Occlusal Force

The existence of both anterior and posterior components of occlusal force was confirmed by the observations of increased interproximal contact tightnesses noted anterior and posterior to a given loaded tooth. Graphical presentation of the mean anterior/posterior components of occlusal force for all ten subjects evaluated are seen in figures 12 - 17.

The graphical data represent the difference between the measured interproximal

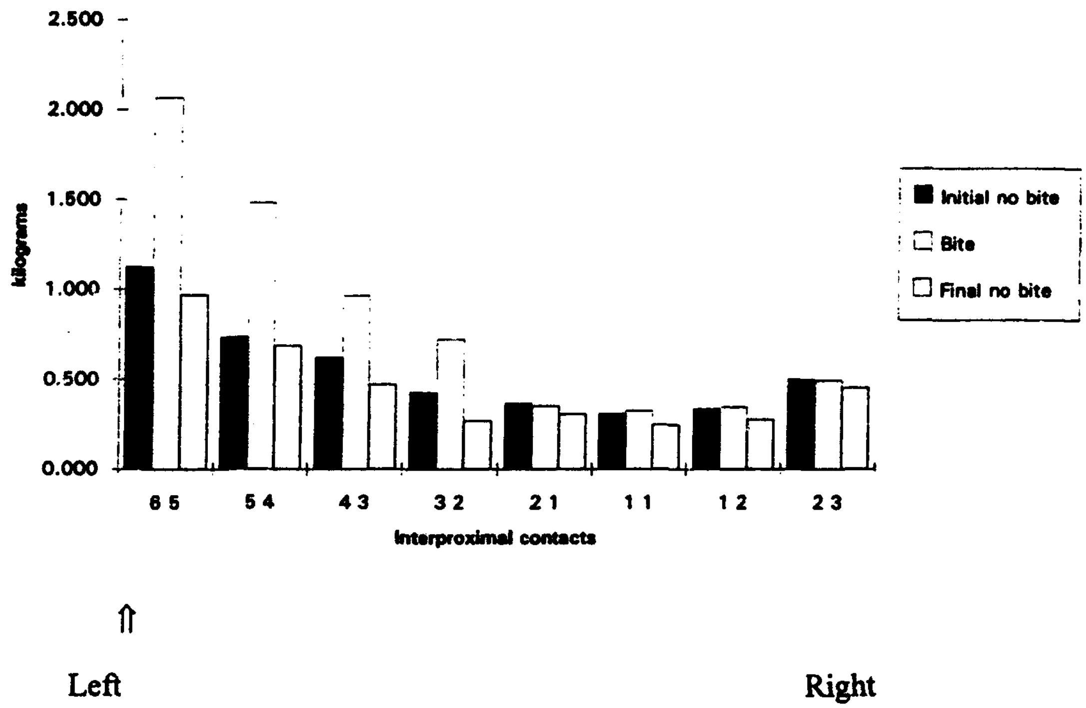


Figure 6. Mean interproximal forces measured with the mesiobuccal cusp of the mandibular first molar loaded (arrow) with 2.0 kg axial force

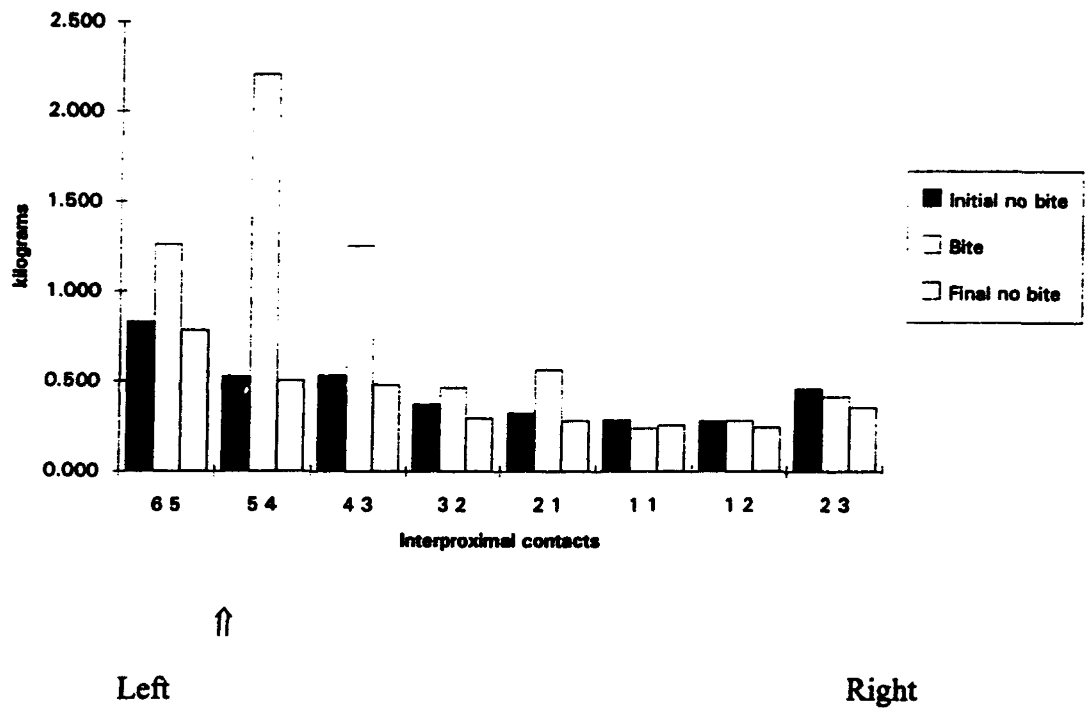


Figure 7. Mean interproximal forces measured with the buccal cusp of the mandibular second premolar loaded (arrow) with 2.0 kg axial force

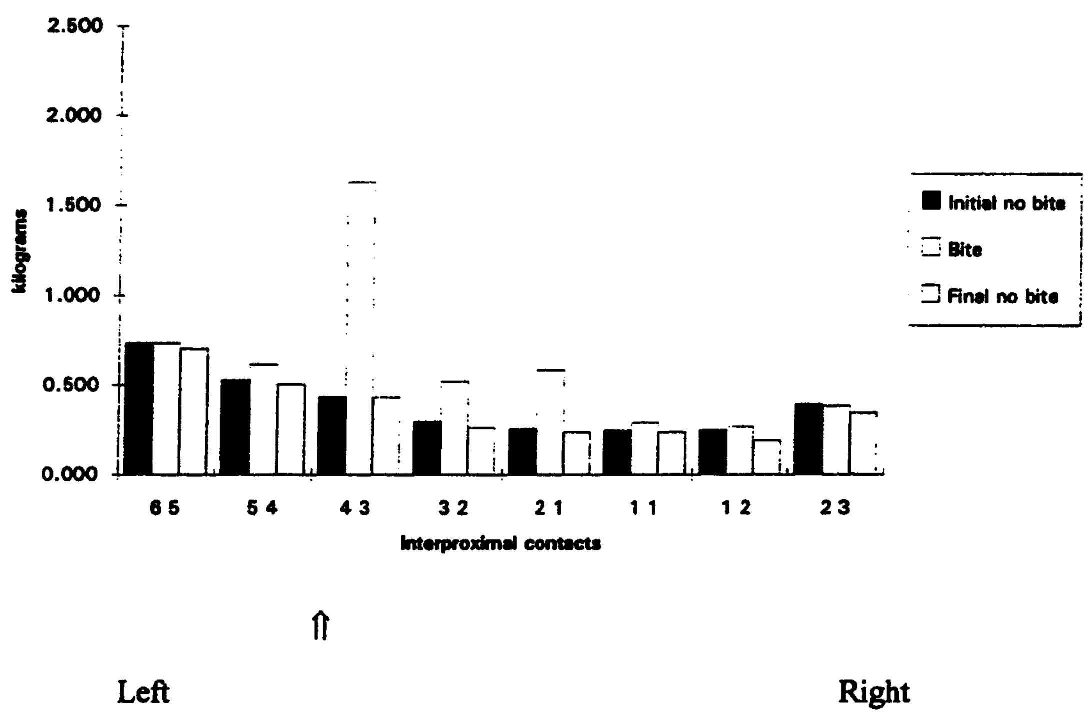


Figure 8. Mean interproximal forces measured with the buccal cusp of the mandibular first premolar loaded (arrow) with 2.0 kg axial force

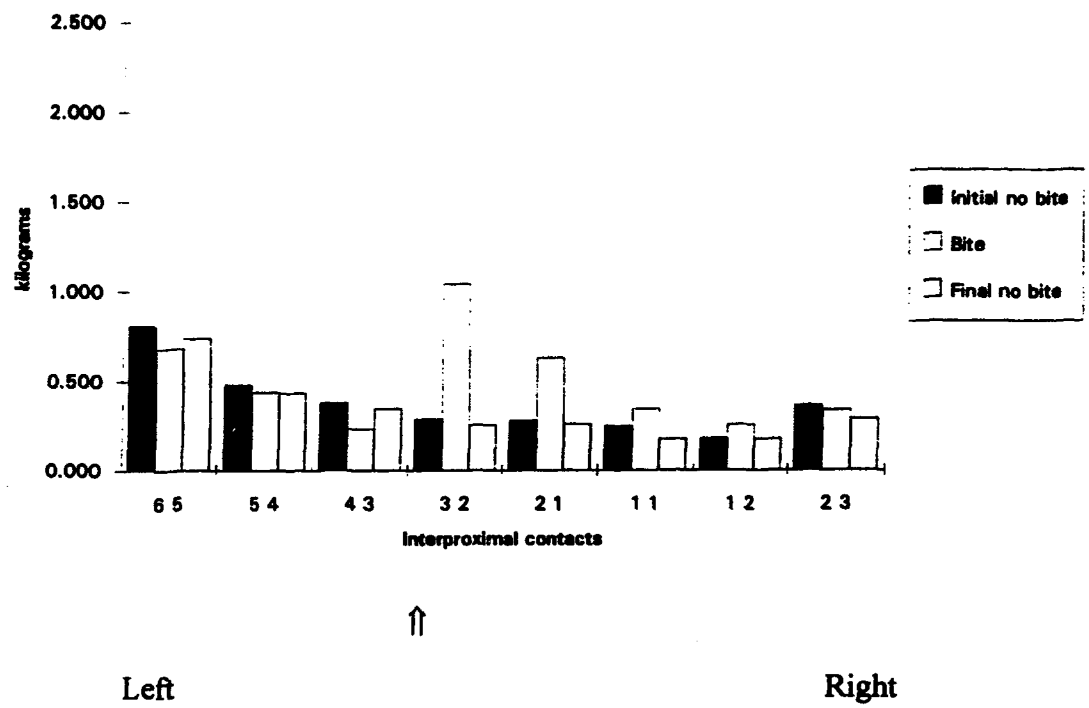


Figure 9. Mean interproximal forces measured with the cusp tip of the mandibular canine loaded (arrow) with 2.0 kg axial force

