THREE DIMENSIONAL COMPUTER MODELING OF HUMAN MANDIBULAR BIOMECHANICS

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ABSTRACT

Previous analyses of mandibular biomechanics have incorporated a wide variety of approaches and variables in attempts at describing the relationships between the forces generated by the muscle and the forces of resistance at the dentition and temporomandibular joints. The most difficult element to determine in man has been the role of the joint forces which require indirect analyses. A critical literature review points out the problems associated with previous analyses of mandibular mechanics and predictions of joint loading and the need for the incorporation of all relevant anatomical and physiological parameters in order to realistically quantify these relationships.

A computerized mathematical model of human mandibular biomechanics for static functions is presented which allows the determination of forces occurring at the dentition and the joints due to the individual muscle force contributions. Utilizing the principles of static equilibrium the model provides for the determination of these forces for any individual for whom the necessary input parameters have been derived.

Anatomically, this model requires the designation of the three dimensional coordinates of the origin and insertion points of nine pairs of masticatory muscles, any position of tooth contact, and the temporomandibular joint positions. Determination of the forces generated by the individual muscle groups, and therefore the overall muscle force resultant acting on the

system, is given by the product of a number of physiological parameters. These include the physiological cross-section, the intrinsic force per unit of cross-sectional area, and the relative activation level of each muscle for the specific static function. Also required is the three dimensional orientation of tooth resistance force at the designated position of tooth contact, as well as that of the left joint force in the frontal plane. This information reduces the variables in the equilibrium equations to a determinate number which has a single unique solution for each of the tooth and two joint resistance forces. The magnitudes as well as three dimensional orientations of the resultant vectors of the muscles, the tooth resistance force and the two temporomandibular joints are thereby determined mathematically.

Both bilaterally symmetrical and unilateral clenching functions as well as three intervals near the intercuspal position of chewing were tested with this model using data derived from literature sources from real subjects. This data was incorporated into a hypothetical average individual data file. Using this data, derivation of the magnitudes and orientations of muscle and tooth forces were made providing predictions as to the nature of temporomandibular joint loading for this individual.

The extent of muscle force generated for static maximal clenching tasks modeled was a maximum of 1000 to 1200 N during intercuspal clenching. The orientation of muscle force with respect to the occlusal plane varied from about 90 degrees in the lateral plane, for more posterior molar functions, to

64 degrees for incisal functions. Maximal tooth resistance forces were around 500 to 600 N at the molars versus only 130 to 140 N at the incisors. Unilateral functions showed the working side joint to be more heavily loaded than the balancing side especially for a more posterior function (i.e. molar). Less muscle and therefore tooth force was produced unilaterally but with the benefit of even less residual joint force. Thus, unilateral functions appear to be much more efficient in terms of the distribution of forces between the dentition and joints. Variation in tooth orientation produced variations in both the orientation and magnitudes of the joint forces exhibiting a functional interrelationship of these forces. Based on the analysis in general, the joints were predicted to be capable of resisting up to 300 N of force per side directed anterosuperiorly at about 60 to 100 degrees in the lateral plane. More divergent forces at the joints were found to be of substantially lower magnitude in the lateral and frontal planes. These findings are in good agreement with other studies.

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INTRODUCTION

The basic mechanical components which comprise the masticatory apparatus consist of the dentition, the muscles of the jaws, and the temporomandibular joints. Depending upon the nature of an individual's craniofacial form, and resulting anatomical relationships, it would seem likely that certain biomechanical associations would also exist between the forces generated by the muscles, and the opposing forces of resistance which occur at the joints and teeth. Since the relationships between these components determine the biomechanical nature of the system, they would be expected to be functionally interdependent. As such, any changes or disturbances (surgical, traumatic or pathological) to one component would potentially influence another. Evidence for this is provided by clinical observations of patients with functional disturbances of the masticatory system.

It is apparent, that the mechanical components of the masticatory system are intimately related from a functional and dysfunctional point of view. Hence, certain associations of form (which relate the muscles, the joints, and the dentitions) and function must also exist. Determination of the normal functional relationships between these components will greatly aid in our understanding, and treatment of dysfunctional states involving abnormal biomechanical relationships of the system.

Although some components of this system are amenable to direct functional study (eg. electromyography, kinesiography, transducer loading, etc.), others, in particular the loads borne by the joint, are not. Here indirect modeling approaches are attempted, at least in man, and usually involve deductive techniques based upon the principles of static mechanics.

A. MANDIBULAR BIOMECHANICS AND MODELING - LITERATURE REVIEW

Over 60 years ago Alfred Gysi (1921) stated that two questions pertaining to mandibular activity which had "been long and sometimes bitterly discussed" were, (1) which class of lever was represented by the mandible during hard clenching, and, (2) what was the extent of the forces produced at the teeth and temporomandibular condyles. Apparently many investigators of the time were of the opinion that the mandible was one of nature's engineering failures. Gysi attributed this to the persistence of studies, up to that time, which considered only the working side of the mandible. The balancing side influences of muscle activity, "were either overlooked or assumed to be the same as those in the working half." As such each side of the mandible seemed to act as a separate class III lever and thus appeared to be very inefficient.

Gysi (1921) further stated that around 1918 a new school of thought had emerged proposing that the mandible was not a lever at all and the entire force of the muscle was distributed entirely through the teeth. This concept has persisted until fairly recently (eg. Gingerich, 1971 and 1979) and has become known as the "link" theory whereby the mandible is suspended in a sling of muscles and merely links the muscle force to the force at the teeth. Gysi also considered this view to be a result of overly simplistic assumptions.

Gysi's own analysis (1921) was based on the following statement,

> "any articulating joint may be fixed by muscle action at any stage of its possible motion and become just as much a fulcrum for lever action as if it were a rigid anatomical structure."

Leverage analyses had predicted that from one-third to two-thirds of the muscle force exerted was not effective at the teeth, which had contributed to the opinion of mandibular inefficiency. Gysi attributed this "lost" force as that "required to fix the condyles, as fulcrums, upon the inclined and lubricated surfaces of the eminentia."

Utilizing both a mathematical derivation and a mechanical model he showed that during the unilateral crushing of food, the two sides of the mandible acted as two class III levers connected at the symphysis. The result of this was such that the fulcrum producing effect of the balancing side muscles on the condyle would act through the symphysis to contribute significantly to the crushing force on the working side, as well as reduce the force at the working condyle due to the fulcruming action of the muscles pulling on that side. Therefore, the resistance forces at the teeth and condyles would be inversely related. This three dimensional analysis produced a much more efficient and complete picture than that of the two dimensional considerations. According to his theory, unilateral crushing of a hard object more anteriorly along the dentition would result in a relative increase in working side condyle force. His analysis also showed that this force would be "neutralized" at the second molar region. Accordingly, at the third molar position hard food could not be crushed since the fulcrum reducing force acting on the working condyle would be negative and of such magnitude as to tear the ligaments and disclude the joints. The force at the balancing condyle Gysi determined to be constant, regardless of the position of the working side bite point, and equivalent to one third the total force applied. In all instances this force was greater than that of the working side condyle.

In deriving these relationships Gysi incorporated remarkably detailed anatomical parameters for his time including the three dimensional positions of the dentition, the condyles and the points of application and orientation of the muscles. He derived values for the cross sectional areas of each of the muscle groups and determined their maximum force capabilities. It is worth noting here that, according to their alignment of fibers, he subdivided the muscles into distinct groups consisting of superficial and deep masseter, medial pterygoid, anterior, middle and posterior temporalis, and superior and inferior lateral pterygoids. The only information which was unavailable to him were the relative activities of each muscle group which would not be measurable for another thirty years. He therefore assumed all muscles to be active to the same extent, despite the point of tooth resistance used, since no one knew otherwise at the time.

Due to the complexity of factors involved, their interplay, and the necessity of indirect assessments, many of the analyses of mandibular mechanics since Gysi's work exhibit widely differing approaches to the determination of the functional relationships which exist. By necessity they all share the assumption of static equilibrium, but that is where the similarity ends. Unfortunately, they have for the most part been very limited in their consideration of the multiple factors which can become involved in jaw mechanics depending upon the function. Most have oversimplified the variables and/or have been restricted to two dimensions only (sagittal representations). As a consequence many erroneous or misleading conclusions and interpretations have arisen. These different points of view have continued to fuel arguments over which factors, or relationships between factors, are most important. Much of the controversy which has persisted concerns whether the mandible acts strictly as a lever, with some of the functional load produced by the muscles taken up by the joints, or whether it functions as a so-called "link". There has even been some discussion among lever proponents as to what type of leverage system is at work (ie. class I, II, III, or a combination) (Davis, 1955; Turnbull, 1970; Smith, 1978).

1. Two Dimensional Models

a. Non-Lever Models

At about the same time as Gysi proposed his models G.H. Wilson (1920 and 1921) was refuting the lever action theory basing his ideas on somewhat simple qualitative analyses of the orientations and combined action of the masseter and temporalis muscles. He concluded that the resultant muscle force acted at right angles to the occlusal plane, and for this reason, "the whole force of these muscles is expended upon the bolus of food and not any portion of it upon the condyle" (Wilson, 1920). Although he made no distinction between unilateral or bilateral functions Wilson implies that this principle holds true for all cases. However, it would not be enough for the resultant to be merely oriented perpendicular to the occlusal plane, as Wilson suggested. It must pass directly through the bite point as well, (Roydhouse, 1955; Hylander, 1975).

Some years later Robinson (1946) determined a resultant force position for the masseter/medial pterygoid and temporalis muscles in the sagittal plane and concluded that it did, in fact, pass through the molar teeth. Hylander (1975) argued that the anatomical relationships Robinson incorporated in his analyses were erroneous since he considered only selected muscle fiber alignments and disregarded relative muscle size, and hence, force capabilities (see Figure 1). Hylander further pointed out that the contribution of the anterior temporalis had been underestimated and that of the masseter-medial pterygoid complex positioned too far anterior relative to the teeth. The position of the dental arch, which is critical to Robinson's argument, also appears to be too far posterior (see also Page, 1954). The muscle force vector could therefore not pass through the dentition (Roydhouse, 1955).

The premise to Robinson's theory was that the tissues comprising the joints were not suited to resist compressive stresses. This argument has been one of the main reasons why some investigators have opposed the lever action theory and sought alternate explanations to account for the seeming incompatability between lever-type mechanics and histological features. Robinson showed that the articular disc contains synovial tissue, blood vessels, nerves and lymphatics and is composed of fibrocartilage. Since none of these tissues are characteristic of the stress-bearing joints found

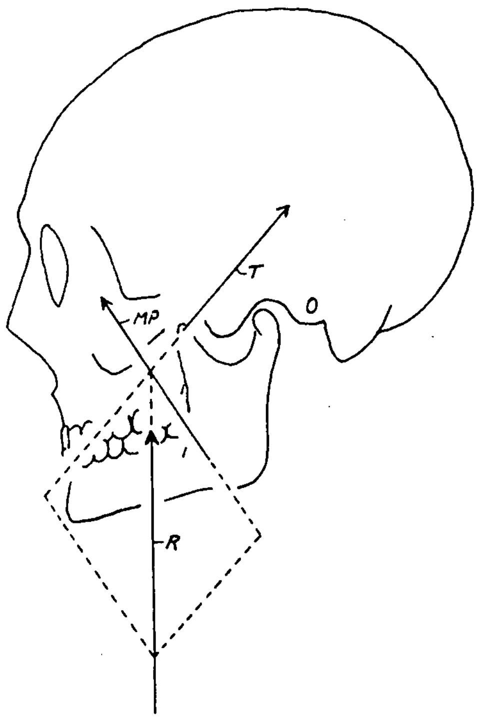

Figure 1. ROBINSON'S PARALLELOGRAM OF MANDIBULAR FORCES. The muscle forces are those due to the temporalis (T), masseter and medial pterygoid components. R represents the resultant of these components and passes through the tooth row (After Robinson, 1946).

between some long bones of the body Robinson argued for the stress-free function of the temporomandibular joint. He assumed that the point of any articulation would be within the glenoid fossa of the joint which has a very thin bony roof and would, by itself, be incapable of bearing any compressive load. However the actual stress bearing region of the joint is not within the fossa, but between the fibrocartilaginous surfaces of the condyle and the opposing surface of the articular eminence, which is supported by a relatively thick cortical plate of bone (Oberg and Carlsson, 1979; Carlsson and Oberg, 1979). This area of articulation corresponds with an area of the intervening disc which is avascular and completely lacks both a synovial layer, and nerves (Rees, 1954; Hylander, 1975). It is the posterior aspect of the disc opposing the roof of the fossa which contains the non-stress elements (Hylander, 1975). The fibrocartilage covering the articular surfaces of the temporomandibular joints, as opposed to the articular hyaline cartilage of stress bearing joints of the body, is considered by many to possess stress bearing qualities similar to hyalin cartilage under compression. It has also been attributed with the ability to provide superior resistance to both tensile and shearing forces (see Hylander, 1975). The histologic differences between the temporomandibular joint and the other stress bearing joints of the body may be related more to the embryological differences between long bones and the mandible. Long bones are derived from cartilaginous precursors via epiphyses, whereas the mandible arises from membrane bone. Thus the lack of epiphyseal development in the mandible may reflect developmental, rather than functional differences (Barbenel, 1969; Oberg and Carlsson, 1979).

Tattersall (1973) also believed the lever action hypothesis incorrect on the grounds that the tissues of the joint, as well as the condylar neck, were inadequate to support the large reaction forces which would occur. The inherent inefficiency of such a system would not have survived natural selection pressures and would not have evolved according to him. It may be noteworthy, however, that Tattersall's conclusions were based on analyses of the masticatory apparatus of an extinct group of primates.

Hylander (1975) tested the hypothesis that the condylar neck is too weak to support the forces arising (shearing and bending) in man which he reasoned to be greatest during incisal biting. Using a dried human mandible, known muscle activities (Moller, 1966) and lines of action (Schumacher, 1961), and the mechanical properties of bone (Alexander, 1965) Hylander determined the condylar neck to be capable of withstanding an average of at least 238 kg of shearing stress, based on the cross sectional area of compact bone at this level. He determined the amount of bending force required to break the condyle during incisal biting to be at least 60 kg per condyle which corresponds to incisal bite forces of 70 kg or greater. Maximum incisal bite recordings in humans have consistently shown this force to be of the order 20-25 kg or less (Linderholme and Wennstrom, 1970; Rugh and Solberg, 1972; Ringquist, 1973; Helkimo et al. 1975 and 1976; Mansour, 1977; Finn, 1978; Helkimo and Ingervall, 1978). Thus the condyle of his analysis was clearly of sufficient strength to support large reaction forces.

Nevertheless, Moyers (1950) interpreted his own pioneering electromyographic work on the functional activities of the muscles of mastication in support of Robinson (1946). Although Moyers did not test the hypothesis, he speculated that the coordination of the muscles he had observed in mandibular movements would also interact to eliminate forces at the joints (via reflexes arising in the joints themselves). This implies some sort of combined or "coupling" action of one muscle (eg. temporalis) to reduce or eliminate the stress-inducing action of another (eg. masseter-medial pterygoid complex) at the joint. A similar effect has been either proposed or implied by Scott (1955), based on qualitative anatomical comparisons of sheep, dog and human; by Davis, (1955), using dissections of the spectacled bear, Tremarctos ornatus; by Turnbull, (1970) in a variety of mammalia with functionally different masticatory schemes; and by Roberts and Tattersall, (1974) for the mammalia in general.

Roberts (1974), and Roberts and Tattersall (1974) believed this coupling effect rotated the jaw, in both elevation and depression, and occurred around the mandibular attachment of the spenomandibular ligament. According to them the jaw would rotate around this fulcrum within the muscular sling of the temporalis/masseter-medial pterygoid complex without the necessity of a condylar fulcrum, and thus no resulting joint force. The unlikelihood of a ligamentous fulcrum point had been exhorted very early in the literature by Wilson himself (1920, 1921).

Smith (1978) has since pointed out that forces which form a true couple are not collinear, are equal in magnitude, and are opposite in direction. Thus the "couple" formed by the forces of the temporalis and masseter-medial pterygoid muscles of Roberts and Tattersall (1974) do not satisfy the latter two requirements and therefore do not constitute a couple. Also, their analysis only accounts for the rotational effects due to the anteroposterior components of muscle force. The effects of the vertical components of their muscle resultants, which they have neglected, must be accounted for by some other force somewhere in the system. It follows that since the "couple" due to the anteroposterior muscle force "components" must be generating the necessary force at the teeth, by virtue of their rotational effects the only other area where a force resisting the vertical component of muscle force can occur is obviously at the joint. The lever analyses of both Davis (1955) and

Turnbull (1970), also fail to consider the vertical components of their muscle forces and are subject to the same criticisms as Roberts (1974), and Roberts and Tattersall (1974).

Finally, Smith (1978) has also criticized such analyses on the grounds that the muscle "vectors" assigned are purely arbitrary and, as such, provide no basis for any conclusions to be drawn. Roberts (1974) had suggested that since the three "vectors" (masseter-medial pterygoid, temporalis, and bite point) form a closed triangle when added geometrically, there was no additional joint reaction force necessary. Since his suppositions appear to be untrue, so must his conclusions.

Although the term "couple" maybe inappropriate in these studies the effect these investigators were trying to describe is apparent, and the ability of the muscles to cooperate, in at least reducing some of the resulting joint forces, has been described by a number of other workers (Smith and Savage, 1959; Crompton, 1963; Greaves, 1974 and 1978; Noble, 1979). This matter is discussed later.

The most simplistic analysis of the link variety was that of Frankel and Burstein (1970). They considered two muscles only (masseter and temporalis) and assigned apparently arbitrary vectors to both as well as to the tooth resistance force. They maintain that since these three "vectors" form a closed triangle when geometrically added all forces in the system are accounted for. Vector addition such as this does hold, but only when the vectors are real. As already stated no credible conclusions can be drawn from mechanical analyses incorporating arbitrary vectors. Hylander (1975) also leveled the same criticism at the masseter vectors of this analysis as that of Robinson (1946) since they are positioned too far anteriorly with respect to the teeth.

In 1971 Gingerich coined the term when he proposed his "link" action of the jaw based on a previously unknown masticatory movement which he called "orthal retraction" (upward and backward) and made the questionable assertion that the temporalis is the main adductor of the mandible. He maintained that the alignment of the fibers of the temporalis were such that their anterior projection past the coronoid insertion formed an envelope which included the entire tooth row and thus any potential bite point (See Figure 2). Therefore, an upward and backward effort by the component of the temporalis aligned with the given bite point would transmit its force to the occlusion via the coronoid process rather than through the condyles. The translatory capabilities of the joints would be most suited to this. Such a system, according to Gingerich, would be much more efficient than the lever system as no "wasted" force would be necessary at the joint. He also felt it to be more reasonable than the non-lever system of Robinson (1946) since the orientation of the temporalis would not need to be as far back on the cranium (ie. corresponding to the posterior portion of the muscle) as in Robinson's proposal.

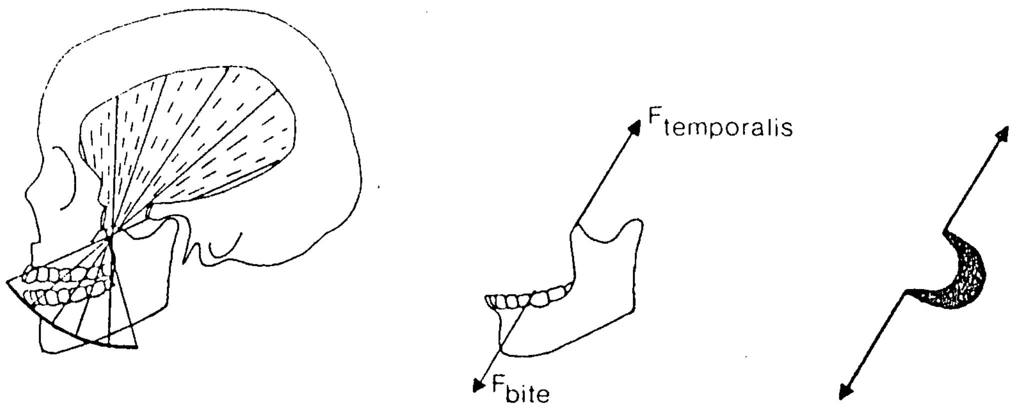

Figure 2. "LINK" CONCEPT OF MANDIBULAR FUNCTION AS PROPOSED BY GINGERICH. The alignment of the temporalis muscle fibers projected anteriorly enclose the entire dentition. It was therefore suggested that for any bite point the temporalis could account for the generated bite force without necessarily involving the temporomandibular joints. The mandible would thus act singly as a link between the two forces (Based on Gingerich, 1971).

The obvious limitation with this system is Gingerich's neglect of the other muscles which he, himself, states "are not aligned with any bite point" and "their force of contraction is divided between useful bite force and wasted reaction force at the jaw joint." It would therefore seem more appropriate to interpret this system as a lever with a means of increasing its own efficiency by containing a "link" effect which could reduce the "wasted" force occurring at the joints. However, as Hylander (1975) convincingly shows, neither the premise of "orthal retraction" type movements, nor the necessary isolated activities of the temporalis, are supportable.

In each of these non-lever theories the limitations of their generalizations (eg. two dimensional) and often qualitative and/or erroneous analyses in explaining the actual events involved with mandibular function are obvious. More importantly, they serve as examples of the fallacy in ascribing too much importance to too few variables.

b. Lever Models

The lever action postulate has generally been more widely accepted (eg. Hylander, 1975; Smith, 1978) as a first approach to understanding mandibular mechanics. The fulcrum effect attributed to the condyles has formed the basis of a variety of analyses aimed at explaining these mechanics in man as well as numerous other creatures (eg. Ostrom, 1964).

Simple class III lever analysis, in the sagittal plane, assumes a fulcrum point at the joints and predicts a linear increase in bite force as the occlusal contact point moves posteriorly along the dentition, given a constant applied force (Mainland and Hiltz, 1933; Gosen, 1974). This is because the length of the moment arm from the fulcrum decreases with more posterior contacts. Since the applied load of the muscle remains constant larger posterior tooth loads are necessary to produce the same moment about the fulcrum which must balance, or oppose that due to the muscle force. The morphological differences between the anterior and posterior teeth reflect the need for greater distribution of occlusal loads posteriorly.

Based on purely morphological analyses it has been shown that the consistent similarities in the jaw forms of carnivores and in those of herbivores, seems, in large part, to be based on differences in general lever mechanics which have evolved in response to the nature of the given animal's food type (Becht, 1953; Smith and Savage, 1959; Barghusen, 1972; Scapino, 1972; DuBrul, 1974). Carnivores, for instance, all have in common relatively large temporal versus masseter-medial pterygoid muscles, a condyle close to the level of the tooth row, a tall coronoid process with respect to the condyle and tooth row, and a virtually hingelike articulation of the jaw (Smith and Savage, 1959; Dubrul, 1974). Smith and Savage (1959) have suggested that the alignment and relatively large size of the temporalis muscle (unlike the masseter-medial pterygoid complex) would prevent disarticulation of the joints by a struggling prey pulling in the opposite direction as would the anteroposteriorly rigid joint articulation. It has also been pointed out that both the tall coronoid process (Ostrom, 1964) with a relatively long moment arm for the large temporalis, and the low position of the condylar fulcrum relative to the tooth row* are adaptations which could produce a powerful (ie. bone-crushing) bite (Smith and Savage, 1959; Barghuson, 1972; Crompton and Hiiemae, 1969). This arrangement would also produce a large downward and backward force at the condyle tending to cause disarticulation which could be reduced (but not eliminated) by synergistic activity of the masseter muscle pulling upwards and forwards (Smith and Savage, 1959; Greaves, 1974; Nobel, 1979).

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*Greaves (1974) has taken exception to the significance of low condylar position and has argued that adaptive changes in the vertical position of the condyle with respect to the tooth row, may not effect any change in mechanical advantage of the system as a whole. He bases this on the assumption that both the masseter and temporalis muscles are equally important in static mechanical function of the organism. According to Greaves, an elevated condyle in the herbivore would reduce the moment arm, and mechanical advantage, of the temporalis and increase that of the masseter. However, since the usually unilateral nature of herbivorous mastication requires that the adaptive changes favor the action of the working side masseter and medial pterygoid in order to maximize the transfer of muscle force to the teeth (Smith and Savage, 1959) the reduction in temporalis effectiveness may be less important. In fact the relative size of this muscle is greatly reduced compared to carnivores which have very different working versus balancing side requirements.

Further evidence for the latter point is provided by morphological observations of ancient mammal-like reptiles (eg. cynodonts) which exhibit a progressive reduction in size and strength of the jaw-joint (dentary-squamosal joint at this point in evolution), accompanied by an increase in mass of the adductors and presumably also a subsequent increase in jaw joint reaction force (Crompton, 1963; Parkyn, 1963; Barghusen and Hopson, 1970; DuBrul, 1974; Noble, 1979). This apparent paradox, is believed to be due to the concurrent reorientation of the muscle forces with changes in muscle attachment points. Reorientation would produce the moderating effect of the temporalis/masseter-medial pterygoid synergism described above, which reduces joint forces concurrent with increasing muscle and tooth forces. This effect has been correlated with the appearance of "molariform" teeth capable of withstanding the increased tooth forces (Crompton, 1963).

Bramble (1978) took the two dimensional lever model a step further in his explanation of evolutionary trends and joint forms in mammalian feeding complex. He proposed a "bifulcral" model which considers the bite point, as well as the jaw joint, to act simultaneously as fulcra in the system. Analyzing the rotational effects of the muscle vectors in this way Bramble showed that there is a secondary moment produced at the joint due to rotational effects at the bite point fulcrum. This is in addition to the primary moment produced at the bite point due to rotation about the joint fulcrum. This secondary moment at the joint requires a resistance force to maintain equilibrium. Bramble showed that the magnitude of this joint force due to the rotational effects at the bite fulcrum varies with the position of the bite point, and orientation of the muscle vector considered. His model suggests that each muscle will have a specific positive or negative loading effect at the joint depending on the location of the tooth contact anteroposteriorly. Also, depending on its orientation, each muscle has a theoretical "neutral point" somewhere along the tooth row where it would not generate any rotational forces at the joint by itself. Only translational forces are present. Based on this, Bramble suggested that when the temporalis and masseter muscle vectors are considered together their net effect may be to minimize the joint loads through functional synergism. He concluded that the jaw joints of early mammal-like reptiles were not subject to heavy compressive loading but more likely underwent small, neutral, or even slightly tensile loads.

Bramble showed how many of the evolutionary changes observed in the jaw form of cynodont therapsids (so-called mammal-like reptiles) such as development of a coronoid process, elaboration of the superficial masseter muscle, rearward growth of the condylar process, and development of the retroarticular process (also present in extant carnivores) could be explained according to this model. As he also points out, the likelihood of differential activities of the muscle groups and the resulting variety of muscle lines of action, and subsequent interaction, would add to the potential combinations of function and therefore form.

Both Craddock (1951) and Roydhouse (1955) attempted to provide a general mathematical solution to the analysis of the joint function in humans based on essentially qualitative analyses using simple class III lever mechanics. Craddock limited his analysis to a single vertical component of assumed muscle force in the sagittal plane and determined the difference in joint force for an incisor versus molar bite point. Roydhouse, on the other hand considered both the horizontal and sagittal plane as well as different directions of pull between the various muscles (superficial and deep masseters, medial pterygoid, different portions of the temporalis, and lateral pterygoid). He assumed the net force of the muscles to be within a zone somewhere between the two coronoid processes posterior to the anterior border of the ramus, and perpendicular to the occlusal plane. He stated that under equilibrium conditions, "the lines of action of the purely vertical resultants of muscular action and food resistance [at the teeth] cannot coincide, unless food is chewed on the rami." Since these forces are not collinear a third vertical force is required to maintain equilibrium which Roydhouse believed must lie at the joints, thus generating a resistance force on one or both condyles.

Prior to this both Moyers (1950) and Carlsoo (1952) had applied the new techniques of electromyography to the masticatory muscles and established their differential nature of activity and contributions to various movements. Roydhouse showed very generally, that for differential activity in the right and left side muscles the position of a single vertical resultant in the horizontal plane would lie closer to the side of greatest effort. Thus the condyle resistance force would be expected to be unequal on the two sides.

The analyses of both Craddock and Roydhouse have been criticized for having considered only vertical forces and ignoring "horizontal" (anteroposterior) components. Barbenel (1969, 1972, 1974) pointed out that the combination of both vertical and horizontal components of muscle force could produce a net resultant which might cross the tooth region or zone

(Robinson, 1946). Since only the magnitude of tooth forces and not their orientations had ever been measured, Barbenel (1969) suggested that the simultaneous muscle and tooth force resultant vectors, for a specific function, could theoretically be collinear. In such cases little or no load would exist at the joint, in the sagittal plane at least. He therefore presented a two dimensional (i.e. bilaterally symmetrical) sagittal analysis of jaw function for which the lines of action and moment arms (measured from a fulcrum assumed to be at the condyles*) of the masseter, temporalis, medial and lateral pterygoid muscles had been determined by dissection. Assuming static equilibrium conditions to hold, Barbenel postulated that three simultaneous linear equations would exist such that, (1) the sum of the vertical force components; (2) the sum of the anteroposterior force components, and; (3) the sum of the moments, (forces times their moment arms or perpendicular distance to an arbitrarily assigned fulcrum point) about the intercondylar axis (fulcrum point), would all equal zero.

In order to solve these equations to determine the joint load and its orientation both the magnitude and orientation of the occlusal load must be known as well as the magnitudes of the individual muscle forces. Barbenel

*Grant (1973) has stated that the moments should be determined about a center of mandibular rotation which varied with the position of the mandible. He concluded that these "instantaneous" centers of rotation for given jaw positions (in the sagittal plane) provided an improved estimate of the jaw closing moments of each muscle and correlated better with their anatomical alignments and known functions. However, because equilibrium conditions prevail during static functions the point in space about which all moments would act is unimportant, since the net sum of all moments about any point is zero. Grant failed to include the moments of reaction force at the teeth and joints (Stern, 1974). As such, the amount of force at the dentition would be the same regardless of where the fulcrum point is located. Thus, his instantaneous centers of rotation are of questionable use in determining static mandibular function (Hylander, 1975).

had determined the spatial orientations of the latter. He then used what appears to be a somewhat complex mathematical process (at least as far as his description of it goes) namely "linear programming analysis" to determine the theoretical "minimum" value of joint force compatible with equilibrium. For changes of the tooth force angle (from apparently any specified initial angle of tooth resistance) of 15 degrees in either direction (relative to the occlusal plane) positive (ie. compressive) loading of the joints was predicted. The extent of this loading increased with more anterior positions of the occlusal point. Barbenel then tested the theoretical minimum predictions experimentally, using surface recordings of the electromyographic activity of all but the lateral pterygoid muscle. Barbenel used these to assign force magnitudes to the muscle vectors during measured vertical loading of the mandible. Since the magnitude of lateral pterygoid force as well as the magnitude and orientation of the joint force remained unknown Barbenel was only able to determine these joint force parameters as a function of the ratio of assumed lateral pterygoid force to occlusal load. However the force of a given muscle is really the product of its normalized EMG activity and its relative maximal force capability (Weijs, 1980; Weijs and Dantuma, 1980; Pruim, 1980), which is related to the muscle's relative size. Barbenel did not consider the latter. Instead he assumed that since the relation between EMG levels and isometric muscle force is linear, the proportionality constant* between the two for a given muscle, multiplied by

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*This can be determined under isometric conditions from a least square regression of the relation between the tooth force and the integrated EMG (Weijs, 1980).

its integrated EMG activity, would give the relative force for that muscle. However, Weijs (1980) has stated that this method serves as a first approximation only, and depends on the properties of the recording electrodes, among other things. Therefore, Barbenel's muscle forces render his conclusions suspect, even though they are only relative, proportional observations. Nevertheless, he concludes that the joint is loaded and that the minimum muscle force principle does not apply, i.e. there is more force applied to the joint than the "minimum" predicted from his analyses. All in all, this is not a very good return of information for the effort involved and the usefulness of further analyses along these lines, other than as an interesting algebraic exercise, is questionable (eg. Barbenel, 1983). However the basic approach taken by Barbenel (1969) to include all the relevant information (ie. lines of muscle pull, their vector length, and moment arms, as well as the magnitude and orientation of the occlusal load vector) does allow the determination of joint force magnitude, and orientation, if static equilibrium theory is used. The only prerequisite is knowledge of the values of each variable for the task at hand, in each plane or planes of reference. Under such conditions no movement can take place and, as described above, all forces are completely opposed, thus satisfying Newton's third law, and all static requirements.

c. Lever-Link Considerations

The idea that the components of the mandibular system may interact, in certain instances, to reduce the force transmitted through the condyles seems appropriate. There is some experimental evidence to suggest that human jaw mechanics are not strictly those of a simple class III lever and that other, more complex relationships may exist. For instance, various workers have observed a decrease in maximal bite force recorded at relatively more posterior positions (ie. the second molar) during both bilateral (Pruim et al., 1980, Tradowsky and Dworkin, 1982) and unilateral biting (Mansour and Reynick, 1975). If the mandible really is only a lever then posterior teeth should be capable of producing relatively more force, for the same muscle effort, than anterior teeth. However, the ability of the system to function in more sophisticated ways than as a lever may not be limited to considerations of posterior tooth forces.

Hylander (1978) determined both the orientation and magnitude of human incisal bite forces at 10 to 30 mm of anterior jaw opening. He concluded that since observed vertically and anteriorly directed incisal tooth forces could not be resisted by the muscle forces alone, and thus required concurrent joint resistance forces, the mandible must act as a lever. Gingerich (1979) re-evaluated Hylander's results and concluded that the orientations of the incisal forces of resistance were such that the mandible functioned as both a lever and a link. Based on similar assumptions as in his earlier work (1971) Gingerich surmised that contraction of middle and posterior temporalis fibers, acting perpendicular to the incisal bite forces, contributed to the link portion. These muscles would not be capable of contributing to any joint forces and could, in fact, reduce as well as stabilize them. Contraction of the masseter-medial pterygoid muscles would produce joint forces and thus contribute to the lever portion of the mechanics.

There is also certain experimental evidence in support of the notion that concurrent lever and link effects may exist. Ferguson (1977) noted a consistent rocking movement of dental casts from many different patients. This occurred about a pivot or fulcrum in the premolar area, and persisted even in older patients with significant occlusal wear. It was only absent in casts of patients who had undergone orthodontic, or occlusal equilibration treatment. Ferguson suggested that the two centric occlusion positions observable (one anterior, one posterior) were some sort of tolerance to compensate for joint compression. This would imply that the mechanics of the system are different for anterior tooth contacts as opposed to posterior contact (Bramble, 1978).

Tradowsky and Kubicek (1981) observed the same phenomenon and hypothesized that the resultant force vector of the mandibular adductor muscles, in bilateral clenching, intersected the occlusal plane at the premolars. Such an occurrence requires the sum of the individual vectors in this plane to interact in a particular way other than as a simple lever mechanism. Consequently these workers concluded that the extent of joint loading would vary depending on the position of the bite point with respect to this "physiological equilibrium point of the mandible." For bite points corresponding with this position no, or little joint loading would occur. More posterior contacts would provide a tooth fulcrum behind the muscle resultant and thus tensile joint forces. Anterior contacts would provide for more compressive joint forces. These are the same conclusions reached by Bramble (1978).

However, implicit in this argument is the assumption that the activities of each muscle and the overall muscle resultant remain the same for different points of tooth contact, which is not necessarily so.

Confirmation that both lever and link conditions may apply depending upon the circumstances is provided by Hylander (1979c), who measured the *in vivo* bone strain of the condylar necks of macaques under a variety of conditions. He found that unilateral isometric biting at the premolars, or first two molars produced compressive ipsilateral joint forces, whereas at the third molar these forces tended to be either minor, non-existent, or tensile.

d. Role of Craniofacial Form

The importance of establishing a reliable model of the masticatory system is not limited to a determination of whether or not the joints are loaded. Many orthognathic surgical procedures (eg. mandiublar advancement, Le Fort I osteotomies) are specifically aimed at rearranging the relationships of the maxilla and mandible. Such procedures can effectively also rearrange the alignments of one muscle to another, and hence, change the morphological relationships of the entire system.

A number of investigators have observed the differences between a variety of the morphological relationships which determine human facial height, and the resulting bite force capabilities in individuals with so-called "long" versus "short" facial types (Sassouni, 1969; Ringqvist, 1973 1973; Schendel et al., 1976; Ingervall and Helkimo, 1978; Opdebeek and Bell, 1978; Finn et al., 1980a; Proffit et al., 1983a and b). Long-faced individuals with skeletal open bite are not able to generate the same magnitude of bite force as short-faced persons with skeletal deep bites. According to Throckmorton, and coworkers (1980) the reasons for this may include such factors as (1) differences in muscle size (2) architecture and fiber type distribution, (3) activity levels, and (4) mechanical advantage. These workers presented a two dimensional model based on class III lever mechanics from which they determined the effect of changes in mechanical advantage* of the human masseter and temporalis muscles. Alterations in maxillary height, gonial angle, and ramus height were simulated. It was found that any changes which effectvely decreased the moment arm of the muscles, and/or which increased that of the tooth load, resulted in a reduction of mechanical advantage of the muscles. Subsequent observations of long and short-faced individuals suggested that the greater bite forces reported in the latter group were due to similar morphological differences which favored improved mechanical advantage in the short-faced individuals. Their model suggests that some surgical procedures aimed at correcting such disharmonies of facial form may significantly effect the mechanical advantage of certain jaw muscles.