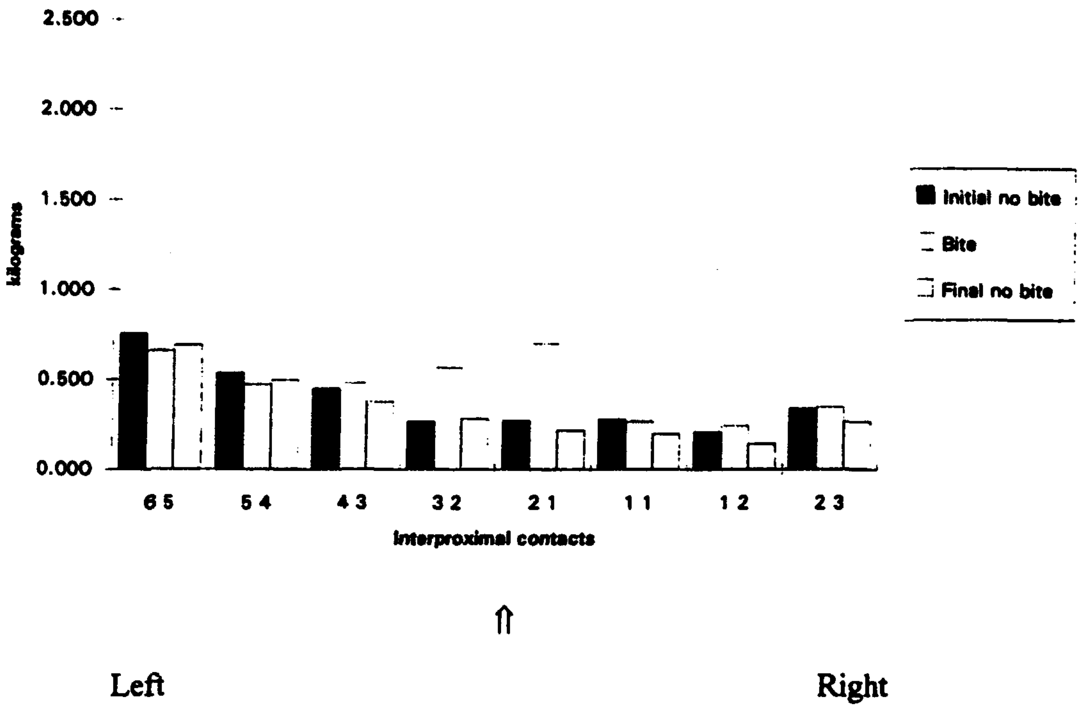


Figure 10. Mean interproximal forces measured with the center of the incisal edge of the mandibular lateral incisor loaded (arrow) with 2.0 kg axial force

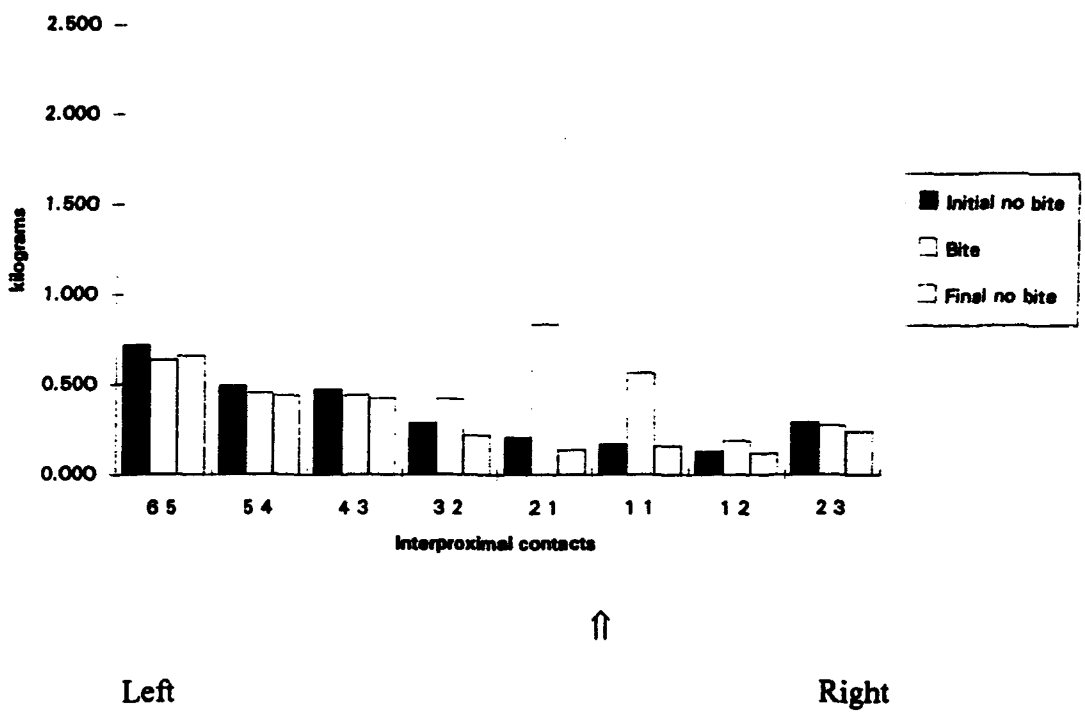


Figure 11. Mean interproximal forces measured with the center of the incisal edge of the mandibular central incisor loaded (arrow) with 2.0 kg axial force

contact tightness when an axial bite force of 2.0 kilograms was being applied to the indicated tooth and the average value of the "initial no bite" and "final no bite" interproximal contact tightness measurements. A positive value indicated that the contact increased in tightness. If the contact being examined was anterior to the specific tooth being loaded, it can be interpreted that an anterior component of occlusal force was expressed through that contact. If the contact being examined was posterior to the specific tooth being loaded, it can be interpreted that a posterior component of occlusal force was expressed through that contact. Negative values indicated that the interproximal contact tightness decreased when the specific tooth was axially loaded.

The contacts measured when the first molar was loaded were all anterior to the loaded tooth and all exhibited increased tightness as noted in figure 12. The magnitude of the interdental contact tightness increase upon axial bite force loading of the first molar mesiobuccal cusp, the anterior component of force magnitude, decreased with increasing distance from the loaded molar, dissipating to near zero in the incisor region.

The mean increase in interdental contact tightness posterior (contact 6 5) to the axially loaded mandibular second premolar (figure 13) was evidence of a posterior component of occlusal force. The magnitude of the posterior contact tightness increase was approximately 25% of the magnitude of the mean anterior component of occlusal force expressed between the first and second premolars. The magnitude of the anterior component of occlusal force dissipated with increasing distance from the loaded second premolar although the mean magnitude of the contact tightness change was greater between the incisors than between the canine and lateral incisor.

The mean increases in interproximal contact tightness both posterior and anterior to the axially loaded mandibular first premolar suggested that both posterior and anterior components of occlusal force were registered. The magnitude of the mean posterior contact tightness increase was approximately 10% of the magnitude of the mean anterior component of force expressed between the first premolar and canine. The magnitude of the anterior component of occlusal force decreased anterior to the loaded first premolar in a manner consistent with the decrease noted anterior to the loaded second premolar.

The interdental contacts posterior to the axially loaded canine exhibited negative posterior component of occlusal force values. This meant that the contacts were tighter during the resting, or no bite, phases of the measurement cycle than during the bite force loading of the mandibular canine. The contacts posterior to the loaded tooth loosened whereas an anterior component of force which gradually diminished in magnitude with increasing distance from the loaded tooth was observed.

The calculated anterior and posterior components of occlusal force resulting from the loaded lateral and central incisors can be considered together. The contacts immediately mesial and distal to the loaded teeth demonstrated the largest calculated values. The magnitude of the increase in interdental contact tightness dissipated with increased distance from the loaded incisor. A mean posterior component of occlusal force was observed in that the first premolar - canine contact exhibited a slight increase in contact tightness with the incisors loaded. The contacts distal to the first premolar exhibited a decrease in tightness. The significance of changes "anterior" versus "posterior" relative to incisors appeared to be smaller than the significance of distance from the loaded incisor. Interdental contact tightness changes following loading of incisors appeared to be better related to mesial or distal relationships versus sagittal (anterior or posterior) relationships.

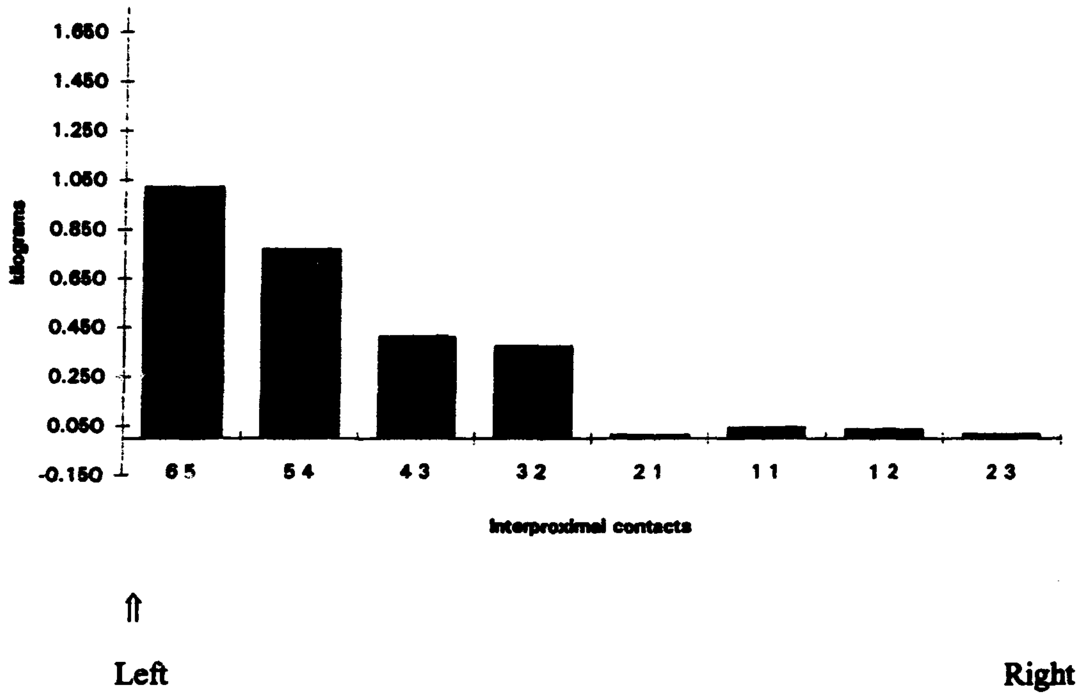


Figure 12. The mean anterior component of occlusal force with the mesiobuccal cusp of the mandibular first molar loaded (arrow) with 2.0 kg axial force

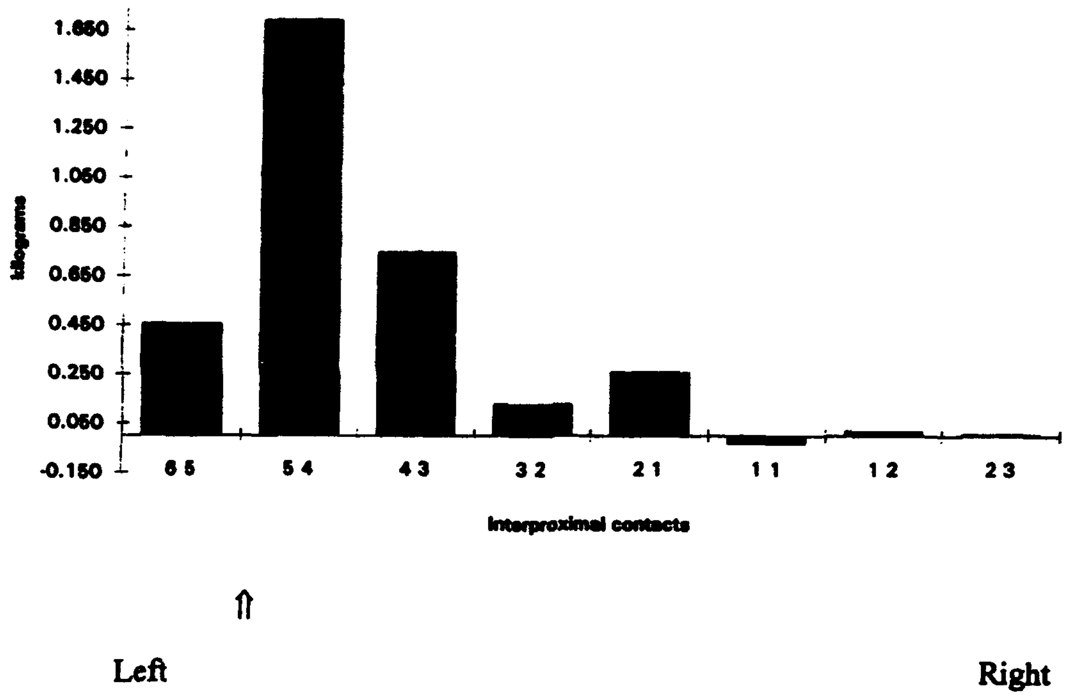


Figure 13. The mean posterior and anterior components of occlusal force with the buccal cusp of the mandibular second premolar loaded (arrow) with 2.0 kg axial force