Finn and coworkers (1980 a and b) reached similar conclusions when the same modeling scheme was applied to reductions in maxillary vertical dimension and also to those incorporating correction of mandibular deficiency. They suggested that the potential for relapse following surgical correction of vertical dysplasias of this type was related to abnormal

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*Mechanical advantage in this study was defined as the ratio of moment arm length from condyle (fulcrum) to muscle, versus that from condyle to tooth load (first molar).

masticatory muscle function. The reasons for this abnormal function could be due to abnormalities of any or all of the four factors suggested by Throckmorton et al. above. The inability of a surgical procedure to reduce these abnormal relationships, or the inability of the muscles to adapt to the changes so produced, were cited by Finn et al. (1980a) as significant factors. They concluded that such morphological alterations affect the physiology of the muscles as well as their mechanical relationships. Observed lower muscle activities in long versus short-faced individuals were suggested to be a reflection of the relatively hypertrophied muscle fibers in the latter individuals. Therefore it would seem that the relationships between muscle, joint, and tooth forces, which are determined in part by the physiology of the muscles, are also capable of influencing the physiological development and subsequent abilities of the muscles themselves. Nevertheless, in order to determine the actual relationships between these forces, knowledge of the magnitude and orientations of the tooth and muscle forces involved, are an absolute requirement.

e. Role of Muscle Forces

There are two determinants of the force produced by a given muscle during a particular function. The first is the maximum potential force which the muscle is capable of generating. This is considered to be proportional to its physiological cross section (eg. Weijs and Hillen, 1984a and b), which can be defined as "the summed cross section of its individual fibers" (Weijs, 1980*). Values for the maximum force per unit area vary between 2 to 14 kg/cm^2 for humans (see Weijs, 1980 for review). Most recent estimations place them between 30 and 50 N/cm^2 (3 to 5 kg/cm^2) (Weijs and Hillen, 1984). The second factor is the extent to which each muscle is active during a particular functional act. Various muscles exhibit different proportions of their maximal activity and thus exert different forces depending on the position of the mandible (which also affects the alignment of the muscle+) the direction of applied effort and/or the position of any tooth contacts involved (MacDonald and Hannam, 1984). As such, a muscle force vector is described by: (1) its orientation; and (2) the product of its relative maximum potential force and extent of effort, or relative activity. Electromyographic responses have been used to estimate the latter, using muscle activity during maximum effort as a yardstick for comparison. The various modeling analyses mentioned to here, with the exception of Barbenel (1969, 1972, 1974), have all neglected to consider one or more of these essential elements in defining their vectors.

The human experimental work of Pruim and his coworkers (1978 and 1980) appears to be one of the more complete studies in this regard. They measured the vertical bite force (bilaterally) at three anteroposterior bite positions; the first premolar and the first and second molars. They

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*A large muscle is stronger than a relatively smaller one although the degree of pinnation known to exist in certain muscles of many species (eg. masseter complex in the pig, Herring _et al_., 1979) may lead to an underestimation of this force.

+This becomes extremely important in analyses involving tooth force measurement which use devices requiring the jaw to be opened to any great extent (Hylander, 1978).

correlated this with the normalized, simultaneous electromyographic activity exhibited by the various muscles involved including anterior and posterior temporalis, masseter, and the digastric. Maximum responses for each muscle were determined to which all other responses for that muscle were normalized for each task modeled. However, they assumed that medial pterygoid activity was represented by that of the masseter and they did not record at all from the lateral pterygoids. The muscle alignments were determined for each subject from predictions based on lateral cephalograms. Physiological cross sections were assigned according to Schumacher (1961). From this information the muscle vectors were determined in two dimensions and the resulting joint forces derived according to static equilibrium theory.

The results of Pruim et al. (1980) showed that under conditions of static equilibrium considerable joint forces could be expected. These increased almost linearly, with increasing bite force, for all three bite positions. Under a constant bite force joint forces also increased as bite positions were moved more anteriorly which might be expected according to lever mechanics (eg. Gosen, 1974). As a consequence of monitoring muscle activity, these workers were also able to show that the overall muscle force resultant exhibited a more anteriorly directed orientation for more anterior bite positions.

Maximum bite forces occurred at the first molar and corresponded with relatively greater muscle and joint forces when compared with those at either the premolar, or second molar positions. Pruim et al. concluded that the mechanics of the system, during these kinds of functions, were subject to some form of joint capsule inhibition and were therefore determined by an upper limit of joint force corresponding to that seen during first molar clenching.

One of the more interesting findings of this study was a significantly reduced bite force at the second molar. As was previously mentioned, others have also observed a similar phenomenon experimentally during unilateral biting (Mansour and Reynick, 1975) in bilateral biting (Tradowski and Dworkin 1982) and clinically (Hawthorn, 1984). The apparent reduction of occlusal load at a more posterior position appears to be in direct conflict with that expected from simple two dimensional lever mechanics (Gosen, 1974) which predict relatively greater bite forces at more posterior positions, along with reduced joint loading. However, part of the phenomenon may be due to the simultaneous reduction in overall muscle activity shown to occur by Pruim and coworkers (1978 and 1980) at this bite position. Pruim et al.(1980) attribute the decrease in occlusal load to a centrally acting inhibition due to the possible need for more accurate regulation of equilibrium because the muscle force resultant would lie close to the bite point. This too would imply that some sort of synergism between the muscles is at work to maintain this equilibrium.

On the other hand, it should be kept in mind that the alignment of a unidirectional force transducer will only register those forces parallel to its axis. It has been shown that tooth resistance forces are quite variable in their orientation in both bilaterally symmetrical functions (Hylander, 1978) and unilateral activities (Graf et al., 1974). Although Pruim et al. (1980) conclude that the muscles are capable of generating maximal bite forces at the first molar position it is also possible that the actual alignment of the bite force produced by the muscles in this position were closer to parallel with the axis of the measuring device. Experimental measurements of human bite force orientation indicate that the assumption of purely vertical bite forces (i.e. perpendicular to the occlusal plane) is an oversimplification (Weijs, 1980). Incisal bite orientations have an anterior as well as vertical component (Hylander, 1978) and unilateral molar bite forces have been shown to include the mediolateral component as well (Graf, et al., 1974). Similar finding have also been reported for other species (Weijs and Dantuma, 1975 and 1981). Thus, at either the second molar or premolar positions (which have already been stated to produce different alignments of the muscle resultant force) the possibility that the bite force may be underestimated cannot be discounted. Thus the analysis of Pruim et al. (1980) took only the vertical components of bite force into account (Pruim et al., 1978), although, both the vertical and anteroposterior components of muscle force were considered.

The equilibrium equations of Pruim et al. (1980) state the following:

(1) The sum of the rotational moments of the various components of the system is given by

$$(\Sigma\ EMG_m \times \emptyset_m \times \Gamma \times a_m) + (F_b \times a_b) = 0.$$

The first term (in brackets) represents the muscle moments where, EMG_m is the relative activity of muscle m, $\emptyset_m$ is its cross section, Γ is the force/unit cross section, and a_m is the lever arm length of muscle m. The second term is the moment of the bite force, F_b (which is the measured vertical force only) due to its moment arm, a_b. The joints are considered the fulcrum and thus have no moment. All of the above are known, or assumed, except r. Therefore, an underestimation of bite force (F_b) will effectively push this value up in order to maintain equilibrium within the equation.

(2) The sum of the vertical (y) components is written as

$$\Sigma F_m \sin \alpha_m + F_j \sin \alpha_j + F_b = 0.$$

The first term, F_m, is the vertical component of force of muscle m aligned at angle α with respect to the x (anteroposterior) axis, and the second term is that of the joint force, F_j. The latter force is fixed at a specific alignment by these workers. Again since only F_j is unknown, and the equation must be satisfied, low values of bite force (F_b) will also push the joint force value up. The fact that its alignment is fixed can result in a further increase or decrease in the vertical component depending upon the assumed orientation, and the amount of error.

(3) The sum of the anteroposterior (x) components is

$$\Sigma F_m \cos \alpha_m + F_j \cos \alpha_j + F_p = 0.$$

The first two terms have been described. Since only the vertical bite force is ever considered in this analysis, no anteroposterior component exists in this equation. F_p however is the force of the lateral pterygoid muscle. According to Pruim _et al_. (1980) this muscle has only an anteroposterior component and therefore only appears in this equation. It is also the only unknown variable here. The value of F_j is derived from the expression of the vertical components described above and is subject to the same problems of misalignment. Therefore the values derived for the force of the lateral pterygoid muscle are also subject to error due to incorrect bite force values, and joint force orientation.

A more appropriate analysis might have been: (1) to measure both dimensions of bite force (vertical as well as anteroposterior) to better match the muscle vector analysis; (2) to let the relative proportions of vertical versus anteroposterior components of joint force be derived from the equilibrium equations, and; (3) to include the electromyographic recordings of both medial and lateral pterygoid muscles. By letting the two components of joint force be derived from the equations both the magnitude and orientation of the resulting vector necessary to maintain equilibrium are established without constraining the results.

With regard to the last point, Pruim et al. (1980) acknowledged some of the limitations of their analysis when they found that the masseter EMG activity was not necessarily representative of the medial pterygoid as well. The assumption that medial and lateral pterygoid function is dependent upon the activity of other muscles is a gross oversimplification. Nevertheless, the type of approach taken by Prium and coworkers (1980) provides valuable insights into the complexity of the problem. Despite the limitations of their analysis the conclusions which may be drawn from this study regarding human jaw function are among the most reliable thus far. The possibility that a specific position of bite force application (i.e. first molar) is more efficient than those predicted from purely mathematical analysis, is of major significance.

2. Three Dimensional Models

Most of the analyses discussed to this point have been limited to the sagittal plane and have assumed bilateral symmetry. Although two dimensional analyses are sufficient for incisor or bilateral molar biting, the mandible also functions (and dysfunctions) in three dimensions. Simple two dimensional approaches are therefore insufficient to model unilateral functions (Walker, 1976). As Weijs (1980) has stated,

> "If muscle force estimations are used in a three dimensional static analysis, bite forces and joint reaction force are found different from those resulting from one (simple lever) or two dimensional static analysis. The explanation of tooth and joint morphology is influenced by these modifications."

However, previous attempts at modeling the three dimensional biomechanics of the mammalian masticatory system have virtually all oversimplified the muscle forces involved.

In their reviews of biomechanical analyses of the jaw, both Hylander (1975) and Weijs (1980) point out the need for considering the differential activities which are known to exist between the muscles of the two sides of the jaw (as well as between those of the same side) in unilateral functions (eg. Moller, 1966).

The three dimensional model proposed by Gysi (1921), which was described earlier, did not incorporate this information since it was not available at the time. Therefore his assumption that each muscle was maximally active during a unilateral task could lead to possible over-estimations of the force contributions of the various muscles involved. It was not until some years later that Mainland and Hiltz (1933) first speculated that potential differences in muscle force contributions might exist between the two sides of the jaw (albeit for somewhat simplistic reasons) by suggesting that the muscles of the right side might be stronger than those of the left. They determined absolute values for the three dimensional force capabilities of the various jaw muscles from measurements of muscle angulation and cross section from cadavers. They were also interested in determining the resulting potential occlusal force generated at the second molar. These they compared to gnathodynamometer recordings reported for unilateral clenching at this tooth on both sides of the jaw. However, in the determinations of their predicted tooth forces they neglected the balancing side altogether as well as all mediolateral components of force. They simply calculated the force at the right second molar, due to the moments produced by the right side muscles, and added it to that for the left side. Although this is a gross oversimplification they reported agreement with certain unilateral bite forces recorded from living subjects.

Oversimplifications due to a lack of understanding of the functional relationships between the two sides of the jaw, and even complete dissociation of the two sides in analyses of unilateral function, are not uncommon. Hekneby (1974) used a three dimensional static model to determine the joint forces for equal tooth loads applied to either the first bicuspid, or the second molar of human mandibles. Although she acknowledged the possible contribution of the various portions of the muscles, as well as the differential activities of the two sides, her determinations considered only the vertical forces of the working side. Based on an arbitrary derivation of the working side muscle force resultant, Hekneby determined the working side joint force required to balance the applied tooth load. The sum of the working side muscle, tooth and joint forces were assumed to equal zero. The contribution of the balancing side muscles to force production, and the balancing side joint to force resistance, were assumed to balance each other and thus not influence the greater working side forces to any extent. Similar oversimplifications in an analysis by Nagle and Sears (1958) were criticized by Hylander (1975) for ignoring working side muscle activities.

Hylander (1975) noted that since the working side muscles had been shown to be more active than the balancing side muscles in unilateral molar biting (Moller, 1966) most effort would be expected to occur nearer the bite point in the frontal plane. He suggested that in such functions, owing to lever action effects, the working condyle is subject to less (or perhaps even negligible) loading than the balancing side condyle. He further suggested that this might explain the clinical observations that patients with unilateral joint dysfunction tend to find contralateral (balancing or nonaffected side) chewing (and/or incisal biting) more painful, thereby preferring to chew on the ipsilateral (working or affected) side. Incisor biting, likewise, produces greater joint forces according to lever mechanics. For this to occur there must be some transmission of the forces from one side of the mandible to the other. Hylander (1975) and Beecher (1979) have both proposed that the fused mandibular symphysis of primates is an adaptation to accommodate greater symphyseal stress arising from the balancing side muscles during powerful unilateral biting. In subsequent primate studies Hylander provided convincing experimental support of this concept.

Using single element strain gauges and/or rosettes (i.e. multidirectional) bonded directly to the lower mandibular border of Galago crassicaudatus Hylander (1977 and 1979a) measured the in vivo stress patterns arising during various functions, including biting a force transducer. This particular species of monkey possess an unfused mandibular symphysis. Not surprisingly, he found that very little of the balancing side muscle force contributed to the occlusal force generated at the working side. The latter had from five to ten times the strain of the balancing side during unilateral functions. Thus the two sides of the mandible in this species are somewhat functionally independent. Conversely, similar analysis of Macaca fascicularis, which does possess a fused symphysis, show that this species employs a relatively greater amount of balancing muscle force to generate a particular unilateral occlusal force (Hylander 1979a). The difference between the working versus the balancing side muscle forces in the two species is approximately 1.5 to 1 in macaques and 3.5 to 1 in galagos during unilateral molar biting (Hylander 1979b). Thus based on the distribution of mandibular bone strain, the fused symphysis is an adaptation to maximize the contribution of balancing side muscle forces in function and thereby increase occlusal forces (Hylander, 1975, 1979a, 1979b; Beecher, 1979). In addition, certain other adaptations in jaw form (eg. vertically deep and/or transversely thick jaws) which accompany the mechanics involved have been shown to correspond with the ensuing distribution of force (eg. Badoux, 1965). The close correspondence between primate mandibular form, its stress distribution, and its function have been thoroughly reviewed by Hylander (1979b).

Smith (1978) considered the mandible to function according to two different mechanisms depending upon the activity. He suggested that the mandible acts as a class III lever during the dynamic closing stroke without any occlusal load. When tooth contact is made during mastication for instance, and loading of the system occurs both Smith (1978) and Walker (1978) proposed that the mandible then acts as a stationary beam. This beam can be considered to exist in a state of instantaneous equilibrium at any given moment during bite force generation. This latter situation would require more significant adaptive change than those necessary to minimize the relatively light forces involved in simple jaw elevation, which really only act against the weight of the mandible itself. As such, the morphology of the system would more likely reflect the mechanics of the beam rather than the class III lever. Hylander (1979c) has pointed out that whether one considers the jaw as a "beam" or a "lever" is irrelevant when externally applied forces (such as those of the muscles, teeth and joints) are considered since, mechanically the two act identically under these conditions. Beam theory becomes more appropriate for consideration of internal forces of the mandible such as bending or shearing stresses. Nevertheless, according to this model the three areas of contact which can potentially resist the applied forces are at the point of tooth contact and at the two joints.

In the sagittal plane Smith (1978) proposed that the beam could be considered as a line drawn between the condylar head and point of tooth contact (see Figure 3). Forces were assumed to be applied by the temporalis, masseter, and medial pterygoid uniformly over their lengths of overlap with this line as seen in sagittal or frontal projection. Therefore, a position along the beam behind which occurs the greatest amount of overlap of muscle fibers was considered by Smith to be subject to the greatest muscle forces. Smith also assumed the relative contribution of each muscle would be proportional to its weight, although he points out that this serves only as an approximation and that many other factors are also involved.

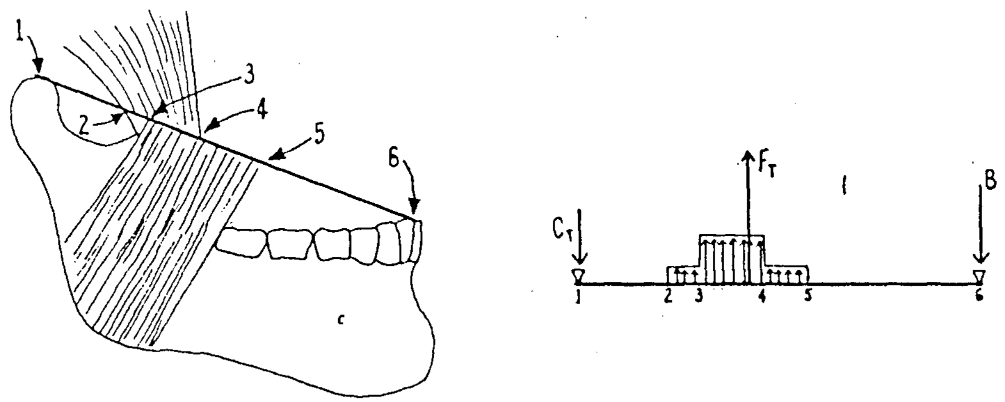

Figure 3. THE MANDIBLE AS A STATIONARY BEAM ACCORDING TO SMITH (1978). CT, total condylar reaction force (balancing and working sides); B, bite force; FT, muscle force as a vector resultant of the "distributed" force between points 2 and 5 (balancing and working sides). The extent of "overlap" of the muscles across the beam are considered by Smith to determine the position of this resultant (After Smith, 1978).

Smith's analysis proposed that the total muscle forces, viewed in the sagittal plane, could be resolved into a single vector acting at a known position along the beam. Assuming that the magnitude of the bite force was known, both the muscle resultant magnitude and that of the total condylar reaction force (right plus left) could then be determined by resolving the equilibrium relationships of the static forces, and the moments they produce. The derivation of the individual forces at each of the condyles was achieved by applying similar procedures to the beam projected in the frontal plane. According to Smith the position of the resultant muscle vector in this plane was determined by, and calculated from, the relative magnitudes of the muscle forces of the two sides. As mentioned, evidence suggests (Moller, 1966) the working side muscles of mastication are more active than the balancing side. However, the magnitude of the difference between the single working side muscle vector versus the balancing side muscle vector is uncertain in this specific analysis. Therefore, Smith selected, as an upper limit, a ratio of 2:1 of working to balancing side muscle force and as a lower limit a ratio of 1:1. The difference, according to him, alters the distance of the combined resultant muscle force from the working side condyle. Smith applied this model to dissected specimens of three species of monkeys and to humans, from which he derived the mean vectors for muscle force and the resulting condylar reaction forces for assumed incisal and molar bite forces. His results show that significantly greater condylar reaction forces occur in incisal, versus molar biting, in all four species. With a 1:1 ratio of working to balancing side muscle forces Smith also found that the balancing condyle accounts for most (80%) of the total joint load. He further concluded that the muscles probably function close to a 1:1 ratio of muscle activity for the two sides. Smith clearly intended only to present a simplified example of this approach to three dimensional analyses and its application to real data. However some of the oversimplifications of this analysis bear pointing out as they represent common problems in other three dimensional analyses which contribute to their dubious applicability as models of the real (absolute) relationships.