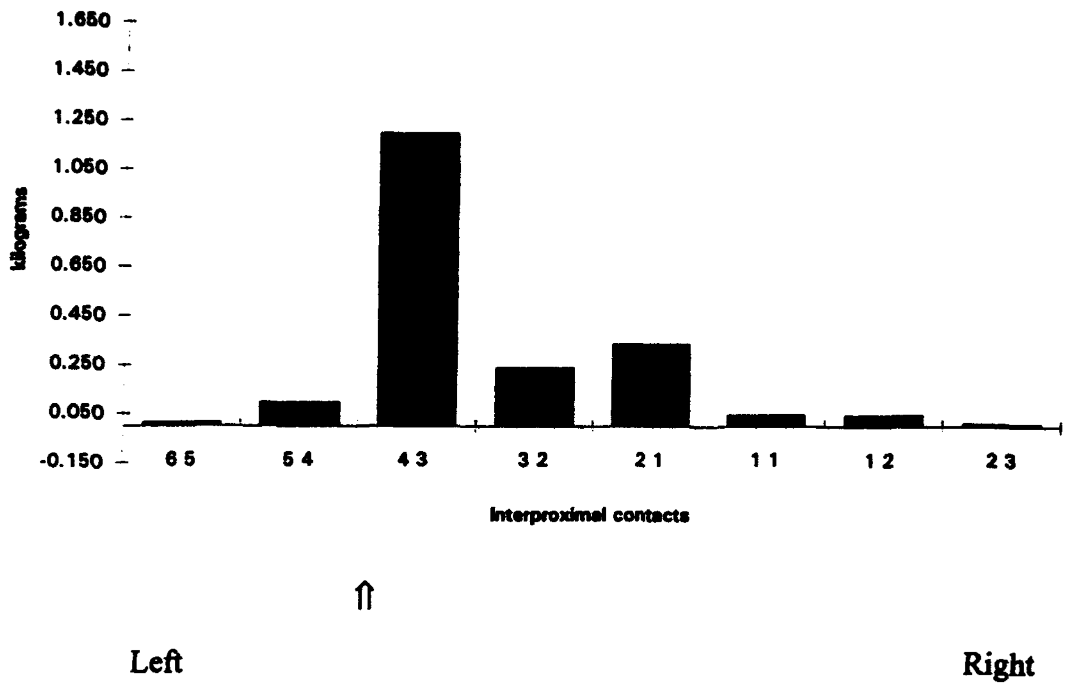


Figure 14. The mean posterior and anterior components of occlusal force for the buccal cusp of the mandibular first premolar loaded (arrow) with 2.0 kg axial force.

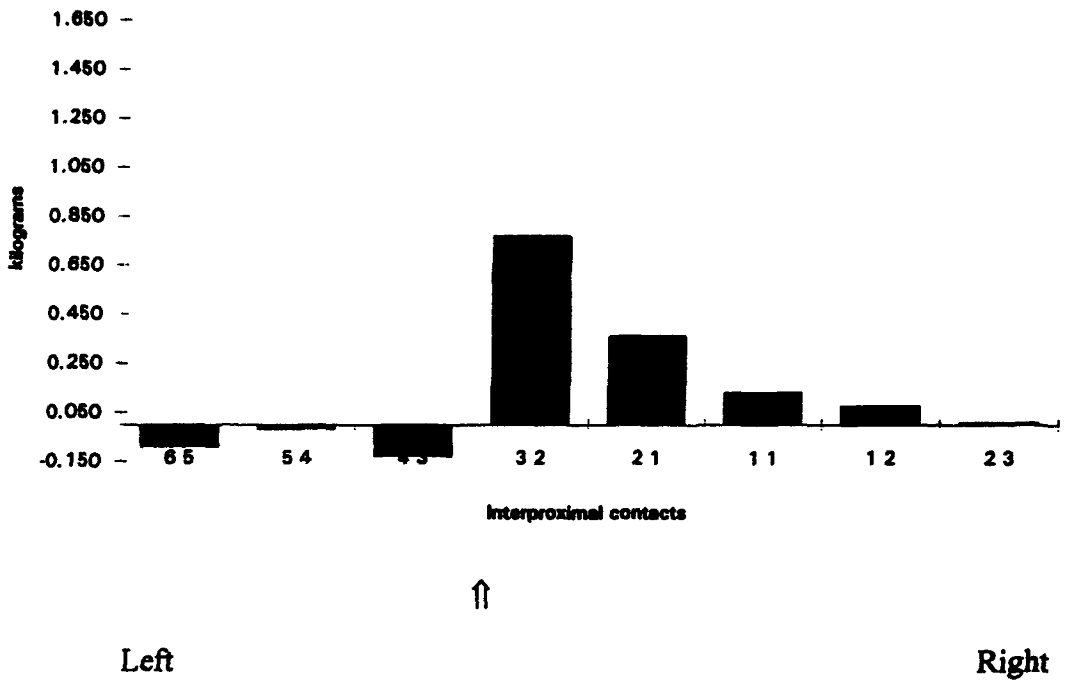


Figure 15. The mean posterior and anterior components of occlusal force with the cusp tip of the mandibular canine loaded (arrow) with 2.0 kg axial force.

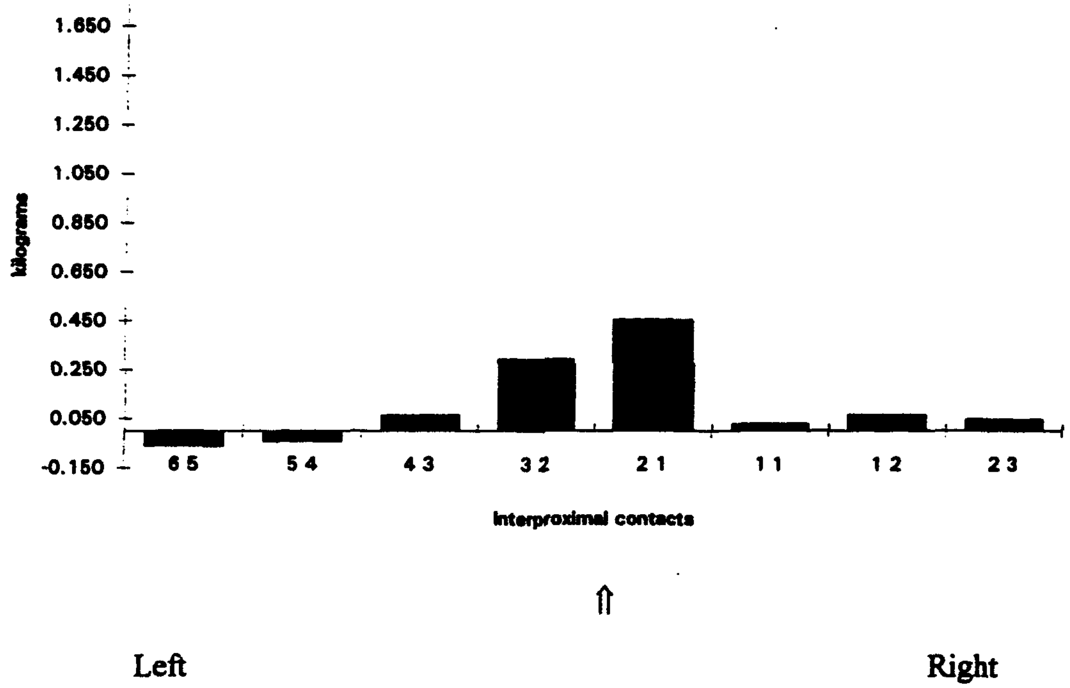


Figure 16. The mean posterior and anterior components of occlusal force with the center of the incisal edge of the mandibular lateral incisor loaded (arrow) with 2.0 kg axial force.

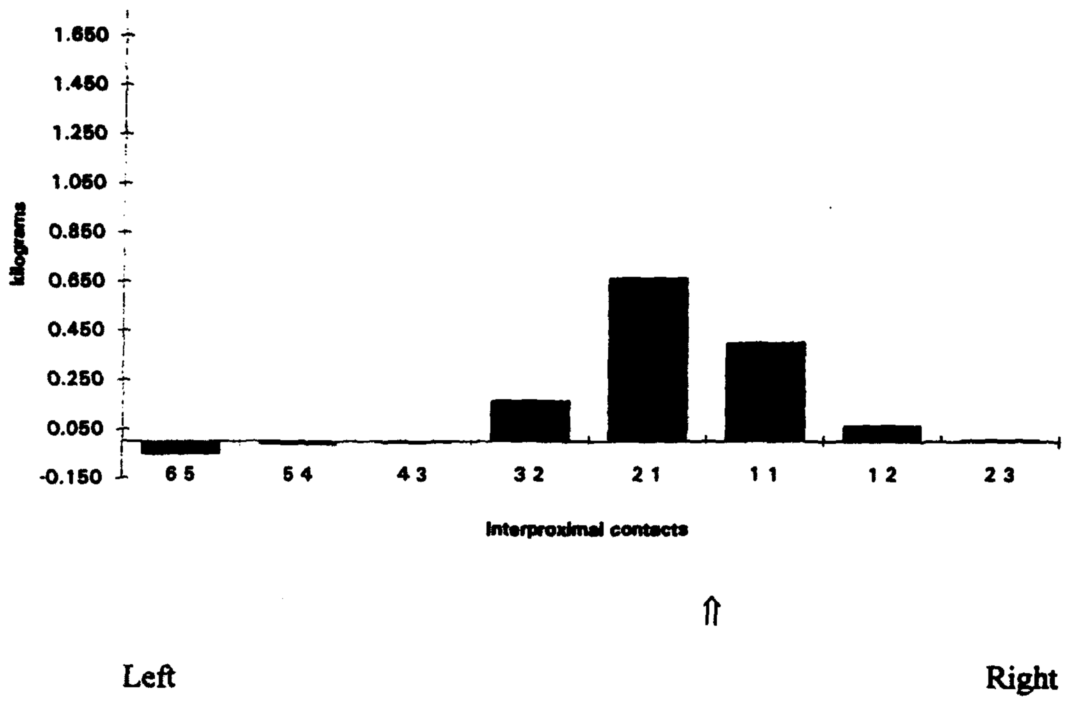


Figure 17. The mean posterior and anterior components o. occlusal force with the center of the incisal edge of the mandibular central incisor loaded (arrow) with 2.0 kg axial force.

CHAPTER V
DISCUSSION

Effects on Interdental Forces

To my knowledge, this is the first reported study of the effects on interproximal contact tightness of sequentially loading each tooth in a mandibular quadrant from the first molar forward. Variability between the subjects was high, reflecting differences in morphologic and anatomical orofacial relationships. Consistent results were observed when the mean data were analyzed.