First of all in determining the individual muscle forces acting on the beam Smith considered that only the vertical components, in each plane, contribute to the bite force. As was discussed regarding the studies of Pruim et al., (1978 and 1980) this assertion is true if, and only if, the bite and joint forces are also limited to purely vertical components, and vice versa. Smith assumed this to be the case in his analysis as he neglected any muscle force components not perpendicular to the beam axis, as well as all mediolateral components. However the limitations of such an assumption become clear when clenching tasks oriented in a direction with components other than perpendicular to the beam are considered (i.e. medially, protrusively, or retrusively).

Secondly, the assumption that the extent of muscle/beam overlap is an indication of the position of the net effect of muscle pull is clearly questionable. The appropriate position of any resultant force is determined by the vector addition of its component parts. Thus, force vectors for each muscle would have to be determined, and geometrically added. Smith however, determined this position by assuming each muscle to generate a force, in proportion to its weight, which was evenly distributed along its width of overlap with the beam. Using his own form of vector addition, he combined these forces, due to the three muscles considered, and picked the middle of this distributed load as the position of the resultant so produced. The magnitude of the resultant was determined, for this position, as that necessary to counter the applied tooth force. A more appropriate, and accurate means of deriving these variables would be to determine the individual muscle forces. However this requires knowledge of individual muscle responses, in turn requiring live subject data.

Finally, the idea that the three dimensional static muscle force vectors can be combined into a single resultant seems to be widespread among investigators (eg. Hekneby, 1974; Greaves, 1978), and is wrong. Force vectors can only be resolved into a single resultant vector if the component vectors are collinear, coplanar, or parallel (Beer and Johnson, 1977). If the mechanics of the system are considered to be bilaterally symmetrical with no net mediolateral components of force then the vectors can be considered to act in a midline sagittal plane. Such two dimensional analyses can be considered to have coplanar vectors and their resolution into a single vertical and anteroposterior component, (or a single resultant at a specific orientation), is lawful. However when asymmetric forces are involved, which require the third dimension, vectors which do have various mediolateral components, cannot be considered to be coplanar, and they certainly are neither colinear nor parallel.

Resolution of muscle vectors in a three dimensional system of force vectors can be expressed by either of two equivalent systems of forces. The first involves simply the determination of the total vertical, anteroposterior, and mediolateral components of static muscle force from the sum of the same components in individual muscles. In the lateral (sagittal) plane or view, on to which the total vertical and anteroposterior components can be projected, the axis along which each component acts can be determined from the total rotational moment <u>for that plane</u>, also obtained from the sum of individual muscle moments. In this view, or plane, any mediolateral force has no effect on the system since it is oriented perpendicular to this plane. However, in the frontal plane, which has a different total moment, the anteroposterior component would have no effect whereas the mediolateral and vertical would. Similarly, in the horizontal view the vertical component would not contribute to the equilibrium of forces, whereas the anteroposterior and mediolateral would. All three orthogonal components do not necessarily pass through the same point in space. As such any resultant force determined in the lateral plane (from the vertical and anteroposterior components) is not likely to be equivalent in position, orientation or magnitude, to that determined in the frontal (from the vertical and mediolateral components) or the horizontal planes (from the anteroposterior and mediolateral components). In other words there will be three separate orthogonal resultants, one for each plane, which are neither colinear, coplanar nor parallel, and which therefore cannot be resolved into a simpler equivalent system of forces.

A second system of equivalent forces is referred to as a "wrench" which, simply stated, is actually a single vector with a particular moment about the fulcrum but which also has a secondary twisting effect about the axis of that vector (see METHODS for a more complete discussion). The extent of the twisting effect is referred to as the "pitch" of the wrench and is perpendicular to the moment effect of the vector to the fulcrum (Beer and Johnson, 1977). As such this system of forces (which would have the same effect as the three orthogonal resultant vectors described above for a given system of forces) also requires all three dimensions to be considered simultaneously.

In Smith's (1978) analysis the single resultant of muscle force in the sagittal plane was also assumed to act in the frontal plane as well. Because Smith assumed only vertical (parallel) forces were acting, it was possible to derive a single three dimensional resultant vector for his system. However, his sweeping assumptions limit the application of this type of analysis, which Smith acknowledges. Similar criticisms apply to the assumptions of Hekneby (1978).

Greaves (1978) proposed a three dimensional lever model to explain the jaw form of anisognathus ungulates from a mechanical point of view. This model was very similar in many respects to the beam proposal of Smith (1978) and is thus subject to similar limitations. Nevertheless, the information gained from simplified models such as these has most certainly contributed significantly to the understanding of the workings of the mandibular system. Greave's model points out some of the relationships between the joint forces of the working versus balancing side, for variable unilateral tooth contact points and muscle force positions. Like Smith, Greaves (1978) made the assertion that, "the components of the muscle force that close the jaws can be resolved into a single vertical vector." He showed that for unilateral biting, the two joints, and point of tooth load application, form a triangle of support when viewed in the horizontal plane. The distribution of the total forces of resistance between these three points, due to the vertical muscle resultant of applied force, varies with the position of this resultant. Accordingly, for this tripod to be stable the effective vertical muscle pull must lie somewhere within this triangle otherwise a dislocating force will arise at one of the contact points.

Using this simplified system Greaves predicted the theoretical anterior and posterior limits for the position of the masticatory tooth row in selenodont artiodactyls. The anterior limit was that point beyond which the tooth force decreased due to (1) a reduced lever efficiency more anteriorly, and (2) a smaller muscle resultant. The posterior limit is that point beyond which the muscle resultant would come to lie outside the triangle of support described above, and produce dislocation of the working side joint. Despite some of the constraints imposed by Greave's assumptions he reports good agreement with the actual location of the tooth row in such artiodactyls and proposed his model as a good working hypothesis of the system in such animals.

Subsequently, Druzinski and Greaves (1979) applied this model to the jaw mechanism of various reptiles (assuming symmetry in muscle activity). They also found a close correlation between the observed and expected positions of the most posterior bite point as predicted according to this model. One important point to note with the model is that it is not necessarily limited to static conditions but appears to be compatible with simple dynamic considerations. Furthermore, Greaves (1978) points out the need for measurements of the various jaw forces involved, including the need for considering the relative electromyographic activities of the various muscles involved, and/or measuring the actual joint forces themselves.

Hylander and Bays (1978) and Hylander (1979c) presented the first experimental studies measuring in vivo forces occurring at the joints.

Hylander found that the joint reaction forces predicted from strain deformation at the lateral aspect of the condyler necks of monkeys (Macaca fascicularis and Macaca mulatta), suggested that compressive loading occurred during normal functions. These included the power stroke of mastication and incision of food, as well as isometric molar and incisal biting. The joint forces were directed vertically and posteriorly in most instances when tooth contacts occurred anterior to the third molar, although anteriorly directed compressive forces were also observed. Furthermore, these forces were greater on the balancing versus the working sides (cf. Gysi 1921; Hylander, 1975; Smith, 1978; Greaves, 1978). As discussed earlier, the pattern of loading of the working joint in unilateral isometric biting showed a surprising difference at the third molar compared to more anterior bite points. At this position the pattern of subcondylar bone strain was reversed from the compressive loading pattern observed at the first molar, suggesting that at the third molar the working joint was subjected to unloading or tensile forces. This supports the predictions of joint function and loading characteristics according to Greave's (1978) model. Models proposed by Gysi (1921), Hylander (1975, 1979b), Hylander and Sicher (1979), and Smith (1978) also predict zero or negative working side joint loads at more posterior contacts. Similarly, Hylander (1979c) found greater (working side) subcondylar reaction forces during premolar than during molar biting which might be expected from lever principles if muscle force remains the same or similar at both bite positions.

More recently, Hohl and Tucek (1982) implanted an instrumented prosthesis in an anesthetized baboon to replace the neck of the temporomandibular condyle. This prosthesis incorporated calibrated strain gauges which recorded the condylar (neck) forces exerted during simulated incisal bites. Although their data were subject to a variety of problems, including failure of the prosthesis, they found the joint to be loaded axially at magnitudes comparable to those measured at the incisors (up to 8 lbs.) during these incisal bites. However due to the nature of this experiment no inferences to natural events could be drawn.

Similarly, other in vivo studies on monkeys (Macaca arctoides) have utilized a piezoelectric pressure sensitive foil implanted directly on the articular surface of the mandibular condyle (Brehnan and Boyd, 1979; Brehnan et al. 1981; and Boyd et al., 1982). This allows for direct measurement of the compressive reaction forces occurring at the condylar head as opposed to the indirect measurements of Hylander (1979c), and Hohl and Tucek (1982).

Although the initial findings of these workers (Brehnan and Boyd, 1979) suggested that the condyles were non-stress bearing they subsequently found evidence (eg. Brehnan et al., 1981; Boyd et al., 1982) that the temporomandibular joints were, in fact, stress bearing. However, as Hylander (1985) has pointed out in his review of these studies the interpretation of the masticatory joint forces is difficult as no correlation was made between the forces recorded and the corresponding jaw position.

Recently Smith et al. (1986) presented a somewhat qualitative numerical model of human condylar loading based on static analyses of a hypothetical mandibular system. They mathematically determined the relative range of condylar loading forces and their magnitudes, due to various combinations of forces exerted by three muscle groups on each side of the mandible. These were done for unilateral points of tooth contact along the dental arch.

This model was designed to determine only minimal possible joint loads according to relative changes in the contributions of these muscle groups. They found the temporomandibular joint to be loaded in compression as well as tension "over the normal functional range of bite force positions and angles." These loads were maximally compressive at incisal contacts, minimally compressive at the second molars and tensile at the distal of the third molars. Joint loads were found to be relatively small when bite forces were aligned parallel to the sagittal plane and corresponded with an orientation perpendicular to the articular eminence. When lateral components were added to the bite forces marked asymmetry between the right and left joint forces resulted. These also produced a wider range of joint force orientations.

These workers concluded that bite forces parallel to, or within 20 degrees of the sagittal plane, are mechanically more stable requiring smaller joint loads oriented more favorably with respect to their force-resisting morphology. However, these investigators also point out that because the relative magnitude of the muscle forces are unconstrained their results are only representative of the minimal relative joint loads possible with respect to the tooth loads. No apparent attempt was made to apply real data to the three pairs of possible muscle forces of this model and no values for the resulting magnitudes of biting force are reported in this work. As such only the relative magnitudes of joint forces compared with the suspect biting forces could be described. This is unfortunate as the application of absolute values to this model may have provided additional interesting correlations between form and function and certainly further credibility to this model.

3. Current Modeling Approaches

The most comprehensive modeling analyses of functional jaw mechanics have been the experimental studies by Weijs and Dantuma on the masticatory system of the albino rat (1975) and rabbit (1981). These investigators considered virtually all of the pertinent variables in their static analyses including: (1) the three dimensional spatial coordinates of the condyles and the teeth, as well as the centers of attachment (origin and insertion) of each of the functional muscle groups; (2) the physiological cross sections of each muscle; and (3) the simultaneously recorded electromyographic activity of each muscle for a given task. From this information the relative forces of the individual muscles were determined for each of the various stages of the chewing cycle, as well as during isometric biting, and vector analysis of the system as a whole was carried out. Each of these stages or functions was considered to be either stationary (biting) or moving at constant speed (power stroke of chewing) under which conditions static equilibrium was assumed to exist (Weijs, 1980). The necessary assumptions involved in their determinations were the following (see Weijs 1980; Weijs and Dantuma 1975; and 1980):

(1) That muscle groups act or pull along a line connecting their centers of origin and insertion. Here the potential effects of over simplifying the line(s) of action of a multi-pinnate muscle are apparent unless detailed determinations of the subgroups are made and the activity of each is accounted for (Weijs, 1980).

(2) That proportionality exists between the force exerted by a muscle and its integrated electromyographic response.

(3) That the ratio between instantaneous (specific task response) and maximum possible muscle response level is proportional to the amount of muscle force per unit of physiological cross section (assumed to be 10 kg/cm^2 in their calculations).

From this model Weijs and Dantuma showed that the relationships of the muscle, tooth and joint forces for a specific occlusal task were determined by the specific simultaneous activities exhibited by each muscle, in both species. The three muscle resultant vectors, one for each view or plane, were shown to change their position, magnitude and orientation depending upon the phase of the chewing stroke or biting task. As a consequence, these parameters for the resulting forces of resistance at the teeth and joints were also variable. In the rat these workers (1975) found that during mastication* virtually all of the applied muscle force was transmitted to the molar teeth leaving the temporomandibular joints unloaded. During incisal biting, the increase in gape shifted the resultant of the muscle forces more posteriorly, as well as vertically. This produced significant

*According to Weijs and Dantuma (1975) during this "anteriorly directed masticatory grinding stroke, the resultants of the muscle forces at each side are identical" (i.e. bilaterally symmetrical).

joint loading because the muscle and tooth forces were not coincident, i.e. the tooth force now occurred farther anteriorly than the muscle resultant. It is for this reason, they speculated, that the observed activity levels of most masticatory muscles are lower in biting than during chewing, in both rat and rabbit (Weijs, 1980).

For unilateral chewing in the rabbit Weijs and Dantuma (1981) observed asymmetric activity between the working and balancing side muscles. Three dimensional static analysis of unilateral molar contact showed a distribution of joint loading forces very similar to those recorded by Hylander (1979c) in monkeys. The working side joint remained unloaded during the power stroke of chewing while the balancing joint remained loaded throughout. Furthermore, manipulations of the model predicted that a decrease in balancing side muscle force increases the load on the working side while decreasing bite force. Increases in balancing side forces would increase the bite force but tend to dislocate the working joint due to the creation of tensile force there (Hylander, 1979c). This is to be expected if the unilateral point of tooth contact is considered as a pivot point. Increasing balancing side muscle forces tend to balance then surpass those of the working side thus tending to rotate the mandible about this pivot opposite to that where working exceeds balancing side muscle force. "Hence during natural mastication the muscles of both sides act in a proportion ensuring the largest bite force possible without pulling the articulating surfaces of the working side joint apart" (Weijs, 1980, p. 716).

In both animals Weijs and Dantuma found that the resulting tooth forces required to maintain equilibrium in virtually all instances were not purely vertical as assumed by so many other analyses. There existed both an anteroposterior as well as a transverse component of tooth force. Based on their determinations of these forces and their interactions Weijs and Dantuma were able to account for many of the characteristics of form of the two mandibles, and their dentitions, and concluded that the masticatory apparatus is adapted to maximize tooth forces, (Walker, 1978; Weijs and Dantuma, 1975 and 1981; Weijs, 1980).

The incorporation of all simultaneously relevant variables in their analysis, for any given bite point during static masticatory function, lends a great deal of credibility to this type of model. However one point worth noting was their inability to determine the proportions of the total transverse (mediolateral) force acting at each of the two joints (Weijs and Dantuma, 1981). According to them this is determined by the morphology and nature of the articular surfaces of the medial and lateral walls of the condylar fossae. The direction of the joint reaction force is stated by Weijs (1980) to be the determinant of the bite force direction. More than likely, however, the nature of the relationships between the tooth and joint forces have evolved together in a reciprocal manner depending upon the functional requirements of the animal. Weijs and Dantuma (1981) made the assumption that the joint force resultant in the lateral plane acted at a specific angle (with respect to the occlusal plane) based on morphological observations (eg. 18 degrees). This allowed the vertical component of joint force to be expressed in terms of the anteroposterior component, or vice versa, since the assumed angulation fixed their relative proportions with respect to each other. Therefore the nine unknown variables contained in their six simultaneous linear equilibrium equations reduced to seven. However, since seven unknowns contained in six equations is still statically indeterminate, a further simplification of variables was required. Weijs and Dantuma accomplished this by considering the transverse of mediolateral joint force components to be represented by a single combined transverse resultant for both joints. Since these two joint components were in a direct line with each other this was permissible but precluded the determination of the two (working side and balancing side) individual components.

The application of similar additional assumptions, (based upon anatomical or physiological measurements) to different variables in these equations can allow the determination of the two transverse components as well (see METHODS). For example, a three dimensional orientation can be assigned to the tooth resistance forces. This has the potential benefit of allowing the incorporation of direct in vivo measurements of the magnitude, as well as orientation, of tooth force. Such measurements, in man at least, are currently feasible (eg. Graf et al., 1974). In any case, whether actual values for the three components of tooth force are used, or the relative proportions between the three (according to the assumed orientation of the resultant), other angular assumptions are needed to determine the proportion of transverse force at each joint. If the additional assumption is made that the angulation of joint resistance force in the frontal plane is known for one of the joints (eg. based on morphology) then the extent of the transverse joint reaction force acting at each side can be determined, along with all other unknown variables.

Weijs and Dantuma obviously did not have the benefit of knowledge of any aspect of the joint reaction forces other than the articular eminence angulation in the lateral plane, which they based on morphological evidence. Their analysis was made possible by this single assumption although a price was paid by their inability to completely describe the nature of each of the two joint reaction force resultants for unilateral activities of the mandible.

A recent modeling study by Hatcher and Coworkers (1986) incorporated a similar assumption although their results are, on the whole, simply qualitative. They developed both a mechanical and a mathematic model to study human temporomandibular joint loading based on the same basic premises as Weijs and Dantumas' analyses. However they were simply correlating the mathematical analysis with that of the straight forward mechanical one. The latter incorporated force transducers at three molar tooth positions as well as at the two joints. Muscle forces due to the anterior and posterior temporalis, the superficial and deep masseters and the medial pterygoid of both sides of the skull were simulated mechanically along their respective orientations. These muscle "forces" were derived simply from cross-sectional data (Schumacher, 1961) and consisted of proportional values only. Variation in both the occlusal as well as the working and balancing joint forces were correlated with arbitrary alterations in the balancing side muscle forces, their angulation and position.

They analyzed these same variations using their mathematic model of their mechanical arrangement based on static equilibrium conditions. In addition however the mathematic model also included estimates of EMG activity which they had also derived from the literature. Their findings were, on the whole, only comparative with some variation between the two models but they showed that the static mathematical model approach fairly closely predicted the same variations in tooth and joint loading as the mechanical model. This, to some extent, substantiates the application of mathematical analysis of the kind used by Weijs and Dantuma to predict actual mechanical events.