Mandibular First Molar Loaded

Resting Interproximal Forces

The resting interproximal contact tightnesses were consistently larger for posterior teeth versus more anterior teeth. Similar findings were reported by Southard (1988) and Southard et al (1989) who suggested that the increased root surface area of posterior teeth may contribute to increased resting (not biting) interproximal contact tightness. The absolute magnitudes of mean not biting (resting) interproximal forces between this study and those reported by Southard (1988) are very similar. Although the exact morphologic or physiologic characteristics responsible for generation and maintenance of resting interdental contact tightness have not been determined, the results of this study support previously reported findings of higher resting interproximal forces which diminish to the mesial. It would be expected that the periodontal ligament plays a role in maintaining the resting interproximal contact force. Picton and Moss suggested the role of gingival transseptal fibers in maintaining this force and Proffit (1978) hypothesized the role of the tongue and cheek musculature. Future studies may consider examining interdental forces between a natural dentition and osseointegrated implants and /or ankylosed teeth.

Changes with Bite Force Loaded

The results graphically portrayed in figure 6 demonstrated that the mean interproximal contact tightnesses from the mesial of the first molar to the distal of the lateral incisor nearly doubled in magnitude from their resting values upon axial bite force loading of 2.0 kilograms to the mesiobuccal cusp of the mandibular first molar. Southard (1988) reported that the mean differences at the same contacts nearly quadrupled in magnitude from their resting values upon axial bite force loading of 20 pounds to the mesiobuccal cusp of the mandibular second molar. The magnitude of bite force applied by Southard (20 lbs.) was nearly five times larger than that used in this study (2.0 kg = 4.4 lbs.). Interproximal contact tightness change magnitudes are therefore related to the magnitude of applied bite force load. Increased bite force load resulted in a greater magnitude of interproximal force increase. The pattern of the increase in interdental contact tightness with bite force load was consistent between this study and that of Southard (1988): the absolute magnitude of the changes dissipated with increasing distance from the applied bite force load.

Mandibular Second Premolar Loaded

Resting Interproximal Forces

The pattern of resting interproximal forces being of consistent magnitude which decreased from posterior in the dental arch to the midline of the arch was again observed. The absolute magnitudes of resting contact tightnesses was less than those observed for the first molar loading sequence. This can be explained because this second set of measurements was made after the first molar loaded set. The periodontal ligament undergoes a viscoelastic response to loading. Repeatedly applying matrix strips between the contacts may result in compression of the periodontal ligament space with time delayed recovery of normal resting interproximal contact tightness which may be an explanation for the decreased magnitudes observed.

Interproximal Force Changes Posterior and Anterior to the Loaded Tooth

The interdental contact posterior to the axially loaded second premolar demonstrated an approximate mean increase of 50 % in contact tightness. The contact anterior to the loaded second premolar more than quadrupled in contact tightness magnitude over resting values. The pattern of dissipation of the bite force load was similar to that observed with the first molar being loaded. Two contacts anterior to the loaded molar and, later, loaded second premolar, the interdental contact tightness more than doubled over resting contact tightness for both the molar and second premolar bite force loads. The magnitude of the changes observed beyond the mandibular midline were minuscule. The quadrupling of the contact tightness magnitude immediately anterior to the loaded tooth was similar to the magnitude of change observed by Southard (1988). The application of a larger bite force load to a multirooted tooth by Southard versus the smaller bite force load to a one rooted mandibular second premolar may help explain the similarities of findings. The differential effect of the loading of the mesiobuccal cusp of the mandibular second molar by Southard versus the axial loading of the second premolar in this study is indeterminate.

Mandibular First Premolar Loaded

Resting Interproximal Forces

A nearly identical pattern of resting interproximal forces of magnitudes similar to those recorded with the second premolar load sequence were observed. This suggested that an equilibrium condition response to the artificial mechanical experimental stresses of inserting and removing stainless steel matrix strips might have been achieved by the time this third set of measurements was made.

Interproximal Force Changes Posterior and Anterior to the Loaded Tooth

The interdental contacts posterior to the axially loaded mandibular first premolar experienced little change from the resting values recorded; between the premolars the contact tightened approximately 100 grams and between the first molar and second premolar essentially no mean change was observed. Anterior to the loaded first premolar a pattern of interproximal contact tightening was noted to be similar to that seen with the first molar and second premolar bite force loaded sequences. The contact between the first premolar and canine nearly quadrupled in tightness. The magnitudes of change observed between the canine and central incisor were consistent with those seen with the second premolar load sequence. Gradual dissipation of interdental forces with progressively smaller magnitudes of change with increasing distance from a loaded tooth were reported by Southard (1988) and observed with the molar, canine, and incisor bite force load sequences in this study. It was expected that greater bite force load changes would be seen between the canine and lateral incisor than between the lateral and central incisor. The small mean magnitude of the seemingly inconsistent data noted can be attributed to a combination of the relatively small sample size, inter subject variability, and experimental error.

Mandibular Canine Loaded

Resting Interproximal Forces

Both the magnitude and the pattern of resting interproximal forces was consistent with those observed for the other tooth loading sequences.

Interproximal Force Changes Posterior and Anterior to the Loaded Tooth

The interdental contact tightness changes observed with the axial bite force loading of the mandibular canine differed significantly from previous findings posterior to the loaded tooth but were consistent with previous findings anterior to the loaded tooth. Posterior to the canine, interproximal forces decreased a magnitude of approximately 33% immediately posterior to the loaded tooth and of smaller magnitudes more distal. The posterior contacts became looser. Potential factors causing a posterior interproximal force decrease with axial loading of the mandibular canine, in contrast to results observed with premolar loading, may be hypothesized. The morphologic shape of a canine crown and its interproximal contact dimensions are different than those of premolars. The root lengths and inclinations of canines differ from those of premolars. The physiologic demands of canine guided occlusion may cause the canine to respond differently to axial bite force loads in an artificial experimental situation versus its response to multidirectional loads in a functional environment. Future studies may yield further insight into the significance of the findings observed in this study.

The contact between the canine and lateral incisor nearly quadrupled in tightness; the contact between the lateral and central incisor more than doubled in interproximal force. The dissipation of the interproximal force increases followed a smooth curve that extended across the midline to the right central and lateral incisor contact. This anterior interproximal force curve was similar in appearance to that presented by Southard (1988) for a loaded mandibular second molar and those noted above in this study.

Mandibular Incisors Loaded

Resting Interproximal Forces

The pattern of resting interproximal forces was consistent with those observed for the other tooth loading sequences. The mean magnitudes of the posterior resting interproximal contacts may have resulted in mild relaxation or fatigue of interproximal forces. The relationships between the magnitudes of the resting interproximal forces remained consistent.

Interproximal Force Changes Posterior and Anterior to the Loaded Teeth

The magnitudes of the changes in interproximal forces with the axial loading of the lateral and central incisors was smaller than the changes observed with any other tooth loaded. The results suggested that distribution of interproximal forces from axially loaded incisors was not affected by the anterior nor posterior direction of affected contacts but rather by the distance the contact was from the loaded tooth. Considering the anterior position of the incisors in the mandibular arch, interproximal force distribution of a bite force load applied to the incisors was not expected to have a significant effect upon molar and premolar interdental contact tightness. The slight decrease in interdental contact tightness seen between the premolars and molars was inconsistent with the hypothesis of mandibular flexion during incisal biting. Flexion of the mandible at its midsgittal (molar) region would cause convergence of molar and premolar crowns, divergence of tooth roots, and thus increased interdental contact tightnesses would have been expected.

The results indicated that axially bite force loading an incisor caused an increase in contact tightness both immediately mesial and distal to the loaded tooth and that the interproximal force increase dissipated with increased distance from the loaded tooth. Interproximal forces trebled over resting values for lateral incisor loading; those forces more than quadrupled over resting values for central incisor loading. The differential impact of loading a single tooth was observed to be greatest for incisor loading. This can be explained by considering the different ways in which those types of teeth are loaded and by which they distribute occlusal loads. The root surface area for premolars is larger than that for incisors; premolar roots are also wider. Incisors can be expected to distribute a greater percentage of occlusal load force via transmission of forces to adjacent teeth, whereas premolars can differentially absorb more force and dissipate that force by its larger periodontal surface area. Premolar interdental contacts are significantly wider than those of incisors. The larger component of interproximal force distribution experienced by incisors distributed over smaller interproximal contact surface areas may be a cause of increased incisor irregularity as observed over time. It is interesting, although perhaps coincidental, to note that the absolute magnitude of mean interproximal contact tightness changes for the incisors remained at nearly the same magnitude (about .5 kg) when loading the canine, premolars, and molar. Loading a given tooth resulted in the greatest magnitude of change in interproximal contact tightness on the contacts that the loaded tooth made in the dental arch. The local stress condition (loading a single tooth) produced effects (changes in interdental contact tightness) that were most pronounced locally (at the contacts that the loaded tooth made with adjacent teeth.)

<u>Existence and Measurement of the Anterior and Posterior Components of Occlusal Force</u>

The results confirm the presence of an anterior component of occlusal force. As hypothesized by Southard et al (1990b), loading teeth anterior to the second molar and recording interproximal contact tightnesses resulted in similar shaped curves of anterior component of occlusal force. The patterns seen represent the dissipation of interproximal forces as the distance from the axially loaded bite force tooth increases. This study demonstrated, as had been hypothesized by Southard (1990c), that the curves describing the anterior component of occlusal force shifted as teeth other than a mandibular second molar were loaded. Being aware of the documented existence of an anterior component of occlusal force, the values for a potential posterior component of occlusal force were indeterminate. The anterior component of occlusal force was believed to be related to mesial axial inclination of buccal segment teeth (Strang 1957). Stallard (1923) proposed that occlusal plane angle or condylar axis height might be involved in anterior component of occlusal force generation. Those factors were shown not to influence the anterior component of occlusal force by Southard et al (1990b). Instead, second molar root width, increased gape, and increased resting and bite forces correlated positively with increased anterior component of occlusal force. A posterior component of occlusal force was documented when the first and second premolars were axially loaded with a known bite force. Interproximal forces posterior to a bite force loaded mandibular canine decreased. Loading incisors had little observable effect on posterior interproximal tooth contact tightnesses. The magnitude of the observed posterior component of occlusal force was much smaller than the anterior component of occlusal force generated by the same bite force loading of a given tooth.

Anterior Component of Occlusal Force

The mean distribution of the anterior component of occlusal force observed in this experiment generally agreed with that reported by Southard (1988) and Southard et al (1989). Southard et al (1989) demonstrated that the magnitude of the anterior component of occlusal force decreased by approximately 50% with the increased distance of interdental contact from a bite force loaded mesiobuccal cusp of a mandibular second molar. The results of this study showed that the magnitude of the decrease between successive contacts for different teeth loaded were not consistent, but that generally the magnitude of the anterior component of occlusal force decreased with increased distance from the loaded tooth. The magnitude of the anterior component of occlusal force found in this study was smaller than that reported by Southard et al (1989). As was previously discussed, the difference is attributable to the difference in the amount of bite force load applied between the two studies. The results of the two studies support the concept that increased bite force magnitude yields an increase in magnitude of an anterior component of occlusal force. For individual subjects in the study, an anterior component of occlusal force was demonstrated anterior to contacts with light resting interproximal forces.

Possible explanations include individual variation in root angulations, mandibular flexure, or experimental errors. The fact that an anterior component of occlusal force was demonstrated for all bite force loaded teeth between the mandibular first molar and central incisor provided impressive confirmation for the existence of an anterior component of occlusal force. Conceptually, the loading of the mesiobuccal cusp of a mandibular second molar as accomplished by Southard (1988) could be argued to differentially tip the selected tooth thus resulting in an artificially induced anterior component of occlusal force. Having observed a mean anterior component of occlusal force for teeth axially loaded on their respective single cusps in this study, the existence and distribution of an anterior component of occlusal force has gained greater credence. Southard et al (1990c) had correlated both increased resting interproximal contact tightness and increased measured anterior component of occlusal force with increased incisor irregularity. Subject selection in this study had eliminated possible subjects with anything greater than mild incisor irregularity. Thus, because of selection bias, it would be invalid to attempt to correlate the results of this study with any measure of incisor irregularity.