The elucidation of the nature of these externally applied forces acting on the mandible has further significance when the internal distribution of these forces within the structure of the mandible is considered. For instance, Hylander (1979c) suggested that the occurrence of variable directions of macaca subcondylar loading was possibly due to rearrangement of the internal force distributions within the mandibular condyles of some subjects. As such, more of the compressive load would be distributed to more medial aspects of the condyles leaving more tensile stress and strain along the lateral aspects during certain functions. Therefore the subcondylar strain or stress measured by Hylander at the lateral aspect could reflect this effect. It follows that the mediolateral position of the point(s) of heaviest resistance of the condylar surfaces and architecture of the supporting bone will determine, or at least influence, this distribution.

A number of papers have specifically dealt with the relationships between externally applied forces and the resulting internal distributions of stress within the mandible. Three dimensional photoelastic stress patterns have been measured directly from dried human mandibles (Mongini et al. 1979). These have shown close correlation between bone trabeculation and jaw architecture, and surface distribution of lines of principal stress. Two and three dimensional models of the human mandible have been developed to simulate these relationships using finite element analysis (Iwata, et al. 1979; Gupta et al. 1972, 1973; Knoell, 1977; Harper, 1982). This is a method whereby a computerized graphic model of the mandible is constructed from an assembly of structural elements interconnected at specific common "nodal" points. Such models have been shown to be a reasonably good representation of the in vitro biomechanical response of the mandible to artificial occlusal loading situations as compared to measurement of dried mandibles under the same conditions (Knoell, 1977).

This information is of great clinical value when its application to prosthetic implants and osseous surgical procedures are considered. Knoell (1977) presented a three dimensional model aimed at describing the bone response to occlusal type loading in the areas adjacent to the teeth. Harper (1982) also incorporated muscle vectors acting on his finite element model due to the masseter, two divisions of the temporalis, and the medial pterygoid.* The muscle loading produces a distortion of the structural nodes (i.e. attachment points) according to the assumed modulus of elasticity of the structure. From this the magnitude of forces occurring at specific nodes, and hence the types of stresses produced, can be determined. This analysis was used to compare changes in mechanical advantage to the muscles for simulations of differing surgical alterations of the mandible

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*These were determined according to some arbitrary and rather simplistic assumptions as to the absolute maximum force generation capabilities of each muscle, as well as their relative differences in activity between occlusal functions.

used to correct prognathism. Thus the three dimensional description of the reciprocal relationships which appear to exist between the externally applied muscle forces, the internal distribution of these forces within the mandible, and the resulting externally occurring resistance forces is potentially of great clinical importance.

B. PURPOSE OF STUDY

A model of any biological system should reasonably predict the possible outcome of any plausible set of conditions imposed on the system. The more real variables one is allowed to incorporate into a model, the more likely are its predictions to be reliable, and therefore useful.

The wide variety of possible combinations of these variables requires a similar degree of latitude in the capabilities of the model. This is most important if real data from a given individual with a particular craniofacial form is to be applied, biomechanically analyzed, and compared to another individual or morphological group (ie. class I, II or III skeletal bases; short versus long facial types; and combinations thereof). One of the main objectives in the design of a three dimensional model therefore would be to provide maximum flexibility in the entry of anatomical as well as physiological parameters, whether real or assumed, and to allow these variables to be entered and/or altered independently.

The purpose of the present investigation was, firstly, the establishment of this interactive and flexible modeling system. The second objective was the application of a realistic and complete set of data to describe and quantify the biomechanical relationships which exist between the forces produced by the muscles of mastication and the resulting reaction, or resistance forces generated at the point of tooth contact and the two joints in a hypothetical normal individual undergoing different static tasks.

Specifically the model and its application to these particular tasks was aimed at answering the following questions:

1 - What is the three dimensional nature of the forces produced by the muscles (magnitude and orientations) for a given task and to what extent do these muscle forces change with changes in the position and type of tooth contact (eg. anterior versus posterior; unilateral versus bilateral; natural versus supported tooth contacts)?

2 - How do these changes in muscle force/tooth contact (i.e. task) affect the magnitude and orientation of generated tooth forces in three dimensions?

3 - How do these changes in muscle force/tooth force affect the magnitude and orientation of generated forces at the two temporomandibular joints?

METHODS

A. PRINCIPLES OF ANALYSIS

As stated previously the primary purpose of this study was to establish a useful three dimensional model of the biomechanical relationships between the forces generated by the muscles of mastication and the forces of resistance which occur at the teeth and/or joints, under static (i.e. isometric) conditions. As such, the principles of static mechanics apply which require the sum of all forces acting on the mandible to effectively cancel one another thereby producing no movement of any part of the system, or the system as a whole. In order for this to be true the sum of the linear forces acting on the mandible in the three orthogonal directions (x, y, and z) must equal zero. That is to say, the sum of all mediolateral (x) forces must be zero as must the sums of the anteroposterior (y) and vertical (z) forces:

ie. (1) $\Sigma F_x = 0$

(2) $\Sigma F_y = 0$

(3) $\Sigma F_z = 0$

In addition each linear vector of force will produce a torque effect, or rotational moment, about the center of rotation, or fulcrum, of the mandible. However static mechanics also requires that the total moment, or torque, about any axis passing through the fulcrum point must also equal zero:

ie. (4) $\Sigma M_x = 0$

(5) $\Sigma M_y = 0$

(6) $\Sigma M_z = 0$

Thus, there can neither be any net linear forces, nor any rotational moments acting on the mandible under these conditions and therefore no net movement. For this reason the position of the fulcrum point and orthogonal axis of rotation can be assumed to lie anywhere in space in relation to the mandible. It is convenient to assign one of the points of resistance (eg. the right condyle) as the fulcrum for the system. In doing so the three orthogonal components of right condylar resistance force, which can exist, will pass directly through the fulcrum along their respective axes. They therefore produce no torquing effect, or moment, on the system. This eliminates the need to include these three particular components in the equations describing the rotational moments of the system (equations (4), (5) and (6) above) and greatly simplifies the subsequent calculations (see Analysis).

The model mathematically determines the reaction forces (if any) which occur at the three points of resistance (i.e. right and left joints plus assumed tooth contact position) for any given mandibular system and static function, according to the muscle force generated. Since each of these three resistance forces can have an x, y and z component three dimensionally, there are therefore nine unknown variables contained in the above six equations (eg. left joint x, y and z; right joint x, y and z; and tooth force x, y and z components). As such, the equations can be satisfied by an infinite number of solutions and are statically indeterminate (Weijs and Dantuma, 1981). However it is possible to reduce these unknowns such that a unique solution will exist by making two important, but reasonable, assumptions regarding the orientations of the resistance forces at (1) the point of tooth resistance and (2) at the left condyle.

First of all, the three dimensional orientation of the tooth resistance force at the designated point of tooth contact was specified. The three orthogonal components of this force could then each be expressed (trigonometrically) in terms of the other, as a ratio. This effectively reduced these three unknowns to a single variable. It is noteworthy that the orientation specified for the tooth resistance force may be assigned arbitrarily, or, assumed to correspond with the known orientation of the overall muscle forces. Conversely, they may be independently assigned according to three dimensional measurements of the actual forces occurring at the given point of tooth contact, for a specific occlusal function. Such measurements could be made simultaneously with muscle EMG recordings in studies specifically designed for this purpose. Nevertheless this would still leave seven unknowns in the six equations, which is still statically indeterminate.

A similar assumption was then applied to the components of the left joint forces by specifying an assumed orientation of joint resistance (eg. based on morphological evidence) in one particular plane that being the frontal plane (see Analysis). The two components of joint force in that plane (mediolateral (x) and vertical (z)) were thus expressed in a single term, also as a ratio. This reduced the unknowns to a total of six which does have a unique solution for all orthogonal components of joint and tooth force.

B. DATA ENTRY

1. Anatomical Variables

a. Coordinate System

The three dimensional spatial coordinates of all anatomical variables were entered as distances in millimeters relative to a common origin at the center of the right condyle. The mediolateral, anteroposterior, and vertical axes are designated x, y and z respectively. A midsagittal plane (yz), a frontal plane (xz) and a horizontal plane (xy) parallel to the occlusal plane, thus represent the three orthogonal planes of reference passing through the origin. The three dimensional coordinates of the centroids of the areas of origin and insertion of the muscle groups, the centers of the right and left condyles, and the points of contact of the mandibular dentition were entered using a Hewlett Packard 9874A digitizer (see Figure 4A and B). Because the digitizer is capable of handling these coordinates in only two dimensions at a time all points were entered from the lateral plane for the anteroposterior and vertical dimensions, then again from the frontal plane for the mediolateral dimension.

Since the program deals with the mandible as a bilaterally symmetrical structure only the right side of the mandible was digitized in the frontal plane. The left side was generated by the computer as a mirror image of the right in both the frontal and the resulting horizontal plane (see Figures 4A and b).

These coordinates may be entered from any detailed full scale image of a given mandibular system whether it be anatomical drawings, tracings from cephalometric headfilms, or directly from such films or other diagnostic imaging reproductions. Although any mandibular "system" (i.e. from any given individual) can theoretically be modeled, the necessity of describing these relationships for a hypothetical "normal" mandibular apparatus required the pooling of mean data originating from a variety of sources in the literature. The origins of the various parameters, the assumptions made regarding their incorporation into a data file representing a hypothetical "normal" individual, and the application of this information to a variety of masticatory tasks is discussed in the following.

b. Muscle Attachments

The coordinates of all the muscles except digastric were derived from the work of Baron and Debussy (1979) which was based on 5 human skulls. No attempt was made to establish the sex, age or ethnic origin of these skulls. As these workers state, "In functional anatomy and biomechanics, the average fiber is represented by an average force, each vector of which has two points of anchorage: one mobile, mandibular, and one fixed, cranio-facial" (p. 547). The determination of the respective areas of origin and insertion for each muscle fascicle were made according to identifiable bony landmarks which are due to traction of the given fascicle, or group, at its attachment sites (Van der Klaauw 1963).

Baron and Debussy described a total of 24 separate muscle fascicles (12 on each side, right and left) within the four major masticatory muscles of each side (excluding digastric; see Figure 4A and B). According to their criteria the masseter muscle is divided into four fascicles or groups; a superficial and intermediate group, and a deep group consisting of an anterior and a posterior portion. The medial pterygoid muscle consists of three fascicles; an anterior part, a superficial posterior part, and a deep posterior part. The temporalis muscle consists of an anterior group which includes the zygomatico-mandibularis portion (identifiable in most mammalian species as a distinct muscle itself, eg. Schumacher, 1961; Turnbull, 1970) a middle group of oblique fibers, and a posterior group of horizontal fibers. Lateral pterygoid is divided into a superior sphenoidal head, and an inferior pterygoidal head. A list of the areas of anatomical origin and insertion described by these workers is included in Appendix I.

Although their study represents one of the most detailed descriptions of the functional divisions of the masticatory muscles to date it was necessary to combine certain of the subgroups of Baron and Debussy to derive components for which physiological data were available. Thus 9 pairs of muscles (18 in all) were included and specified by attachment site (i.e. origin and insertion) including the superficial and deep masseters, medial pterygoid, anterior, middle and posterior temporalis, superior and inferior heads of the lateral pterygoid, and digastric. Their specific orientations were calculated as lines representing the middle of the body of each muscle from origin to insertion (Hiiemae, 1967; Barbenel, 1969 and 1974; Pruim _et al._, 1980).

Figure 4A and B depicts both the muscle subgroups described by Baron and Debussy and the functional subgroups incorporated in this study (Gysi, 1921). Both deep (DM) and superficial masseter (SM) are each represented by a single line of action as opposed to the two fascicles of Baron and Debussy. The three anatomical fascicles of the medial pterygoid (MP) of these workers are

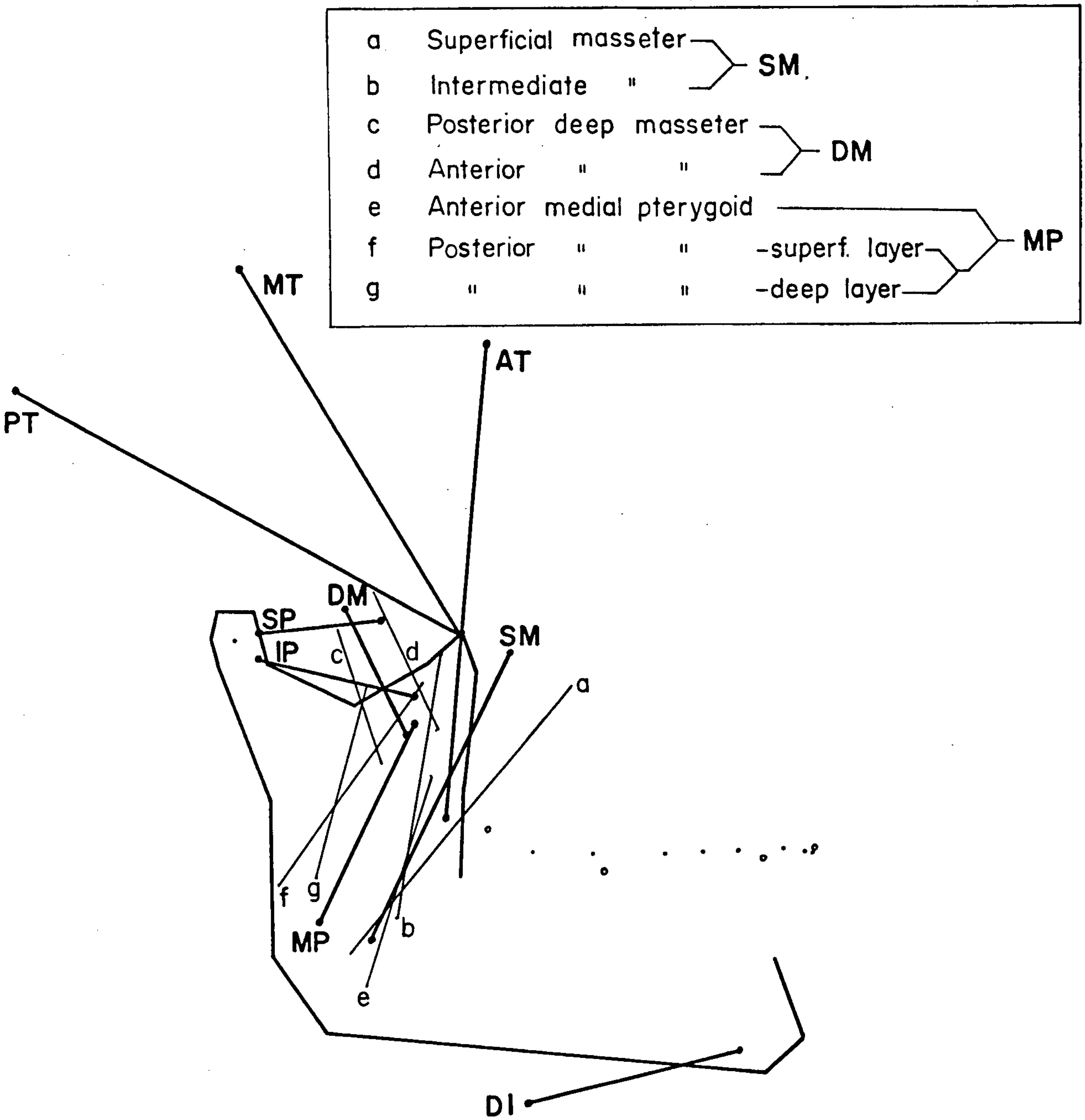


Figure 4A. LATERAL PLANE ATTACHMENT POINTS OF THE NINE MUSCLE GROUPS. The heavy lines represent those groups incorporated in this study: SM, superficial masseter; DM, deep masseter; MP, medial pterygoid; AT, MT, PT, anterior, middle and posterior temporalis respectively; IP, inferior head of lateral pterygoid; SP, superior head of lateral pterygoid, and DI, digastric. Also depicted (thin lines) are the muscle groupings of Baron and Debussy (1979) from which the SM, DM and MP single lines of action and attachment were derived. All other muscle groups, except DI, correspond with the divisions described by Baron and Debussy (see Appendix I). The tooth points of contact from incisor to third molar are depicted (dots) as well as those described by Baron and Debussy (small circles - see text for description). The figure assumes the jaw is in the closed position.

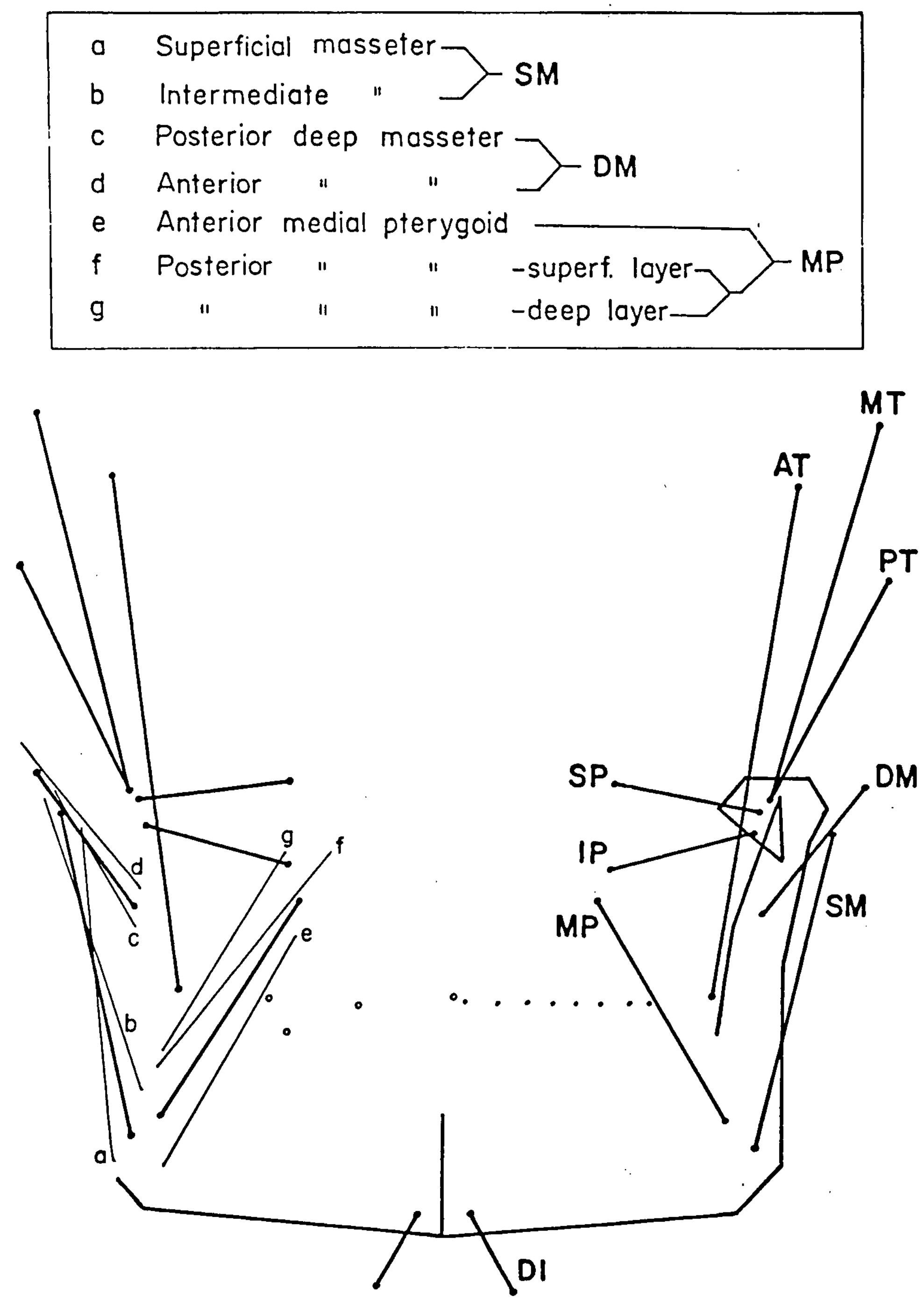


Figure 4B. FRONTAL PLANE VIEW OF THE MUSCLE GROUPS OF FIGURE 4A. On the right of the figure are the muscle groups and tooth contact points incorporated in the model. On the left are the muscle divisions of Baron and Debussy (1979) from which SM, DM and MP were derived, and the tooth contact points they used (see text for description).

likewise represented by a single line of action. The combination of these subgroups into their respective singular lines of action for model analysis was done by determining the geometrical center of the attachment points of Baron and Debussy for the two deep masseter fascicles and the two superficial masseter fascicles. The centers of attachment for the single medial pterygoid were derived by first determining the midpoint of attachment of the superficial and deep posterior group and then similarly determining the midpoint of this combined posterior group and that of the anterior fascicle. Except for digastric the remaining muscle groups (i.e. anterior (AT) middle (MT) and posterior temporalis (PT), and superior (SP) and inferior (IP) heads of lateral pterygoid) used in the computer modeling system correspond to those described by Baron and Debussy.