Posterior Component of Occlusal Force

The results confirmed the presence of a posterior component of occlusal force. The magnitude of the measured posterior component of occlusal force was small compared with the anterior component of occlusal force generated with the same bite force loaded tooth. The dissipation of the posterior component of occlusal force was consistent with the dissipation of the anterior component of occlusal force in that its magnitude decreased with increased distance from the loaded tooth. Negative values for the posterior component of occlusal force were observed when the canine was loaded and also between premolar and molar contacts when the incisors were loaded. The clinical significance of a posterior component of occlusal force, as measured in this study, may be limited. Although it is recognized that most humans chew unilaterally more than bilaterally, efficient mastication does not load the dentition one tooth at a time. The magnitude and distribution of the posterior component of occlusal force recognized in this study may thus be a by product of the methodology employed by the investigators; group function studies (bite force loading of multiple teeth) may yield data of more physiologically generalizable content. A specific restorative dentistry event may produce physiologic changes similar to those represented in this study. If a single tooth was restored to a level placing it in supraocclusion relative to other teeth in the arch, changes similar to those reported in this study may be anticipated. The magnitude of bite force, a feature subject to high interpersonal variability, would still likely be greater than that employed in this study, with resultant higher anterior and posterior components of occlusal force produced.

Limitations and Potential Experimental Errors

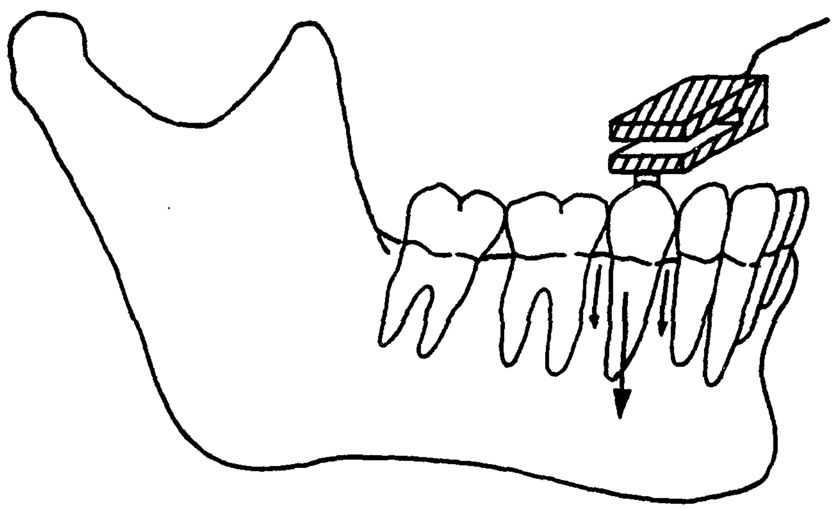
As with any experimental procedure, sources of potential inaccuracies were recognized with this study. Selection bias for the sample population with minimal incisor irregularity limit the generalizability of the findings to the population as a whole. This bias was accepted because the experimental protocol required measurements of incisor interproximal contacts; excessive incisor irregularity would have precluded valid incisor interproximal force measurements. The application of Coulumbs Law requires the use of flat surfaces; the irregular interpoximal contact surface areas commonly found in crowded mandibular incisors would have precluded the proper use of this experimental method. The average loaded bite force was of a magnitude of 2.0 kg which the subjects were trained to consistently produce; it was accepted that not exactly 2.0 kg was produced for each measurement. The subjects were also trained to axially bite load tooth perpendicular to the occlusal plane; it was accepted that purely axial forces were not generated for each measurement. Directional components to the loading of a tooth would likely affect the magnitude of an anterior or posterior component of occlusal force. The difference in the breadth of a contact surface area might be thought to contribute different frictional force measurements; Southard (1988) proved that the size of the contact surface did not make a difference. Southard (1988) also showed that, although the teeth would not be expected to be perfectly dry in an intraoral environment, an essentially identical coefficient of friction between the stainless steel matrix and tooth enamel would be expected.

In this experiment, interincisal gape changed between molar loading and incisor loading due to the relative wedge effect of placing a bite force transducer of fixed interarch width at posterior and anterior locations in the arch. Southard et al (1990b) reported an increased anterior component of occlusal force with increased gape. Fields et al (1986) reported increased bite force with increased gape. In this experiment, bite force was kept at the same small magnitude (2.0 kilograms) at all locations and the changes in gape, although not measured, were small. It is expected that the changes in gape due to positioning of the experiemntal instrumentation did not dramatically effect the results observed.

This study axially loaded a single tooth on only one side of the mandibular arch. Unilateral loading of a tooth with a known bite force has been shown to not be significantly different from bilateral loading in terms of swallowing, normal chewing, and maximum bite force generation (Fields et al 1986). Axial loading of a single tooth in the arch can be conceptualized to have different effects than group function. Loading of the single tooth depresses that tooth relative to adjacent teeth (Figure 18). The loading of a premolar can thus be expected to slightly increase the depth of the curve of Spee resulting in convergence of the dental crowns and increase in interdental contact tightness. The magnitude of the observed posterior component of occlusal force was relatively small and dissipated as distance from the loaded tooth increased. It is postulated that the effects of loading a single tooth can be localized due to the differential wedging effects of loading the tooth and depressing it relative to adjacent teeth.

Southard et al (1990c) had demonstrated differences in interproximal contact tightness with different postural positions. In this experiment, subjects were examined while sitting upright during the entire experimental period. The effects of posture were thus eliminated as a potential source of error for between subject data. Experimental protocol was standardized as much as possible between subjects.

Figure 18. Depression of a bite force loaded tooth relative to adjacent teeth



Clinical Applications of this Research

Based on the results of this study, in which physiologic changes in interproximal forces were observed for bite force loading of single teeth, the reader must be careful not to draw excessive conclusions because of the artificial stimulus response conditions employed. From a restorative dentistry perspective, the importance of the contours and occlusal height of restorations can be appreciated in light of the data presented here. The potential wedging effects of the contours of interproximal restorations resulting in differential anterior or posterior components of occlusal force can be appreciated. Restorations placed in supraocclusion may be expected to subject the teeth in the arch to differential forces as observed in the data of this experiment. However, it is recognized that, in normal physiologic function, the dentition is loaded from many directions in addition to purely from an axial direction. Paranormal habits and their potential long-term influence on the dentition may be better understood in light of this data. Persons who habitually differentially load a single tooth by biting a pen, clenching a pipe, or holding other objects with their teeth may exhibit changes in their dentitions consistent with the forces described here. It is interesting to note that the data for this experiment showed that the canine was the only tooth for which axial loading did not increase the interproximal contact tightness of the distal contact. An anterior component of occlusal force consistent with ›ected results was observed. The factors responsible for the observed results are not known; mesial inclination of the canine, increased root length, the position of the canine at the "corner" of the arch, or other factors may someday be implicated. The results do indicate that canine loading does produce an anterior component of force which may contribute to increased incisor irregularity over time.

Mandibular canines in a functioning, canine guided occlusion would be expected to be loaded in a different manner from that which they were loaded in this experiment. The role of the mandibular canine in distributing physiologic forces and perhaps influencing dental arch stability warrants further research.

Extensions of this Research

The results of this study have demonstrated that anterior and posterior interproximal contacts generally increase in tightness when a single tooth is loaded. In vivo functional occlusion generally is thought to load multiple teeth, not just one tooth differentially with respect to adjacent teeth. Measurement of the effects of functionally loading multiple teeth may provide insight into the question of whether or not functional occlusion contributes to increased interproximal contacts as the loading of a single tooth did in this study. The possible role of alveolar flexure contributing to increased interproximal contact tightness could be investigated by repeating the experiment using a maxillary dental arch quadrant. The differential loading of a single tooth with possible relative intrusion would conceptually be the same in such a study design. Future bite force studies may benefit from using bite force transducers of small width, as described in the literature review, which may more accurately represent the physiologic dimensions of masticatory boluses.

CHAPTER VI

CONCLUSION

The results of this experiment confirm the presence of an anterior component of occlusal force which displayed a similar shaped geometric distribution as different teeth were loaded in the dental arch. The hypothesis proposed by Southard et al (1989) that the distribution and dissipation curves of an anterior component of occlusal force would shift anteriorly with the loading of teeth other than the mandibular second molar was validated.

The results demonstrated that interproximal contact tightness, both anterior and posterior to a bite force loaded tooth, was greatest adjacent to the loaded tooth and dissipated with increased distance from that tooth. The depression of a single axially loaded tooth relative to adjacent teeth with subsequent effect upon interproximal contact tightness was offered as a possible mechanism explaining the observed results.

The quantification of a posterior component of occlusal force represents the first time that such a phenomenon has been reported. The magnitude of the posterior component of occlusal force was observed to be less than that of the anterior component of occlusal force for a given bite force loaded tooth. Mean interproximal forces were observed to decrease posterior to a bite force loaded mandibular canine. The decrease, representing a negative posterior component of occlusal force, was smaller in magnitude than the anterior component of occlusal force for the loaded canine. The mandibular canine appears to play a unique role in interproximal force distribution.

An effect of the experimental methodology used allowed the observation to be made that the resting interproximal force decreased within the short period of time that an interproximal matrix strip was placed between the contacts of adjacent teeth. The magnitude of the observed decrease was small. When the same contact was reentered a few minutes later and resting interproximal forces again measured, the interproximal force level tended to be of a smaller magnitude than that originally recorded. While consistent results were nonetheless recorded for this experiment, changes in interproximal contact tightness following introduction of matrix strips (not to mention wedges) may be clinically relevant for restorative dentists.

The results indicate that occlusal forces produce an anterior component of occlusal force which has been suggested to contribute to increased incisor irregularity. When considered with previous findings (Southard 1988), the results demonstrate that increased bite force yields an increased anterior component of occlusal force magnitude. The results may be of benefit to restorative dentists who are involved with the placement of functional interproximal and occlusal restorations.

APPENDIX A

MEAN INTERPROXIMAL FORCE DATA

Interproximal Contacts for loaded tooth	Mean Initial no bite (kg)	standard deviation	Mean Bite (kg)	standard deviation	Mean Final no bite (kg)	standard deviation
First molar						
6 5	1.123	0.635	2.068	1.160	0.970	0.633
5 4	0.737	0.510	1.482	0.750	0.688	0.513
4 3	0.623	0.435	0.962	0.653	0.472	0.352
3 2	0.426	0.256	0.723	0.871	0.269	0.263
2 1	0.364	0.373	0.350	0.327	0.307	0.298
1 1	0.308	0.421	0.324	0.399	0.249	0.284
1 2	0.337	0.263	0.346	0.292	0.277	0.289
2 3	0.500	0.387	0.496	0.350	0.454	0.347
Second premolar						
6 5	0.830	0.466	1.260	1.419	0.783	0.583
5 4	0.528	0.260	2.204	0.468	0.504	0.276
4 3	0.534	0.461	1.253	0.999	0.480	0.447
3 2	0.373	0.216	0.462	0.336	0.296	0.199
2 1	0.324	0.289	0.562	0.831	0.282	0.256
1 1	0.287	0.347	0.239	0.293	0.257	0.279
1 2	0.280	0.261	0.281	0.240	0.244	0.241
2 3	0.457	0.355	0.414	0.295	0.357	0.289
First premolar						
6 5	0.734	0.404	0.735	0.513	0.702	0.432
5 4	0.529	0.319	0.614	0.581	0.504	0.341
4 3	0.436	0.366	1.627	1.015	0.431	0.415
3 2	0.298	0.239	0.520	0.453	0.263	0.226
2 1	0.258	0.305	0.583	0.970	0.238	0.285
1 1	0.248	0.347	0.290	0.264	0.237	0.287
1 2	0.250	0.233	0.268	0.219	0.191	0.215
2 3	0.393	0.292	0.381	0.283	0.344	0.278
Canine						
6 5	0.808	0.546	0.682	0.509	0.740	0.575
5 4	0.480	0.274	0.438	0.390	0.434	0.240
4 3	0.378	0.319	0.232	0.336	0.347	0.329
3 2	0.288	0.252	1.042	0.955	0.256	0.208
2 1	0.280	0.268	0.631	0.642	0.261	0.271
1 1	0.249	0.341	0.344	0.298	0.176	0.191
1 2	0.179	0.192	0.255	0.272	0.176	0.186
2 3	0.362	0.270	0.336	0.318	0.289	0.253

Interproximal Contacts for loaded tooth	Mean Initial no bite (kg)	standard deviation	Mean Bite (kg)	standard deviation	Mean Final no bite (kg)	standard deviation
Lateral incisor						
6 5	0.755	0.513	0.659	0.527	0.690	0.535
5 4	0.537	0.395	0.472	0.440	0.497	0.394
4 3	0.451	0.508	0.478	0.503	0.377	0.449
3 2	0.266	0.249	0.565	0.571	0.281	0.267
2 1	0.270	0.403	0.698	0.586	0.216	0.324
1 1	0.277	0.352	0.266	0.317	0.197	0.219
1 2	0.210	0.224	0.241	0.244	0.143	0.185
2 3	0.337	0.234	0.347	0.305	0.266	0.235
Central incisor						
6 5	0.721	0.520	0.636	0.440	0.658	0.483
5 4	0.493	0.376	0.452	0.320	0.441	0.346
4 3	0.474	0.525	0.441	0.441	0.425	0.431
3 2	0.287	0.297	0.418	0.372	0.219	0.217
2 1	0.206	0.232	0.833	0.427	0.138	0.234
1 1	0.170	0.366	0.564	0.491	0.160	0.220
1 2	0.130	0.186	0.189	0.201	0.120	0.164
2 3	0.291	0.285	0.273	0.253	0.240	0.239

APPENDIX B

MEAN POSTERIOR AND ANTERIOR COMPONENTS OF OCCLUSAL FORCE DATA

Interproximal Contact for loaded tooth	Mean ACF/PCF (kg)	standard deviation	Interproximal Contact for loaded tooth	Mean ACF/PCF (kg)	standard deviation
First molar			Cuspid		
6 5	1.021	0.982	6 5	-0.092	0.122
5 4	0.770	0.615	5 4	-0.020	0.240
4 3	0.415	0.404	4 3	-0.131	0.197
3 2	0.376	0.869	3 2	0.770	0.988
2 1	0.048	0.094	2 1	0.361	0.501
1 1	0.045	0.134	1 1	0.132	0.160
1 2	0.039	0.091	1 2	0.078	0.133
2 3	0.018	0.078	2 3	0.010	0.100
Second premolar			Lateral incisor		
6 5	0.454	1.015	6 5	-0.061	0.068
5 4	1.688	0.435	5 4	-0.055	0.115
4 3	0.746	0.620	4 3	0.057	0.163
3 2	0.127	0.182	3 2	0.280	0.538
2 1	0.259	0.785	2 1	0.369	0.401
1 1	-0.033	0.112	1 1	0.030	0.130
1 2	0.018	0.054	1 2	0.071	0.110
2 3	0.007	0.083	2 3	0.022	0.076
First premolar			Central incisor		
6 5	0.017	0.291	6 5	-0.031	0.105
5 4	0.098	0.443	5 4	-0.137	0.443
4 3	1.193	0.882	4 3	0.011	0.113
3 2	0.239	0.282	3 2	0.166	0.219
2 1	0.336	0.914	2 1	0.579	0.526
1 1	0.047	0.108	1 1	0.352	0.463
1 2	0.047	0.098	1 2	0.067	0.158
2 3	0.013	0.118	2 3	0.008	0.111

APPENDIX C

INDIVIDUAL SUBJECT INTERPROXIMAL FORCE DATA

SUBJECT 1

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
First molar			
6 5	1.238	2.166	1.131
5 4	0.959	1.962	0.997
4 3	0.724	1.514	0.652
3 2	0.610	1.010	0.483
2 1	0.348	0.424	0.369
1 1	0.500	0.483	0.455
1 2	0.738	0.897	0.879
2 3	1.066	1.010	0.941
Second premolar			
6 5	0.993	1.445	0.855
5 4	0.569	2.176	0.590
4 3	0.379	1.086	0.421
3 2	0.614	0.734	0.345
2 1	0.290	2.793	0.338
1 1	0.359	0.321	0.314
1 2	0.555	0.490	0.386
2 3	1.028	0.852	0.572
First premolar			
6 5	0.838	1.659	0.821
5 4	0.555	1.828	0.479
4 3	0.328	0.421	0.359
3 2	0.445	0.672	0.441
2 1	0.438	0.355	0.410
1 1	0.279	0.331	0.345
1 2	0.424	0.369	0.283
2 3	0.686	0.710	0.617

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
Cuspid			
6 5	1.510	1.197	1.072
5 4	0.800	1.355	0.693
4 3	0.555	0.014	0.472
3 2	0.569	1.552	0.369
2 1	0.472	1.897	0.438
1 1	0.303	0.455	0.162
1 2	0.255	0.455	0.334
2 3	0.507	0.490	0.372
Lateral incisor			
6 5	0.862	0.693	0.779
5 4	0.641	0.490	0.679
4 3	0.438	0.269	0.386
3 2	0.328	0.255	0.428
2 1	0.424	0.455	0.303
1 1	0.293	0.400	0.559
1 2	0.286	0.310	0.000
2 3	0.372	0.441	0.290
Central incisor			
6 5	0.972	0.700	0.945
5 4	0.693	0.545	0.641
4 3	0.497	0.431	0.490
3 2	0.269	0.269	0.269
2 1	0.355	1.021	0.000
1 1	0.000	1.290	0.338
1 2	0.083	0.324	0.117
2 3	0.376	0.407	0.345

SUBJECT 2

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
First molar			
6 5	1.517	3.697	1.269
5 4	0.897	1.428	0.897
4 3	0.269	0.379	0.072
3 2	0.279	0.369	0.169
2 1	0.072	0.279	0.083
1 1	0.017	0.017	0.017
1 2	0.003	0.000	0.000
2 3	0.003	0.000	0.000
Second premolar			
6 5	0.728	0.414	0.548
5 4	0.714	3.214	0.710
4 3	0.331	0.410	0.310
3 2	0.297	0.521	0.262
2 1	0.117	0.162	0.103
1 1	0.000	0.000	0.000
1 2	0.007	0.093	0.000
2 3	0.066	0.059	0.031
First premolar			
6 5	0.676	0.524	0.676
5 4	1.048	0.934	0.972
4 3	0.166	1.924	0.166
3 2	0.131	0.397	0.152
2 1	0.000	0.359	0.086
1 1	0.034	0.338	0.003
1 2	0.034	0.338	0.048
2 3	0.045	0.107	0.062

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
Cuspid			
6 5	0.690	0.531	0.600
5 4	0.776	0.641	0.717
4 3	0.010	0.000	0.097
3 2	0.021	1.186	0.117
2 1	0.083	0.428	0.010
1 1	0.038	0.079	0.066
1 2	0.000	0.079	0.017
2 3	0.031	0.017	0.048
Lateral incisor			
6 5	0.834	0.486	0.514
5 4	0.572	0.617	0.555
4 3	0.000	0.017	0.003
3 2	0.007	0.000	0.000
2 1	0.007	1.241	0.000
1 1	0.007	0.010	0.000
1 2	0.003	0.269	0.010
2 3	0.010	0.007	0.031
Central incisor			
6 5	0.559	0.486	0.514
5 4	0.652	0.576	0.590
4 3	0.010	0.024	0.079
3 2	0.000	0.000	0.000
2 1	0.034	0.000	0.017
1 1	0.000	1.100	0.000
1 2	0.048	0.010	0.038
2 3	0.003	0.276	0.000

SUBJECT 3

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final bite
First molar			
6 5	0.652	0.562	0.645
5 4	0.379	0.407	0.397
4 3	0.472	0.624	0.379
3 2	0.000	0.000	0.000
2 1	0.397	0.524	0.386
1 1	0.000	0.000	0.000
1 2	0.255	0.269	0.000
2 3	0.007	0.262	0.269
Second premolar			
6 5	0.559	0.921	0.514
5 4	0.369	1.348	0.397
4 3	0.283	1.200	0.269
3 2	0.000	0.000	0.000
2 1	0.424	0.338	0.386
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.017	0.090	0.010
First premolar			
6 5	0.445	0.386	0.421
5 4	0.372	0.286	0.338
4 3	0.293	2.983	0.152
3 2	0.000	0.000	0.000
2 1	0.000	0.021	0.000
1 1	0.000	0.083	0.000
1 2	0.276	0.255	0.000
2 3	0.034	0.052	0.062

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final bite
Cuspid			
6 5	0.386	0.321	0.369
5 4	0.290	0.283	0.328
4 3	0.134	0.000	0.000
3 2	0.000	0.000	0.000
2 1	0.000	0.007	0.000
1 1	0.000	0.014	0.000
1 2	0.007	0.017	0.010
2 3	0.000	0.000	0.000
Lateral incisor			
6 5	0.445	0.469	0.407
5 4	0.290	0.321	0.303
4 3	0.000	0.000	0.000
3 2	0.000	0.000	0.000
2 1	0.159	0.986	0.269
1 1	0.007	0.072	0.000
1 2	0.000	0.000	0.000
2 3	0.034	0.107	0.028
Central incisor			
6 5	0.400	0.490	0.393
5 4	0.300	0.310	0.303
4 3	0.262	0.255	0.259
3 2	0.000	0.000	0.000
2 1	0.134	0.848	0.048
1 1	0.000	0.041	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000

SUBJECT 4

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
First molar			
6 5	1.997	3.045	2.166
5 4	1.652	2.686	1.517
4 3	1.252	1.676	0.810
3 2	0.662	0.690	0.372
2 1	0.000	0.000	0.000
1 1	0.310	0.607	0.303
1 2	0.421	0.545	0.321
2 3	0.655	0.693	0.628
Second premolar			
6 5	1.607	5.000	1.972
5 4	0.845	2.500	0.907
4 3	1.603	3.807	1.559
3 2	0.600	0.772	0.607
2 1	0.803	0.710	0.676
1 1	0.310	0.431	0.262
1 2	0.338	0.324	0.341
2 3	0.590	0.607	0.510
First premolar			
6 5	1.297	1.241	1.269
5 4	0.738	0.803	0.724
4 3	1.283	2.393	1.355
3 2	0.659	1.114	0.686
2 1	0.690	0.590	0.479
1 1	0.369	0.431	0.310
1 2	0.310	0.386	0.369
2 3	0.572	0.445	0.472

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
Cuspid			
6 5	1.283	0.866	1.172
5 4	0.610	0.421	0.514
4 3	1.014	0.934	1.014
3 2	0.617	1.028	0.597
2 1	0.531	0.879	0.721
1 1	0.328	0.424	0.317
1 2	0.321	0.759	0.338
2 3	0.686	0.852	0.624
Lateral incisor			
6 5	1.928	1.897	1.914
5 4	1.414	1.483	1.355
4 3	1.683	1.655	1.472
3 2	0.776	0.897	0.793
2 1	0.897	1.693	0.790
1 1	0.317	0.331	0.366
1 2	0.414	0.331	0.359
2 3	0.641	0.890	0.662
Central incisor			
6 5	1.931	1.610	1.734
5 4	1.210	0.962	1.010
4 3	1.886	1.472	1.452
3 2	0.962	0.793	0.648
2 1	0.479	0.438	0.421
1 1	0.000	0.486	0.034
1 2	0.355	0.314	0.338
2 3	0.586	0.566	0.555