Digastric (DG) orientations were derived from Dubrul (1980) and Pruim et al. (1978, and 1980).

c. Tooth Positions

Although any point of the dentition, whether unilateral or bilateral, may in theory be used, it is obvious that a given task which involves a certain occlusal contact will also involve a specific pattern of muscle activities. The mathematical analysis, described further below (see Analysis), assumes "point" contact at the teeth and condyles, and not necessarily bearing "surfaces" as such. It is therefore important to know exactly where the applied point of tooth contact lies in space. The tasks included here therefore consist of those on specific occlusal points, those which were bilaterally symmetrical, or at the very least carried out at an assumed single point or tooth (i.e. chewing). Though not all of the muscle data described was ideally matched, it nevertheless represents the best estimates available for man.

Figure 4A and B shows the four dental reference points chosen (arbitrarily) by Baron and Debussy (1979). From anterior/medial to posterior/lateral they are; (1) the contact point between the two central incisors; (2) the contact point between opposing canines; (3) the most inferior point of occlusal contact of the mandibular molars and (4) the most distal molar point. Whereas Baron and Debussy (1979) chose an occlusal plane corresponding to a line drawn from point 1 to point 4 (incisor to distal most molar point), for computer modeling purposes an occlusal plane was chosen to correspond to an arbitrary line drawn intermediate between the above points in the lateral plane. Figure 4A and B depicts this plane of occlusion as well as the individual points of contact for each tooth including third molars. The contact points were arrived at by comparing relative tooth morphology and cuspal positions on dried skulls and drawing them within the confines of the dental reference points of Baron and Debussy (1979). Molar contact points correspond to mesio-buccal cusps (of the mandibular teeth).

d. Tooth Angles of Resistance

The assumed angle of tooth resistance force in the lateral and frontal planes (α and β; Figures 5 and 6 respectively) were specified to match the overall orientation of applied muscle force in these two planes. As was discussed earlier this feature allows for the incorporation of either arbitrarily determined angles of tooth resistance, or actual orientations measured directly using three dimensional force transducer arrangements designed for this purpose. The latter situation would maximize the correspondence between the overall muscle force alignments and tooth resistance force orientations where both are recorded simultaneously from a given individual.

It should be emphasized here that the program analyzes the relationships of various forces in the system from a purely mathematical point of view. Since the system the program is intended to model is a biological one, certain relationships must be borne in mind and some constraints applied to the analysis as a whole. For instance, the program will accept any angular orientation of tooth resistance specified by the user, whether it is appropriate for the given muscle data or not. It is theoretically possible to specify retrusively directed muscle effort with an inappropriate orientation of tooth resistance (would expect the latter to correspond in nature to resist the muscle effort). Unless specifically matched data are available, eg. as a consequence of experiments designed for the purpose, it is therefore most appropriate to match the nature of the muscle effort with an angle of tooth resistance most likely to occur in the system.

The ability to minimize the number of unknown variables in the six equilibrium equations for these static functions by assigning values to the tooth force orientations has also been discussed (see Principles of Analysis).

e. Condylar Position

The origin of the reference system, as stated lay at the center of the right condyle. The vertex or superior-most outline of the condyles shown in Figure 4A and B was the basis of the coordinate system used by Baron and Debussy (1979). Their abscissa lay along the line joining the vertices of the two condyles. All other dimensions of the condylar and mandibular outlines were drawn arbitrarily and digitized. The latter had no bearing upon subsequent modeling procedures, and were used only to enhance graphic portrayal of the data.

f. Condylar Angles of Resistance

The orientation of the resistance force occurring at the left condyle in the frontal plane only, was also specified (γ, see Figure 6). This also enabled determination of the static equilibrium equations by further reducing the number of unknown variables (see Principles of Analysis). The frontal angle of this resistance force was chosen arbitrarily over that in the lateral or horizontal plane to minimize constraints on the condylar resistance forces in the latter two planes. Since only this angle was fixed all other condylar resistance force orientations were derived by the computer.

2. Physiological Variables

Force analysis for any simulated task required the determination of the contribution by each muscle to the overall forces of the system. These individual forces were determined, along each muscle's specific line of pull, according to two assumptions:

First, large muscles are capable of producing more isometric contraction force than small ones, the tension in each muscle being proportional to the product of its physiological cross section and an assumed force constant per unit of cross sectional area.

Second was that various static clenching tasks, as well as different phases of the closing stroke in chewing, involve different amounts of activation in a given muscle depending upon the task or phase of the task (MacDonald and Hannam, 1982; Moller, 1966). In other words, the same muscle may exhibit 100% activity during one task or phase and only 50% during another.

Thus, the resultant vector of muscle force (Mir) for a particular muscle in isometric contraction at a specific moment, or during a given task would be given by the product

$$[X_{Mi} \cdot K] \cdot EMG_{Mi} = Mir$$

where X_{mi} is the cross-sectional diameter of muscle Mi in cm^2, K is a constant for skeletal muscle (expressed in N/cm^2), and EMG_{Mi} is the ratio, or scaled value, of the muscle contraction relative to its maximum response for any task (Pruim et al., 1980; Weijs, 1980). The product $[X_{Mi} \cdot K]$ is hereafter referred to as the "Weighting Factor" given to the muscle Mi, and the value EMG_{Mi} as its "Scaling Factor".

a. Weighting Criteria

A variety of studies have estimated the force per unit of cross-sectional area of skeletal muscle, (K). Although there seems to be considerable variation in this value among investigators [Ralston _et al_., (1949), 1.3-2.4 kg/cm^2; Haxton (1944), 3.9 kg/cm^2; Hettinger (1961), 4.1 kg/cm^2; Ikai and Fukunaga (1968), 7.1 kg/cm^2; Gysi (1921), 6.46 kg/cm^2, Morris (1948), 9.2 kg/cm^2; Fick (1910 as cited by Pruim _et al_. 1980), 10.0 kg/cm^2; and Pruim _et al_. (1980), 13.7 kg/cm^2] much of this variation has been attributed to differences in methods and errors in force generation and muscle cross section determinations, and the integration of these data (Weijs, 1980; Weijs and Hillen, 1984a). Such variables as subject motivation, discomfort, muscle resting length, accuracy of cross section measurement and muscle fiber type (i.e. fast versus slow-twitch motor units) all influence these determinations. However, despite these differences and the considerable variation in the force per unit area known to exist between individuals, a mean value of 4.1 kg/cm^2, or 40 N/cm^2, which is independent of sex, age and muscle, seems most appropriate (Ganong, 1977; Weijs and Hillen, 1984a) and was chosen as the weighting constant (K) for this study.

Weighting factors assigned to each muscle and their derivation from determinations of whole muscle cross-sectional areas are given in Table I. The whole muscle group cross-sections are from the CT scan work of Weijs and Hillen (1984a and b), and represent the bilateral mean cross sectional areas of the four main masticatory muscle groups (i.e. masseter, medial pterygoid, temporalis and lateral pterygoid) of 16 male subjects. This group had an average age of 35 years, mean number of missing teeth 1.8 and normal healthy occlusions (Angle class I or II).

Weijs and Hillen (1984b) took CT scans of their subjects at approximately right angles to the mean masticatory muscle fiber directions midway between the origin and insertion points of each with the jaw in occlusion. The orientation of the scan planes had been determined according to previous scans of cadavers such that only three planes were required to study all muscles bilaterally (Weijs and Hillen, 1984a). These planes were: 1 cm above the zygomatic area and parallel to the Frankfort horizontal plane (FH) for temporalis; 3 cm anterosuperior of the mandibular angle at 30 degrees to the FH for masseter and medial pterygoid; and 1 cm anterior to the lateral poles of the condyles perpendicular to FH for the lateral pterygoid muscle (Weijs and Hillen, 1984a and b).

The cadaver study also provided these workers with specific linear regression equations relating the cross sections, measured from the scans, with actual direct determinations of the muscle cross-sections measured according to two different procedures known in the literature as the method of Weber (1946) and that of Buchner (1877) (see Weijs and Hillen 1984a for a complete discussion of the two). The former method is mathematical and is simply the total fiber weight of a given muscle divided by that muscle's average fiber length. The latter is the actual measurement of the total cross section of the teased and stacked fiber bundles of a given muscle. Both are tedious and require detailed dissection and the elimination of all elements of vessels, fat and loose connective tissue, and give slightly different results.

Although Weijs and Hillen (1984b) provide the mean muscle cross-sections of their subjects predicted according to both Weber's and Buchner's dissection methods the predictions for the latter were incorporated in this study. Buchner's method (and thus also the predictions from the scans) was felt to be more accurate and involve less residual error in the linear regression equations when used with scanned cross sections (Weijs and Hillen, 1984a, Table III). It predicts the ratio of the cross sections of masseter: medial pterygoid: temporalis to be 1.00 : 0.6 : 1.1 when the masseter is used as a reference. This agrees fairly well with the same proportions derived from the work of Carlsoo (1952) of 1.0:0.5:1.3 and from that of Schumacher (1961) of 1.0:0.5:1.2 (Pruim et al., 1980). The same ratio, when calculated for the dissected cross-sections of Wiejs and Hillen (1984a), shows the Buchner method (1.0:0.6:1.1) to be somewhat closer to this relation than the Weber method (1.0:0.7:1.1).

Since the anatomical divisions of the muscle groups of the present study are more detailed than the whole muscle cross sections provided by Weijs and Hillen (1984a and b) division of the total cross-sectional areas of each muscle into its component groups was necessary. The division of the masseter into a superficial and deep group in the proportions 0.7 and 0.3 respectively was made arbitrarily but was based on the general relationships depicted in standard anatomical texts (eg. Dubrul, 1980).

The temporalis muscle was divided into the proportions 0.48, 0.29, and 0.23 for the anterior (AT) middle (MT) and posterior (PT) portions respectively (see Table I). This division was based on the ratio between AT and PT of 1.0:0.6 from Carlsoo (1952). In order to split the temporalis into three groups it was decided, arbitrarily, to assign an equal portion of AT and PT to MT. In this way the ratio between these three groups became 1.0 : 0.6 : 0.5 corresponding to the proportions designated.

Although lateral pterygoid is divided into an upper (SP) and lower (IP) group anatomically, the lack of physiological response data (discussed below)for the SP and the overall uncertainty surrounding its actual function (Grant, 1973; McNamara, 1973; Lipke et al., 1977; Juniper, 1981; Mahan et al., 1983), made it impractical to include the SP as a distinct group in all tests at this time. However, the relative proportions of this muscle's overall cross section contributed by each head has been determined, and is included in Table I. According to the data of Honee (1970) the SP and IP heads can be proportioned at 0.30 and 0.70 respectively whether their cross-sections are determined according to Buchner's method or Weber's method. Similar proportions (0.26 and 0.74) are also found in the lateral pterygoid functional analyses of Grant (1973).

The assumed digastric cross-section was that of Pruim et al. (1980) which was based on the dissection of four pairs of anterior digastric muscles from elderly people according to the methods of Buchner and Weber already discussed. These workers actually determined a mean cross section of 0.8 cm^2 per side (S.D. = 0.2 cm^2) but used a value of 1.0 cm^2 in their biomechanical calculations to account for size differences which they felt would exist between their elderly dissection subjects and their young adult biomechanical analysis subjects.

TABLE I - WEIGHTING FACTORS. Values for the nine functional muscle groups of this study according to their proportions of the whole muscle cross-sections of Wiejs and Hillen (1984b), assuming a force capability of 40 N/cm^2. The determination of the proportioning values of the whole muscles into their respective groups is discussed in the text. Whole muscle abbreviations: M, masseter; MP, medial pterygoid; T, temporalis; LP, lateral pterygoid. Muscle group abbreviations: SM, superficial masseter; DM, deep masseter; AT, MT and PT, anterior, middle and posterior temporalis respectively; IP, inferior lateral pterygoid; SP, superior lateral pterygoid; DG, digastric.

WHOLE MUSCLE X-SECTION (cm^2)				MUSCLE GROUP PROPORTION	MUSCLE GROUP X-SECT (cm^2)	MUSCLE GROUP WEIGHT (N)
M	6.80	1.69	SM	0.70	4.76	190.40
			DM	0.30	2.04	81.60
MP	4.37	0.96	MP	1.00	4.37	174.80
			AT	0.48	3.95	158.00
T	8.23	1.13	MT	0.29	2.39	95.60
			PT	0.23	1.89	75.60
LP	2.39	0.45	IP	0.70	1.67	66.90
			SP	0.30	0.72	28.70
			DG*	1.00	1.00	40.00

*Cross-section according to Pruim et. al. (1980).

b. Scaling Criteria

i. Clenching Tasks

Scaling Factors for each muscle are shown in Table II. The values for SM, MP, AT and PT were derived from the work of Macdonald (1982). Those for DM were taken from Belser and Hannam (1986), those for IP activity from Wood et al. (1985), and those for SP and DG (for Tasks 1, 2, 3 and 4) from Mahan et al. (1983) and Gibbs et al. (1984).

The clenching tasks of this study are the same as those used by MacDonald (1982). His electromyographic data for these tasks therefore provided the basis for the Scaling Factors which were used. Scaling Factors for muscle groups for which no representative data could be found in the literature were estimated from available evidence suggesting their likely contributions to a given task. The values for the relative activities seen in Table II represent normalized mean EMG data for maximal voluntary clenches for the six static clenches at the various points of the dentition.

MacDonald's recordings were obtained with acrylic "stops" custom made to each subject's dentition. This produced an increase in vertical dimension of 1mm at the incisors in each case (except Task 1 and 4). His data was averaged for ten to twenty subjects (S = 20) (mean age 31-35 years depending on the test series) performing each task at least 5 times.

The DM data of Belser and Hannam (1986) (S = 20; mean age = 33 years) show the responses of SM and DM to be the same (95%) during maximal voluntary clenching in the intercuspal position. As such DM scaling values for Task 1 of Table II are the same as SM, both of which agree with the above. DM values for bilateral molar clenching (Task 2) were also assumed to match SM values. For unilateral tasks (Task 5 and 6) the DM values were assigned those of the SM of the same side since Belser and Hannam (1986) found no significant difference between these muscle groups during unilateral clenching (although occlusal stops were not incorporated in their study). For incisal clenching Belser and Hannam found SM activity at ~39% which is strikingly similar to the data of MacDonald (1982, Table II, Task 3 and 4). Corresponding DM activity of ~26% for incisal clenching found by Belser and Hannam was therefore assigned in these tasks.

MT activity has been generally neglected as a distinct entity in any form in the literature despite its differences in orientation. To deal with this void of information its scaling values were derived by assuming activity intermediate between the anterior and posterior groups of this muscle.

The inferior pterygoid (IP) activities measured by Wood et al. (1985) (S = 9 with similar age profiles to the above cases) shows mean values of about 27% of maximum for vertical intercuspal clenching, and 71% for incisal clenching on natural contacts (see Table II, Task 1, 3 and 4). By comparison Mahan et al. (1983) (S = 9) and Gibbs et al. (1984) (S = 11) recorded mean activities for these same tasks (but with an anterior splint or stop for the incisal effort) of 27% and 33% for the intercuspal clench respectively and 60% and 72% for the incisal clench. Both these latter workers also found IP to be about 30-40% active for vertical clenching on a 1.5 mm full arch splint (see Table II, Task 2). The greater activity in SP versus IP during clenching, to which IP orientation seems less suited (Grant, 1973), has generally been found by others as well (Juniper, 1981, in man; MacNamara,

TABLE II - SCALING FACTORS (CLENCHING). Values (mean normalized EMG activities) assigned to the various muscles for the given clenching tasks derived from literature sources. The right side is assumed to be the working or ipsilateral side in all cases. Muscle abbreviations are the same as in Table I. Working side (WS) is on the right (R).

	1 INTERCUSPAL CLENCH (NATURAL) CO		2 BILATERAL MOLAR CLENCH (M_2 STOPS) BIMOL		3 INCISAL CLENCH (WITH STOP) INCISS		4 INCISAL CLENCH (NATURAL) INCISN		5 UNILATERAL CANINE CLENCH (CANINE STOP) UNIK9		6 UNILATERAL MOLAR CLENCH (M_1/M_2 STOP) UNIMOL	
	R/WS	L/BS	R/WS	L/BS	R/WS	L/BS	R/WS	L/BS	R/WS	L/BS	R/WS	L/BS
SM	1.00	1.00	0.81	0.81	0.43	0.43	0.40	0.40	0.46	0.58	0.72	0.60
DM	1.00	1.00	0.81	0.81	0.26	0.26	0.26	0.26	0.46	0.58	0.72	0.60
MP	0.76	0.76	0.82	0.82	0.59	0.59	0.78	0.78	0.55	0.47	0.84	0.60
AT	0.98	0.98	0.83	0.83	0.26	0.26	0.08	0.08	0.54	0.14	0.73	0.58
MT	0.96	0.96	0.83	0.83	0.18	0.18	0.06	0.06	0.48	0.20	0.66	0.67
PT	0.94	0.94	0.84	0.84	0.09	0.09	0.04	0.04	0.42	0.26	0.59	0.39
IP	0.27	0.27	0.36	0.36	0.71	0.71	0.71	0.71	0.30	0.65	0.30	0.65
SP	0.59	0.59	0.61	0.61	0.50	0.50	0.50	0.50	----	----	----	----
DG	0.28	0.28	0.33	0.33	0.50	0.50	0.50	0.50	----	----	----	----

SM, MP, AT, PT - from MacDonald (1982) : Figure 17 [Task 1]; Figure 14 [Task 2]; Figure 10 [Task 3, 4 and 5]; and Figure 15 [Task 6 and 7].
DM - from Belser and Hannam (1986)
MT - arbitrarily assigned
IP - from Wood et. al. (1985; Figure 3).
SP, DG - from Mahan et. al. (1983; Figure 5) and Gibbs et. al. (1984; Figure 5).