SUBJECT 5

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
First molar			
6 5	0.876	2.217	0.652
5 4	0.459	1.176	0.400
4 3	0.503	1.648	0.472
3 2	0.438	3.034	0.000
2 1	0.421	0.541	0.321
1 1	1.066	1.210	0.786
1 2	0.438	0.321	0.397
2 3	0.738	0.583	0.603
Second premolar			
6 5	0.652	0.438	0.510
5 4	0.428	1.928	0.379
4 3	0.438	1.224	0.369
3 2	0.428	0.762	0.397
2 1	0.441	0.617	0.290
1 1	0.917	0.869	0.876
1 2	0.486	0.490	0.355
2 3	0.562	0.545	0.424
First premolar			
6 5	0.597	0.472	0.528
5 4	0.341	0.345	0.338
4 3	0.431	1.872	0.438
3 2	0.497	1.314	0.283
2 1	0.269	0.397	0.276
1 1	0.897	0.776	0.841
1 2	0.352	0.369	0.303
2 3	0.621	0.528	0.438

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
Cuspid			
6 5	0.555	0.500	0.559
5 4	0.431	0.338	0.397
4 3	0.497	0.621	0.438
3 2	0.507	0.862	0.441
2 1	0.266	0.441	0.269
1 1	0.876	0.838	0.500
1 2	0.355	0.369	0.321
2 3	0.555	0.407	0.431
Lateral incisor			
6 5	0.572	0.507	0.534
5 4	0.341	0.307	0.269
4 3	0.407	0.617	0.403
3 2	0.438	0.690	0.372
2 1	0.076	0.266	0.000
1 1	0.821	0.879	0.379
1 2	0.383	0.262	0.269
2 3	0.500	0.572	0.486
Central incisor			
6 5	0.490	0.586	0.452
5 4	0.324	0.590	0.269
4 3	0.400	0.693	0.345
3 2	0.338	0.738	0.345
2 1	0.314	0.907	0.138
1 1	0.907	0.810	0.631
1 2	0.341	0.397	0.307
2 3	0.645	0.531	0.472

SUBJECT 6

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
First molar			
6 5	1.290	2.076	0.641
5 4	0.559	1.245	0.438
4 3	0.000	0.314	0.000
3 2	0.000	0.010	0.000
2 1	0.000	0.000	0.000
1 1	0.000	0.003	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000
Second premolar			
6 5	0.659	0.852	0.452
5 4	0.517	2.124	0.403
4 3	0.000	0.979	0.000
3 2	0.000	0.000	0.000
2 1	0.000	0.000	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000
First premolar			
6 5	0.521	0.531	0.541
5 4	0.476	0.345	0.459
4 3	0.000	0.962	0.000
3 2	0.000	0.000	0.000
2 1	0.000	0.000	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
Cuspid			
6 5	0.583	0.600	0.597
5 4	0.386	0.366	0.341
4 3	0.000	0.000	0.000
3 2	0.000	0.000	0.000
2 1	0.000	0.000	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000
Lateral incisor			
6 5	0.545	0.455	0.497
5 4	0.355	0.345	0.307
4 3	0.000	0.345	0.000
3 2	0.000	0.700	0.000
2 1	0.000	0.521	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000
Central incisor			
6 5	0.576	0.455	0.572
5 4	0.331	0.328	0.314
4 3	0.000	0.000	0.000
3 2	0.000	0.000	0.000
2 1	0.000	0.000	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.000	0.000	0.000

SUBJECT 7

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
First molar			
6 5	0.672	3.517	0.562
5 4	0.562	2.655	0.479
4 3	1.141	1.797	0.952
3 2	0.628	0.634	0.517
2 1	0.000	0.000	0.000
1 1	0.676	0.486	0.455
1 2	0.428	0.431	0.338
2 3	0.510	0.545	0.279
Second premolar			
6 5	0.576	0.438	0.586
5 4	0.517	2.097	0.414
4 3	1.010	1.372	0.741
3 2	0.483	0.486	0.386
2 1	0.000	0.000	0.000
1 1	0.572	0.321	0.407
1 2	0.359	0.428	0.303
2 3	0.403	0.438	0.355
First premolar			
6 5	0.603	0.534	0.541
5 4	0.369	0.383	0.321
4 3	0.759	3.034	0.824
3 2	0.379	0.634	0.314
2 1	0.000	0.000	0.000
1 1	0.379	0.407	0.403
1 2	0.355	0.269	0.283
2 3	0.386	0.659	0.314

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
Cuspid			
6 5	0.514	0.321	0.428
5 4	0.321	0.031	0.321
4 3	0.555	0.297	0.500
3 2	0.279	1.341	0.338
2 1	0.000	0.000	0.000
1 1	0.555	0.555	0.331
1 2	0.366	0.355	0.269
2 3	0.310	0.403	0.293
Lateral incisor			
6 5	0.428	0.372	0.403
5 4	0.352	0.293	0.307
4 3	0.634	0.845	0.528
3 2	0.269	1.962	0.369
2 1	0.000	0.000	0.000
1 1	0.676	0.262	0.276
1 2	0.521	0.614	0.407
2 3	0.500	0.424	0.345
Central incisor			
6 5	0.483	0.431	0.417
5 4	0.452	0.355	0.359
4 3	0.617	0.590	0.659
3 2	0.541	0.903	0.255
2 1	0.000	1.169	0.000
1 1	0.431	1.121	0.293
1 2	0.000	0.459	0.000
2 3	0.000	0.000	0.000

SUBJECT 8

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
First molar loaded			
6 5	0.793	0.979	0.869
5 4	0.352	0.828	0.276
4 3	0.745	0.717	0.572
3 2	0.686	0.569	0.490
2 1	0.483	0.379	0.386
1 1	0.000	0.000	0.000
1 2	0.359	0.448	0.310
2 3	0.628	0.621	0.514
Second premolar			
6 5	0.917	1.507	0.786
5 4	0.355	2.059	0.352
4 3	0.572	1.403	0.562
3 2	0.472	0.772	0.331
2 1	0.386	0.345	0.366
1 1	0.000	0.000	0.000
1 2	0.331	0.338	0.328
2 3	0.641	0.524	0.448
First premolar			
6 5	0.883	0.641	0.686
5 4	0.338	0.000	0.290
4 3	0.497	1.403	0.452
3 2	0.366	0.541	0.359
2 1	0.310	3.207	0.266
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.490	0.452	0.479

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
Cuspid			
6 5	0.686	0.686	0.528
5 4	0.269	0.266	0.262
4 3	0.438	0.000	0.369
3 2	0.383	0.483	0.286
2 1	0.324	0.283	0.255
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.531	0.455	0.421
Lateral incisor			
6 5	0.603	0.503	0.586
5 4	0.355	0.000	0.286
4 3	0.441	0.459	0.469
3 2	0.397	0.372	0.428
2 1	0.000	0.455	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.514	0.455	0.355
Central incisor			
6 5	0.524	0.479	0.459
5 4	0.000	0.000	0.000
4 3	0.459	0.421	0.352
3 2	0.452	0.862	0.355
2 1	0.000	0.779	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.428	0.355	0.366

SUBJECT 9

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
First molar			
6 5	0.000	0.359	0.000
5 4	0.000	0.962	0.000
4 3	0.000	0.000	0.000
3 2	0.297	0.266	0.000
2 1	0.255	0.290	0.234
1 1	0.000	0.010	0.000
1 2	0.000	0.000	0.000
2 3	0.369	0.307	0.314
Second premolar			
6 5	0.000	0.000	0.000
5 4	0.000	2.300	0.000
4 3	0.000	0.000	0.000
3 2	0.279	0.000	0.145
2 1	0.000	0.000	0.000
1 1	0.248	0.000	0.293
1 2	0.000	0.000	0.000
2 3	0.283	0.293	0.307
First premolar			
6 5	0.000	0.000	0.000
5 4	0.000	0.000	0.000
4 3	0.000	0.000	0.000
3 2	0.000	0.000	0.000
2 1	0.000	0.000	0.000
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.255	0.138	0.145

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
Cuspid			
6 5	0.000	0.000	0.000
5 4	0.000	0.000	0.000
4 3	0.000	0.000	0.000
3 2	0.021	3.314	0.028
2 1	0.255	1.341	0.266
1 1	0.000	0.531	0.000
1 2	0.000	0.000	0.000
2 3	0.290	0.000	0.045
Lateral incisor			
6 5	0.000	0.000	0.000
5 4	0.000	0.000	0.000
4 3	0.000	0.000	0.000
3 2	0.038	0.355	0.017
2 1	0.000	0.010	0.010
1 1	0.000	0.000	0.000
1 2	0.000	0.000	0.000
2 3	0.290	0.000	0.014
Central incisor			
6 5	0.000	0.000	0.000
5 4	0.000	0.000	0.000
4 3	0.000	0.000	0.000
3 2	0.000	0.293	0.000
2 1	0.052	1.507	0.062
1 1	0.000	0.321	0.000
1 2	0.000	0.000	0.000
2 3	0.231	0.000	0.121

SUBJECT 10

Interproximal Contacts for loaded Tooth	(kg) Initial no bite	(kg) Bite	(kg) Final no bite
First molar			
6 5	2.200	2.062	1.762
5 4	1.548	1.472	1.479
4 3	1.121	0.955	0.810
3 2	0.659	0.648	0.662
2 1	1.303	1.066	0.979
1 1	0.510	0.421	0.472
1 2	0.724	0.545	0.524
2 3	1.024	0.934	0.997
Second premolar			
6 5	1.607	1.590	1.607
5 4	0.962	2.297	0.893
4 3	0.724	1.048	0.572
3 2	0.559	0.572	0.490
2 1	0.776	0.652	0.659
1 1	0.459	0.445	0.414
1 2	0.728	0.645	0.728
2 3	0.979	0.738	0.914
First premolar			
6 5	1.483	1.359	1.534
5 4	1.048	1.217	1.124
4 3	0.600	1.276	0.569
3 2	0.500	0.524	0.397
2 1	0.869	0.907	0.862
1 1	0.524	0.531	0.469
1 2	0.745	0.690	0.624
2 3	0.841	0.724	0.855

Interproximal Contacts for loaded Tooth	**(kg) Initial no bite**	**(kg) Bite**	**(kg) Final no bite**
Cuspid			
6 5	1.876	1.797	2.072
5 4	0.917	0.676	0.772
4 3	0.576	0.455	0.583
3 2	0.483	0.652	0.386
2 1	0.866	1.034	0.652
1 1	0.386	0.545	0.386
1 2	0.483	0.517	0.466
2 3	0.714	0.734	0.659
Lateral incisor			
6 5	1.334	1.203	1.262
5 4	1.045	0.862	0.910
4 3	0.907	0.576	0.503
3 2	0.407	0.421	0.407
2 1	1.141	1.348	0.790
1 1	0.652	0.703	0.393
1 2	0.493	0.628	0.383
2 3	0.510	0.572	0.445
Central incisor			
6 5	1.272	1.121	1.093
5 4	0.969	0.855	0.921
4 3	0.607	0.524	0.614
3 2	0.310	0.324	0.317
2 1	0.690	0.831	0.693
1 1	0.359	0.469	0.303
1 2	0.472	0.386	0.403
2 3	0.641	0.593	0.538

APPENDIX D

INDIVIDUAL SUBJECT POSTERIOR AND ANTERIOR COMPONENTS OF OCCLUSAL FORCE DATA

SUBJECT 1

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**	**Interproximal Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	0.981	6 5	-0.095
5 4	0.984	5 4	0.609
4 3	0.826	4 3	-0.500
3 2	0.464	3 2	1.083
2 1	0.066	2 1	1.441
1 1	0.005	1 1	0.222
1 2	0.088	1 2	0.160
2 3	0.007	2 3	0.050
Second premolar		Lateral incisor	
6 5	0.521	6 5	-0.128
5 4	1.597	5 4	-0.171
4 3	0.686	4 3	-0.143
3 2	0.255	3 2	-0.122
2 1	2.479	2 1	0.091
1 1	-0.016	1 1	-0.026
1 2	0.019	1 2	0.167
2 3	0.052	2 3	0.110
First premolar		Central incisor	
6 5	0.829	6 5	-0.259
5 4	1.310	5 4	-0.122
4 3	0.078	4 3	-0.062
3 2	0.229	3 2	0.000
2 1	-0.069	2 1	0.843
1 1	0.019	1 1	1.121
1 2	0.016	1 2	0.224
2 3	0.059	2 3	0.047

SUBJECT 2

Interproximal Contact for loaded tooth	PCF/ACF (kg)	Interproximal Contact for loaded tooth	PCF/ACF (kg)
First molar		Cuspid	
6 5	2.303	6 5	-0.114
5 4	0.531	5 4	-0.105
4 3	0.209	4 3	-0.053
3 2	0.145	3 2	1.117
2 1	0.202	2 1	0.381
1 1	0.000	1 1	0.028
1 2	-0.002	1 2	0.071
2 3	-0.002	2 3	-0.022
Second premolar		Lateral incisor	
6 5	-0.224	6 5	-0.188
5 4	2.502	5 4	0.053
4 3	0.090	4 3	0.016
3 2	0.241	3 2	-0.003
2 1	0.052	2 1	1.238
1 1	0.000	1 1	0.007
1 2	0.090	1 2	0.262
2 3	0.010	2 3	-0.014
First premolar		Central incisor	
6 5	-0.152	6 5	-0.050
5 4	-0.076	5 4	-0.045
4 3	1.759	4 3	-0.021
3 2	0.255	3 2	0.000
2 1	0.316	2 1	-0.026
1 1	0.319	1 1	1.100
1 2	0.297	1 2	-0.033
2 3	0.053	2 3	0.274

SUBJECT 3

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**	**Interproximal Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	-0.086	6 5	-0.057
5 4	0.019	5 4	-0.026
4 3	0.198	4 3	-0.067
3 2	0.000	3 2	0.000
2 1	0.133	2 1	0.007
1 1	0.000	1 1	0.014
1 2	0.141	1 2	0.009
2 3	0.124	2 3	0.000
Second premolar		Lateral incisor	
6 5	0.384	6 5	0.043
5 4	0.966	5 4	0.024
4 3	0.924	4 3	0.000
3 2	0.000	3 2	0.000
2 1	-0.067	2 1	0.772
1 1	0.000	1 1	0.069
1 2	0.000	1 2	0.000
2 3	0.076	2 3	0.076
First premolar		Central incisor	
6 5	-0.047	6 5	0.093
5 4	-0.069	5 4	-1.357
4 3	2.760	4 3	-0.005
3 2	0.000	3 2	0.000
2 1	0.021	2 1	0.757
1 1	0.083	1 1	0.041
1 2	0.117	1 2	0.000
2 3	0.003	2 3	0.000

SUBJECT 4

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**	**Interproximal Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	0.964	6 5	-0.362
5 4	1.102	5 4	-0.141
4 3	0.645	4 3	-0.079
3 2	0.172	3 2	0.421
2 1	0.000	2 1	0.253
1 1	0.300	1 1	0.102
1 2	0.174	1 2	0.429
2 3	0.052	2 3	0.197
Second premolar		Lateral incisor	
6 5	3.210	6 5	-0.024
5 4	1.624	5 4	0.098
4 3	2.226	4 3	0.078
3 2	0.169	3 2	0.112
2 1	-0.029	2 1	0.850
1 1	0.145	1 1	-0.010
1 2	-0.016	1 2	-0.055
2 3	0.057	2 3	0.238
First premolar		Central incisor	
6 5	-0.041	6 5	-0.222
5 4	0.072	5 4	-0.148
4 3	1.074	4 3	-0.197
3 2	0.441	3 2	-0.012
2 1	0.005	2 1	-0.012
1 1	0.091	1 1	0.469
1 2	0.047	1 2	-0.033
2 3	-0.078	2 3	-0.005

SUBJECT 5

Contact for loaded tooth	**PCF/ACF (kg)**	**Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	1.453	6 5	-0.057
5 4	0.747	5 4	-0.076
4 3	1.160	4 3	0.153
3 2	2.816	3 2	0.388
2 1	0.171	2 1	0.174
1 1	0.284	1 1	0.150
1 2	-0.097	1 2	0.031
2 3	-0.088	2 3	-0.086
Second premolar		Lateral incisor	
6 5	-0.143	6 5	-0.047
5 4	1.524	5 4	0.002
4 3	0.821	4 3	0.212
3 2	0.350	3 2	0.284
2 1	0.252	2 1	0.228
1 1	-0.028	1 1	0.279
1 2	0.069	1 2	-0.064
2 3	0.052	2 3	0.079
First premolar		Central incisor	
6 5	-0.090	6 5	0.116
5 4	0.005	5 4	0.293
4 3	1.438	4 3	0.321
3 2	0.924	3 2	0.397
2 1	0.124	2 1	0.681
1 1	-0.093	1 1	0.041
1 2	0.041	1 2	0.072
2 3	-0.002	2 3	-0.028

SUBJECT 6

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**
First molar	
6 5	1.110
5 4	0.747
4 3	0.314
3 2	0.010
2 1	0.000
1 1	0.003
1 2	0.000
2 3	0.000
Second premolar	
6 5	0.297
5 4	1.664
4 3	0.979
3 2	0.000
2 1	0.000
1 1	0.000
1 2	0.000
2 3	0.000
First premolar	
6 5	0.000
5 4	-0.122
4 3	0.962
3 2	0.000
2 1	0.000
1 1	0.000
1 2	0.000
2 3	0.000

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**
Cuspid	
6 5	0.010
5 4	0.002
4 3	0.000
3 2	0.000
2 1	0.000
1 1	0.000
1 2	0.000
2 3	0.000
Lateral incisor	
6 5	-0.066
5 4	0.014
4 3	0.345
3 2	0.700
2 1	0.521
1 1	0.000
1 2	0.000
2 3	0.000
Central incisor	
6 5	-0.119
5 4	0.005
4 3	0.000
3 2	0.000
2 1	0.000
1 1	0.000
1 2	0.000
2 3	0.000

SUBJECT 7

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**	**Interproximal Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	2.900	6 5	-0.150
5 4	2.134	5 4	-0.290
4 3	0.750	4 3	-0.231
3 2	0.062	3 2	1.033
2 1	0.000	2 1	0.000
1 1	-0.079	1 1	0.112
1 2	0.048	1 2	0.038
2 3	0.150	2 3	0.102
Second premolar		Lateral incisor	
6 5	-0.143	6 5	-0.043
5 4	1.631	5 4	-0.036
4 3	0.497	4 3	0.264
3 2	0.052	3 2	1.643
2 1	0.000	2 1	0.000
1 1	-0.169	1 1	-0.214
1 2	0.097	1 2	0.150
2 3	0.059	2 3	0.002
First premolar		Central incisor	
6 5	-0.038	6 5	-0.019
5 4	0.038	5 4	-0.050
4 3	2.243	4 3	-0.048
3 2	0.288	3 2	0.505
2 1	0.000	2 1	1.169
1 1	0.016	1 1	0.759
1 2	-0.050	1 2	0.459
2 3	0.309	2 3	0.000

SUBJECT 8

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**	**Interproximal Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	0.148	6 5	0.079
5 4	0.514	5 4	0.000
4 3	0.059	4 3	-0.403
3 2	-0.019	3 2	0.148
2 1	-0.055	2 1	-0.007
1 1	0.000	1 1	0.000
1 2	0.114	1 2	0.000
2 3	0.050	2 3	-0.021
Second premolar		Lateral incisor	
6 5	0.655	6 5	-0.091
5 4	1.705	5 4	-0.321
4 3	0.836	4 3	0.003
3 2	0.371	3 2	-0.040
2 1	-0.031	2 1	0.455
1 1	0.000	1 1	0.000
1 2	0.009	1 2	0.000
2 3	-0.021	2 3	0.021
First premolar		Central incisor	
6 5	-0.143	6 5	-0.012
5 4	-0.314	5 4	0.000
4 3	0.929	4 3	0.016
3 2	0.179	3 2	0.459
2 1	2.919	2 1	0.779
1 1	0.000	1 1	0.000
1 2	0.000	1 2	0.000
2 3	-0.033	2 3	-0.041

SUBJECT 9

Interproximal Contact for loaded tooth	**PCF/ACF (kg)**	**Interproximal Contact for loaded tooth**	**PCF/ACF (kg)**
First molar		Cuspid	
6 5	0.359	6 5	0.000
5 4	0.962	5 4	0.000
4 3	0.000	4 3	0.000
3 2	0.117	3 2	3.290
2 1	0.045	2 1	1.081
1 1	0.010	1 1	0.531
1 2	0.000	1 2	0.000
2 3	-0.034	2 3	-0.167
Second premolar		Lateral incisor	
6 5	0.000	6 5	0.000
5 4	2.300	5 4	0.000
4 3	0.000	4 3	0.000
3 2	-0.212	3 2	0.328
2 1	0.000	2 1	0.005
1 1	-0.271	1 1	0.000
1 2	0.000	1 2	0.000
2 3	-0.002	2 3	-0.152
First premolar		Central incisor	
6 5	0.000	6 5	0.000
5 4	0.000	5 4	0.000
4 3	0.000	4 3	0.000
3 2	0.000	3 2	0.293
2 1	0.000	2 1	1.450
1 1	0.000	1 1	0.321
1 2	0.000	1 2	0.000
2 3	-0.062	2 3	-0.176

SUBJECT 10

Interproximal Contact for loaded tooth	PCF/ACF (kg)	Interproximal Contact for loaded tooth	PCF/ACF (kg)
First molar		Cuspid	
6 5	0.081	6 5	-0.178
5 4	-0.041	5 4	-0.169
4 3	-0.010	4 3	-0.124
3 2	-0.012	3 2	0.217
2 1	-0.076	2 1	0.276
1 1	-0.071	1 1	0.159
1 2	-0.079	1 2	0.043
2 3	-0.076	2 3	0.048
Second premolar		Lateral incisor	
6 5	-0.017	6 5	-0.095
5 4	1.369	5 4	-0.116
4 3	0.400	4 3	-0.129
3 2	0.048	3 2	0.014
2 1	-0.066	2 1	0.383
1 1	0.009	1 1	0.181
1 2	-0.083	1 2	0.190
2 3	-0.209	2 3	0.095
First premolar		Central incisor	
6 5	-0.150	6 5	-0.062
5 4	0.131	5 4	-0.090
4 3	0.691	4 3	-0.086
3 2	0.076	3 2	0.010
2 1	0.041	2 1	0.140
1 1	0.034	1 1	0.138
1 2	0.005	1 2	-0.052
2 3	-0.124	2 3	0.003

APPENDIX E

INDIVIDUAL SUBJECT IRREGULARITY INDICES

INDIVIDUAL SUBJECT IRREGULARITY INDICES

Subject	Irregularity Index
1	4.09
2	0.82
3	---
4	0.98
5	5.06
6	0.59
7	0.61
8	0.57
9	0.34
10	3.41

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