1973, in monkeys). For unilateral clenches (Table II, Task 5 and 6) the data of Wood et al. (1985) for the working and balancing side IP groups were assigned.

Scaling values are included for SP and DG for bilateral clenches only (Tasks 1, 2, 3 and 4). No normalized EMG data is available regarding activity in these muscle groups for unilateral clenching, or chewing.

ii. Chewing

Table III represents the approximate Scaling Factors of the muscle groups for unilateral gum-chewing. The three time intervals are: (1) 100 msec prior; and (2) 50 msec prior to the onset of intercuspation; and (3) time zero which was about 10-15 msec after its onset. Except for DM and MT all data were derived from Figure 31 (pp. 80-81) in the work of Moller (1966) which presents the average electrical activity recorded for each muscle group (S = 36). The responses were determined at 150, 200 and 250 msec of his time frame which was referenced to the onset of AT activity. The initial onset of intercuspation occurred slightly before the 250 msec interval by about 10-15 msec. The mean activities determined from this figure are simply the averages of the recorded levels and are not normalized to their respective potential or maximum levels. Therefore each muscle group's normalized scale of chewing activity for these intervals was determined by finding the proportion of its activity relative to a mean maximum recorded during any function. For SM, MP, AT and PT these maximal values were taken from the average mean voltage recorded by Moller (1966) during intercuspal maximum biting (Table 25, p. 144; S = 36). The maximal

TABLE III - SCALING FACTORS (CHEWING). Values assigned to the muscle groups for unilateral gum-chewing (see text for sources). Time zero of Interval 3 occurred about 10-15 msec after the onset of intercuspation. Abbreviations correspond to Tables I and II.

	INTERVAL 1		INTERVAL 2		INTERVAL 3	
	100 msec		50 msec		Time 0	
	R/WS	L/BS	R/WS	L/BS	R/WS	L/BS
SM	0.33	0.23	0.56	0.20	0.36	0.09
DM	0.33	0.23	0.56	0.20	0.36	0.09
MP	0.77	0.63	0.97	0.47	0.75	0.29
AT	0.45	0.31	0.65	0.51	0.45	0.36
MT	0.43	0.32	0.60	0.53	0.37	0.36
PT	0.41	0.33	0.54	0.54	0.29	0.35
IP	0.25	0.18	0.35	0.25	0.15	0.15
SP	----	----	----	----	----	----
DG	0.00	0.00	0.00	0.00	0.00	0.00

mean activity for IP occurred during bread chewing (Table VI, p. 222). DG is not active during this phase of chewing (Moller, 1966; Munro, 1973).

Although Belser and Hannam (1986) describe a difference in mean peak activities between DM and SM on the balancing side for unilateral chewing of 51% versus 24% respectively, they provide no time frame for this difference relative to intercuspation. As such, for the purposes of analysis of unilateral chewing, the deep portion of the masseter muscle was arbitrarily assigned the same scale values as SM.

SP activities are not available for chewing and MT was assumed to exhibit activities intermediate between those of AT and PT.

C. COMPUTER ANALYSIS

With all the necessary input for a task in question entered biomechanical analysis by the computer was carried out. From the angular orientation of each muscle group, its Weighting Factor (maximum force capabilities) and its relative Scaling Factor value (task specific proportional activity) the program determined the resultant vector of force generated by each muscle along its line of action for the specific task being analyzed. From this resultant the computer program then determined the corresponding x, y and z components of force for each muscle group for which the tooth and condylar resistances forces were calculated. As discussed the mechanics of the program were based on the laws of static equilibrium and consisted of the following steps which are summarized in Figures 5, 6 and 7.

1. Lateral Plane - Step 1

Initially, as shown in Figure 5, the system was analyzed in the lateral plane. The condyles were assumed to be coaxial, with the right one acting as the fulcrum. The computer determined the length of each moment arm for the muscle force components (eg. dMy and dMz) as well as those for the tooth force components (dTy and dTz). The moment of force about the fulcrum is given by the force vector component along each axis multiplied by its moment arm (perpendicular distance from the fulcrum). For the situation in Figure 5, which for reasons of clarity includes only one muscle pair (superimposed), the moments of force due to the muscles are the products of

My(dMy) = Y Moment of Muscle Force

Mz(dMz) = Z Moment of Muscle Force

Both of these act anticlockwise about the fulcrum (the condyles). Similarly the moments about the fulcrum due to the components of tooth resistance force are the products

Ty(dTy) = Y Moment of Tooth Force

Tz(dTz) = Z Moment of Tooth Force

both of which are clockwise in direction. There are no moments contributed by any joint forces in this plane as all joint forces pass through the fulcrum. The net moment of rotation of the system is given by the difference between the sums of the total clockwise moments and the total anticlockwise moments. By definition, the sum of the moments must equal zero, since no jaw movement is assumed to take place.

i.e. Σ (TOTAL CLOCKWISE MOMENTS) + Σ (TOTAL ANTICLOCKWISE MOMENTS) = 0

therefore,

(1) Σ (My(dMY) + Mz(dMz)) + (Ty(dTy) + Tz(dTz)) = 0

From equation 1, all variables have known values except Ty and Tz. Since both the angles of the tooth resultant [α, lateral angle; and β, frontal angle) are specified, the relative ratios of the vectors Ty and Tz can be determined from:

$$\tan \alpha = Tz/Ty$$

and

$$Ty = Tz/\tan \alpha \qquad \text{(See Figure 5)}$$

where TR_{LAT} is the resultant tooth force projected onto the lateral plane. Rewriting equation (1), and expressing Ty in terms of Tz this equation becomes:

$$\Sigma\ [My(dMy) + Mz(dMz)] + [(Tz/\tan \alpha)\ (dTy) + Tz(dTz)] = 0$$

or

$$Tz(dTz + (dTy)/\tan \alpha) = \Sigma\ (Mz(dMz) + My(dMy))$$

Since only Tz of this equation is unknown, its value is easily determined. Substitution of the relation Ty = Tz/tan α yields a value for Ty. Since the frontal tooth angle β is also specified (see Figure 6), Tx = Tz/tan β. Thus Tx, the lateral tooth force component viewed in the frontal plane, is determined.

In other words, since the total moments due to the muscle forces are known and must be completely opposed only by the sum of the moments of tooth force in this plane, the procedure determines the relative amounts of tooth force at the designated angular orientations (α and β; see Figures 5 and 6 respectively) necessary along each axis at the specified position of tooth contact. It has already been stated that because the condyles are considered to be coaxial in this step, and act as the fulcrum, there are no contributing condylar moments acting in this plane.

However, the sum of the static linear anteroposterior muscle (My) tooth (Ty) and joint force components (CRy + CLy) must equal zero. Likewise, the vertical components of all forces must sum to zero,

i.e. $\Sigma My + Ty + (CRy + CLy) = 0$

and

$$\Sigma Mz + Tz + (CRz + CLz) = 0$$

therefore

(2) $CRy + CLy = -(\Sigma My + Ty)$

(3) $CRz + CLz = -(\Sigma Mz + Tz)$

Thus the resultant vector of this total joint resistance force (Cr; Figure 4) and its angular orientation in the lateral plane can be determined trigonometrically since $Cr = [(CRy + CLy)^2 + (CRz + CLz)^2]^{-1/2}$ and the lateral plane joint force angle is given by arctan $(CRz + CLz)/(CRy + CLy)$ (see Figure 5).

For a bilaterally symmetrical situation the analysis needs to go no further, (Weijs and Dantuma, 1981). The component of anteroposterior (y) and vertical (z) condyle resistance forces on each condyle (right and left) will be simply half of the sum of the values found in equations 2 and 3 respectively. Any mediolateral forces acting on the system will be equal and opposite on the two sides and will cancel each other completely.

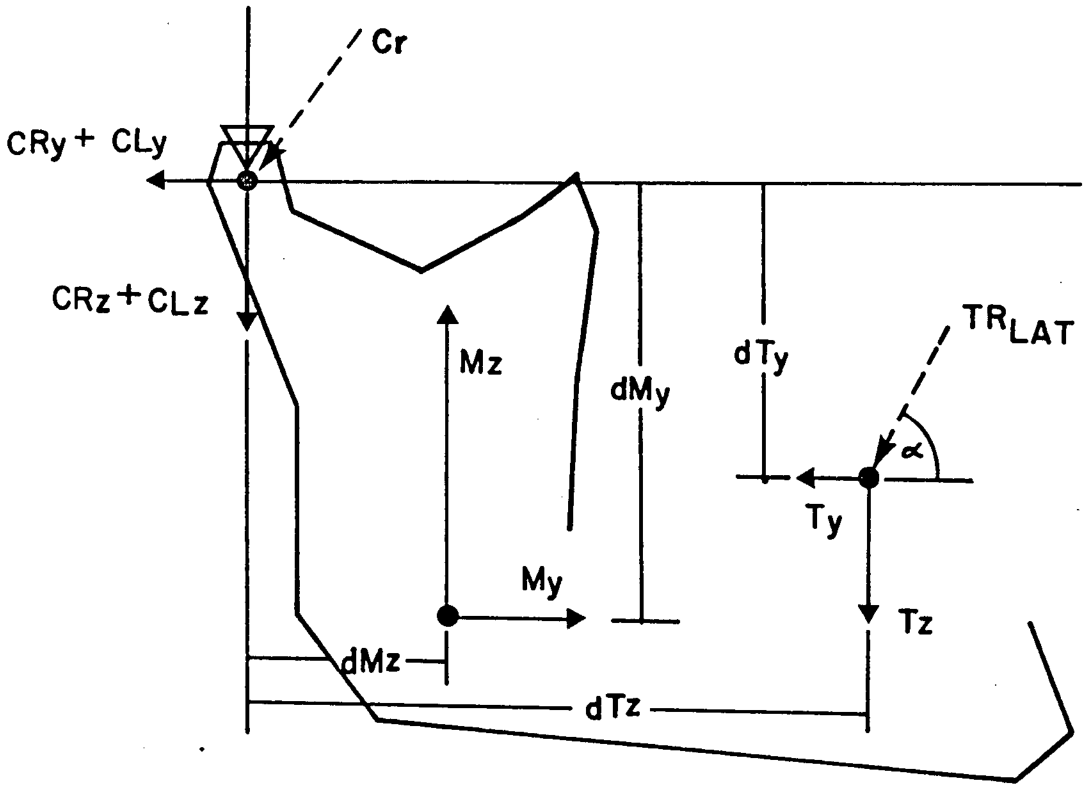


Figure 5. LATERAL (yz) REPRESENTATION OF FORCE COMPONENTS. In this view the coaxial condyles act as the fulcrum. Tooth resistance forces are represented by Ty (anteroposterior) and Tz (vertical), combined joint forces as CRy + CLy (right and left anteroposterior), CRz + CLz (right and left vertical) and muscle forces as My and Mz. TR_{LAT} represents the projection onto the lateral (sagittal) plane of the total 3-dimensional tooth resultant force TR. Respective moment arms are prefixed by d. Only one muscle is shown as the right and left sides are superimposed. is the angular orientation of the resultant vector of resistance force on the tooth in this plane (i.e. lateral tooth angle).

2. Frontal Plane - Step 2

As can be seen in Figure 6, the system is next analyzed in the frontal plane. Again the condyles are assumed to be coaxial with the right condyle acting as the fulcrum. Apparently, therefore, no mediolateral joint force is determinable in this step as any occurring at the left condyle would not produce any net moment about the right condyle fulcrum.

The value of Tx has already been derived from the relation

$Tx = Tz/\tan \beta$.

The total resultant force of resistance (reaction force) at the given point of tooth contact along the specified angles α and β in the lateral and frontal planes respectively is given by

$TR = [Tx^2 + Ty^2 + Tz^2]^{-1/2}$.

The lengths of the moment arms for each muscle and tooth vector

component, x and z, as well as for the z component of force at the left condyle are determined. Incorporating moments arising at both the left and right sides of this figure, the total anticlockwise moment is the sum of the moments

(4) $MRz(dMRz) + MLz(dMLz) + MLx(MLx) = K_o$

and the total clockwise moment is the sum of the moments

$MRx(dMRx) + Tx(dTx) + Tz(dTz) + Clz(dClz) = K_i$.

Only CLz is unknown in these equations thus, the latter may be rewritten,

(5) $K_i = K_{ii} + Clz(dClz)$

where K_{ii} is substituted for the known muscle and tooth variables. Since the static conditions require the sum of the clockwise and anticlockwise moments to equal zero,

$K_o + K_i = 0$

and $K_o + [K_{ii} + CLz(dCLz)] = 0$

or

(6) $CLz = K_1/dCLz$ where $K_1 = -(K_o + K_{ii})$.

Since K_i and dClz are both known variables, the vertical component of force on the left condyle (CLz) is solved. The sum of the static linear vertical (z) force components and the mediolateral (x) components must both also equal zero.

Therefore

$MRz + MLz + Tz + CRz + CLz = 0$

and

$MRx + MLx + Tx + CRx + CLx = 0$

Again only the condylar force variables are unknown and the equations may be rewritten

(7) $CRz + CLz = -(\Sigma Mz + Tz)$

(8) $CRx + CLx = -(\Sigma Mx + Tx)$

Equation 7 is the same as equation 3 derived in step 1 and is therefore redundant. Equation 8 expresses the net total mediolateral reaction force of the right plus left condyles. Since they are coaxial the relative amount of this force on either the right or the left condyle cannot be determined unless the angle at which the resistance force acts at one of the condyles is known. It is for this reason that the angle of left condylar reaction force (γ, of Figure 6) previously mentioned is specified in the initial data entry for a given task.

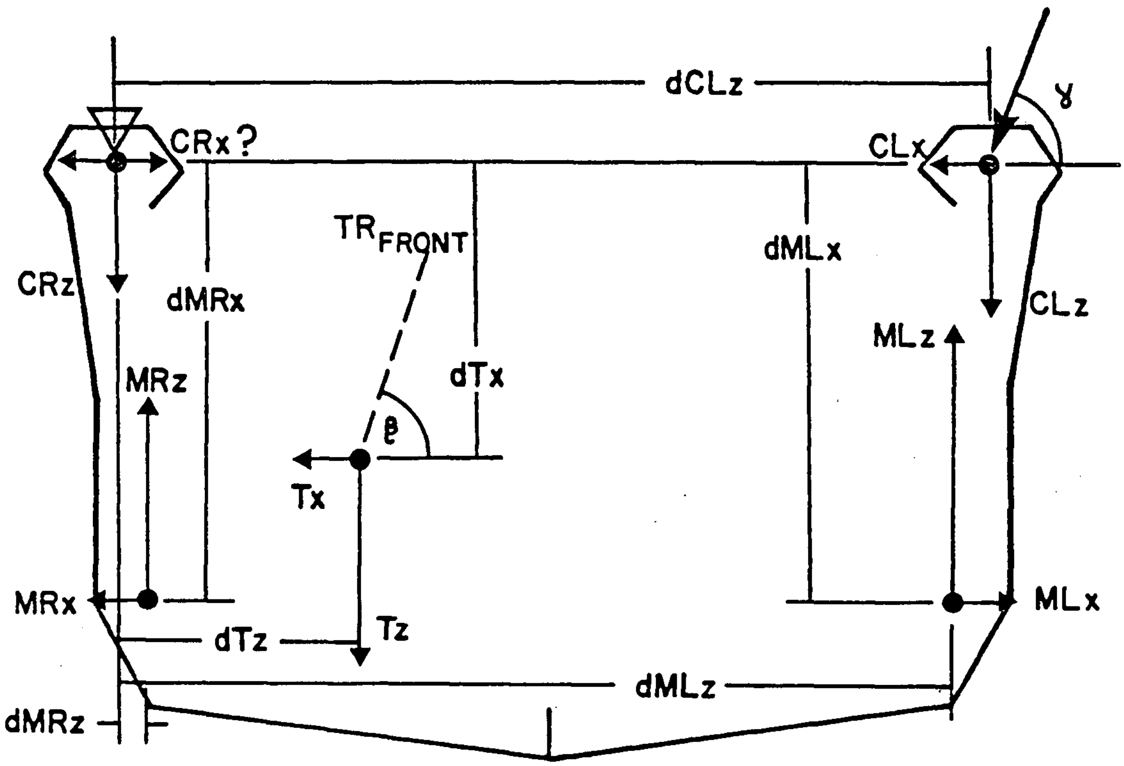


Figure 6. FRONTAL (xz) REPRESENTATION OF FORCE COMPONENTS. In this view the right condyle acts as the fulcrum. Tx represents the mediolateral component of tooth resistance force; TR_{FRONT} the projection onto the frontal plane of the total three dimensional resultant of tooth resistance force TR; and the angular orientation of TR_{FRONT}. MRx and MRz are the right mediolateral and vertical muscle force components; MLx and MLz are those for the left side. is the assumed orientation of the resistance force at the left condyle. All other abbreviations as for Figure 2.

As was the case for the tooth resistance forces the ratio between the two left condylar reaction forces is

$\tan \gamma = CLz/CLx$ or $CLx = CLz/\tan \gamma$

Since the value of CLz was determined in equation 6 and angle γ is specified, substitution into the above gives the value of the left condylar mediolateral component of resistance force, CLx. Substitution of this value into equation 8 gives the value for the right condyle, CRx, since it remains the sole unknown in that equation.

Summarizing to this point, then, vector magnitudes can be derived for;

(a) the components of tooth reaction or resistance force (Tx, Ty and Tz) and the resultant vector of tooth force (TR) at the specified point of resistance at the designated angular orientations;

(b) the vertical components of left and right condylar reaction forces (CLz and CRz)

(c) the mediolateral components of left and right condylar reaction force (CLx and CRx)

The only values remaining to be determined are those of the anteroposterior components of condylar reaction force occurring at the right (CRy) and left (CLy) sides.

3. Horizontal Plane - Step 3

In the horizontal plane (Figure 7) the lengths of all moment arms are derived and a value for the left condylar anteroposterior reaction force, CLy, is determined as follows:

The sum of the anticlockwise moments is given by

(9) $MRx(dMRx) + MRy(dMRy) + MLy(dMLy) + Tx(dTx) = K_{ii}$

and the clockwise moments by

(10) $CLy(dCLy) + MLx(dMLx) + Ty(dTy) = K_{iv}$

or

$$CLy(dCLy) + Kv = K_{iv}$$

where K_v represents the known variables on the left of equation 10.

Combining these clockwise and anticlockwise moments from Figure 7 (which also must completely oppose one another) equations 9 and 10 become

$$K_{iii} + [CLy(dCLy) + K_v] = 0$$

or

(11) $CLy = K_2/dCLy$ where $K_2 = -(K_{iii} + K_v)$.

Since K_2 and dCLy are both known variables, the anterposterior component of force on the left condyle (CLy) is solved. Substituting this value of CLy into equation 2 of Step 1 gives the corresponding anteroposterior component of force on the right condyle, CRy.

In this plane,summation of the static linear x and the y force components similar to the x and z components in step 2, can be expressed by

$$MRx + MLx + Tx + CRx + CLx = 0$$

and

$$MRy + MLy + Ty + CRy + CLy = 0$$

which may also be written

$$CRx + CLx = -(\Sigma Mx + Tx)$$

$$CRy + CLy = -(\Sigma My + Ty)$$

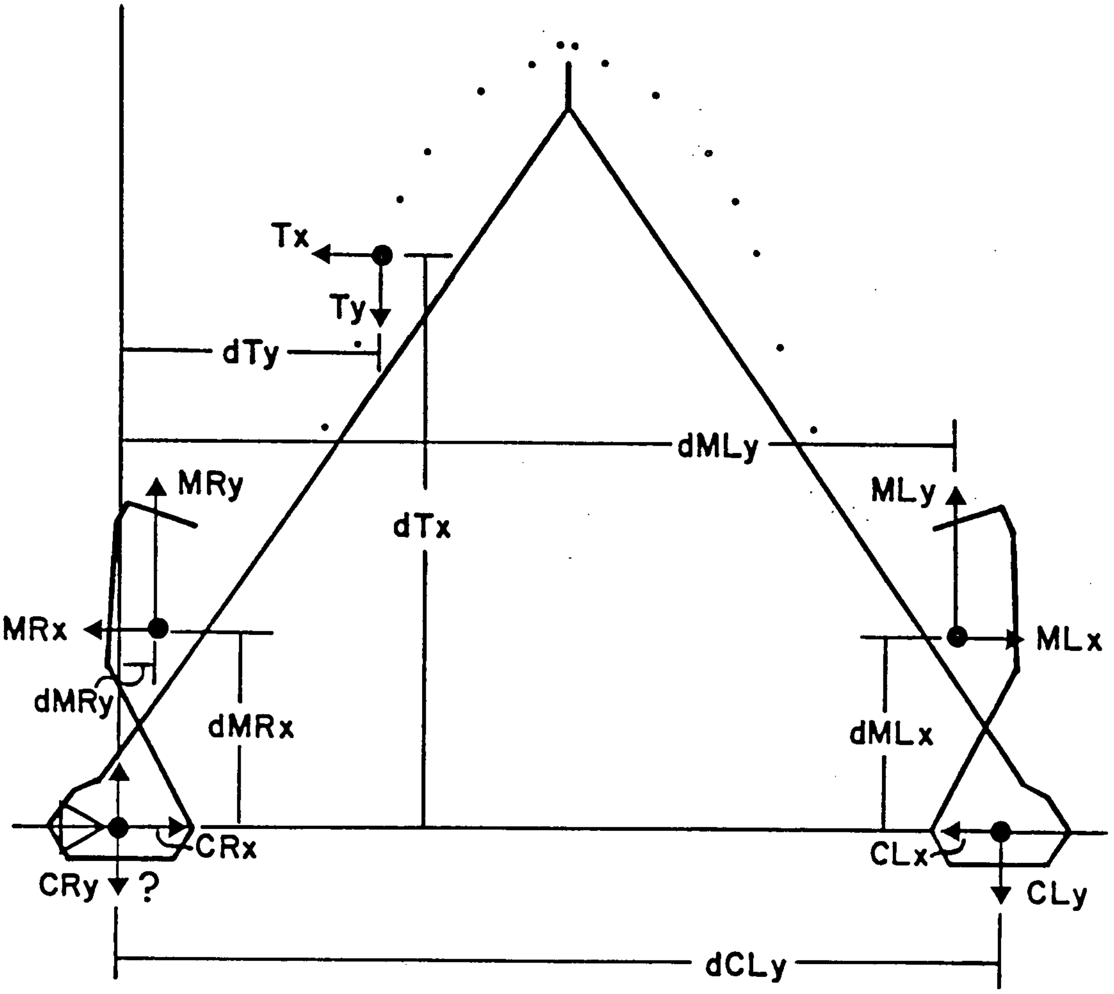


Figure 7. HORIZONTAL (xy) REPRESENTATION OF FORCE COMPONENTS. The coaxial condyles again have the right joint acting as the fulcrum. The figure appears as though viewed from below with the right side on the viewer's left. All abbreviations as for Figures 5 and 6.

However, both of these values were derived previously and are therefore also redundant (see equations 8 and 2 respectively).

The calculated three dimensional components of muscle, tooth and joint force are stored on computer file and are retrievable on either a screen or hard-copy printout. However the data presented in the plots of the RESULTS section are the resultants, or single net vectors of resistance derived from these components at the point of tooth contact, and condyles. Representation of the resultants in this way also gives their angular orientation projected onto the respective plane of view.

4. Constraints On Muscle Resultants

It would seem appropriate and convenient to display, in addition, a net single three dimensional resultant muscle vector and its orientation in each plane (Weijs and Dantuma, 1975; Weijs, 1980; Weijs and Dantuma, 1981) in the plots of the RESULTS which follow. This would enable comparisons of muscle force orientations to the assumed direction of the resulting tooth resistance force in three dimensions. However, this is theoretically not possible because a system of forces acting on a rigid body in space can be reduced to a single force or resultant only if those forces are (1) concurrent (all passing through the same point in space; in this case three dimensionally), (2) coplanar, or (3) parallel (Beer and Johnston, 1977). The muscle force vectors acting on the mandible satisfy none of these conditions.

However in each individual plane the muscle forces can be reduced sufficiently to a resultant which gives an indication of the orientation of the effective muscle pull in that plane only. It must be borne in mind, though, that consideration of each plane in this way is incomplete without also considering the other two at the same time. The resultant muscle forces for a given plane in the respective x, y or z direction are the sum of the individual muscle components of the right and left sides. These summed static linear forces (eg. MLR, MAR, MVR respectively, see Figure 8) are also responsible for a muscle moment about the fulcrum in a given plane.

If, in the lateral plane shown in Figure 8, it is assumed that all of the muscle moment is due to the total anteroposterior muscle component, MAR, alone (i.e. MVR passes through the fulcrum and thereby has zero moment) then it must have the length r_z as its moment arm. Therefore, for this plane,

$$MAR \cdot r_z = \Sigma \text{ MUSCLE MOMENTS.}$$

If, on the other hand, only the vertical component MVR is to produce all of the moment in this plane then its moment arm will have to be of a length such that

$$MVR \cdot r_y = \Sigma \text{ MUSCLE MOMENTS.}$$

MAR and MVR can be combined to give a "resultant" of muscle force in this plane, M_{LAT}, which exists only in this view. It is worth noting that M_{LAT} can lie anywhere along the line indicating its orientation and that the product of its magnitude and its moment arm (r) will always satisfy the moment requirement,

ie. $M_{LAT} \cdot r = \Sigma$ MUSCLE MOMENTS

It's angle (ANG·L) with respect to the y axis therefore represents the orientation of the overall muscle force vectors projected onto the lateral plane.

A similar derivation can be applied to both the frontal and horizontal planes as shown in Figure 8. In this way an indication of the alignment or orientation of the muscle forces acting on the system within each plane (ANG·L, ANG·F, ANG·H) can be determined. However it is most important to keep in mind the fact that the "resultants" shown in Figure 8 (M_{LAT}, M_{FRONT}, M_{HOR}) apply to their respective planes of view only, and all act simultaneously in three dimensions. Although the components (MLR, MAR and MVR) of these "resultants" are consistent in all three planes their effect on the equilibrium of the mandible is unique to each plane, as evidenced by the fact that the lengths of the moment arms rx, ry and rz are different in each plane.

In effect then, the system of muscle forces can be reduced to three force vectors which can be called "resultants" since they cannot be combined any further into a simpler vector scheme*. Depending on the task and the view considered, the components of the muscle resultant may lie a considerable distance from the fulcrum, and often lie outside the limits of both the computer system's output screen and plotter. As such it is not always possible to plot their positions.

The magnitude of the components of these resultants of muscle force (MLR, MAR, MVR) remain constant for each task and are given in the computer

*It is possible to replace these three by what is known as a "wrench" which represents a set of equivalent forces acting at a specific point in space consisting of a single vector F with a moment arm r to the fulcrum, and a twist M about the axis of F. Thus there is really two twists in a wrench; one about the fulcrum, the other about the axis of F.

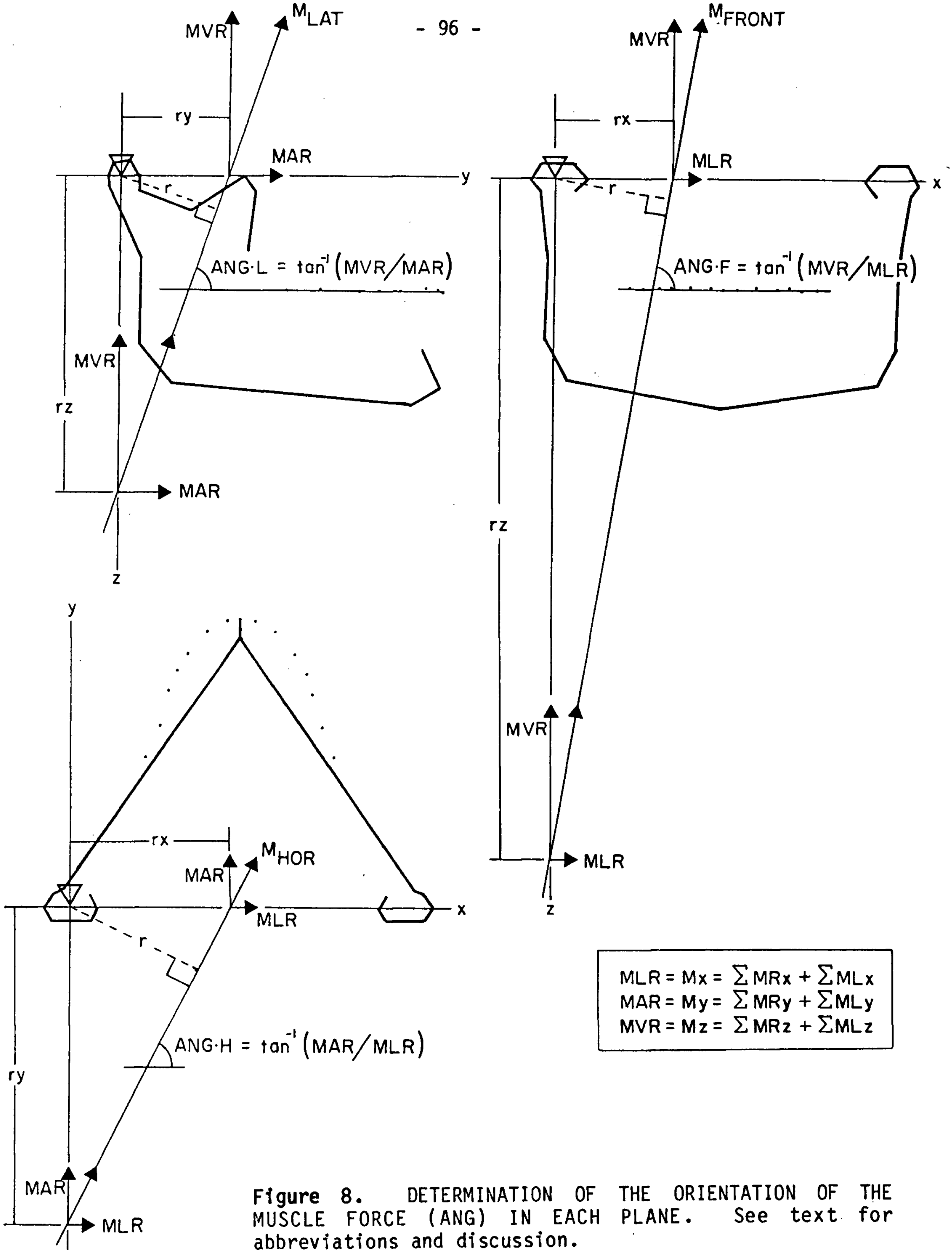


Figure 8. DETERMINATION OF THE ORIENTATION OF THE MUSCLE FORCE (ANG) IN EACH PLANE. See text for abbreviations and discussion.

plots of the resultant tooth and condylar resistance forces of the RESULTS. The orientation of the forces (ANG) is also given for each view. The muscle data (weights and scales) presumably applies to specific acts and/or points of tooth contact. Therefore the angulation of the tooth resistance force in each plane was matched with that of the muscles (as derived above) and comparisons made of the results obtained with those of arbitrarily assigned angles of tooth resistance.

D. COMPUTERIZED ANATOMICAL RECONSTRUCTION

The computer printout of the three dimensional (x, y and z) coordinates of the various possible points of tooth contact for the individual used as the modeling "subject" (hypothetical) are given in Table IV. The center of the right condyle has been specified (arbitrarily) as the center of referencing for the system and the coordinates of the left condyle center are also included here. Any, or all of these components may be changed by the operator by simply specifying the tooth for which a change is required and redesignating the respective x, y and/or z component.

The x, y and z coordinates of the respective origin and insertion points for each muscle are given in Table V. Table V is a computer printout of the muscle data (except Scale Factors) available as another option in the Main Menu of the program. The Weight Factors are all of those derived for each muscle of the "subject". Both the attachment point coordinates and Weight Factors for the individual muscles remain constant throughout this study. Since each different task to be analyzed (eg. incisal, versus unimolar clenching) has a different combination of Scale Factors none are shown in

			LATERAL	ANT/POST	VERTICAL
1	INCISOR	41	45.425	88.000	-33.100
2	INCISOR	42	41.700	86.925	-32.800
3	CANINE	43	36.425	83.575	-32.275
4	PREMOLAR	44	30.975	76.875	-32.625
5	PREMOLAR	45	28.025	71.450	-32.800
6	MOLAR	46	25.850	65.525	-33.200
7	MOLAR	47	23.325	54.625	-33.200
8	MOLAR	48	19.900	45.450	-33.100
9	INCISOR	31	45.425	88.000	-33.100
10	INCISOR	32	49.150	86.925	-32.800
11	CANINE	33	54.425	83.575	-32.275
12	PREMOLAR	34	59.875	76.875	-32.625
13	PREMOLAR	35	62.825	71.450	-32.800
14	MOLAR	36	65.000	65.525	-33.200
15	MOLAR	37	67.525	54.625	-33.200
16	MOLAR	38	70.950	45.450	-33.100
LEFT CONDYLE			90.850	0.000	0.000

<u>TABLE IV</u> - TOOTH AND JOINT COORDINATES (above). Computer printout of the x <u>(Lateral)</u>, y (Ant/post) and z (Vertical) positions of the various tooth contact points measured (mm) from the origin at the center of the right condyle. That of the left condyle is also indicated.

<u>TABLE V</u> - MUSCLE ATTACHMENT COORDINATES (following page). Computer <u>printout</u> of the physiological and anatomical parameters for each muscle group (depicted in Figure 9) which remain constant for every task. WT refers to the muscle group "Weighting Factors". Other abbreviations as per Description of Figures. The Maxillary Origins and Mandibular Insertions are those anatomical attachment positions, for each muscle group measured (mm) along the x (Lateral), y (Ant/Post) and z (Vertical) axes from an origin at the center point of the right condyle (see Figure 9). The sign convention is such that negative values indicate positions to the right of, posterior to, and/or below the origin point. (The "Scale Factors" are variable depending upon the task and are described with each of these later on).

TABLE V

MAXILLARY ORIGINS

RT.SIDE		WT	SCALE	LATERAL	ANT/POST	VERTICAL
1	SM	190.40	0.00	-8.850	41.900	-1.625
2	DM	81.60	0.00	-12.450	16.800	4.950
3	MP	174.80	0.00	25.275	27.475	-12.700
4	AT	158.00	0.00	-3.100	38.425	45.825
5	MT	95.60	0.00	-14.350	.525	57.375
6	PT	75.60	0.00	-16.100	-33.650	38.700
7	IP	66.90	0.00	23.000	27.250	-8.250
8	SP	28.70	0.00	22.775	22.075	3.425
9	DG	40.00	0.00	33.700	45.000	-71.700
LT.SIDE						
10	SM	190.40	0.00	99.700	41.900	-1.625
11	DM	81.60	0.00	103.300	16.800	4.950
12	MP	174.80	0.00	65.575	27.475	-12.700
13	AT	158.00	0.00	93.950	38.425	45.825
14	MT	95.60	0.00	105.200	.525	57.375
15	PT	75.60	0.00	106.950	-33.650	38.700
16	IP	66.90	0.00	67.850	27.250	-8.250
17	SP	28.70	0.00	68.075	22.075	3.425
18	DG	40.00	0.00	57.150	45.000	-71.700

MANDIBULAR INSERTIONS

RT.SIDE		WT	SCALE	LATERAL	ANT/POST	VERTICAL
1	SM	190.40	0.00	1.675	20.600	-46.600
2	DM	81.60	0.00	1.625	26.025	-14.600
3	MP	174.80	0.00	5.950	12.650	-44.175
4	AT	158.00	0.00	8.050	32.125	-27.950
5	MT	95.60	0.00	.425	33.825	1.600
6	PT	75.60	0.00	.275	33.575	1.425
7	IP	66.90	0.00	3.025	3.250	-2.725
8	SP	28.70	0.00	1.100	3.700	1.325
9	DG	40.00	0.00	42.000	77.000	-63.625
LT.SIDE						
10	SM	190.40	0.00	89.175	20.600	-46.600
11	DM	81.60	0.00	89.225	26.025	-14.600
12	MP	174.80	0.00	84.900	12.650	-44.175
13	AT	158.00	0.00	82.800	32.125	-27.950
14	MT	95.60	0.00	90.425	33.825	1.600
15	PT	75.60	0.00	90.575	33.575	1.425
16	IP	66.90	0.00	87.825	3.250	-2.725
17	SP	28.70	0.00	89.750	3.700	1.325
18	DG	40.00	0.00	49.000	77.000	-63.625

Table V. These are shown and graphically displayed, for each respective task, in Figures 10A to 18A of the RESULTS. However, for any given functional task under study the printout of the data shown in Table V would also include the respective Scale Factors for that task (see Appendix II for example).

The computer-drawn plots of the lines of action from origin to insertion point of each muscle, the relative positions of the tooth contact points, and the condyle positions in each plane of reference are depicted in Figure 9 of the RESULTS. The abbreviations for each muscle are as described previously. This is the anatomical basis of the hypothetical subject used by the computer to model the various static occlusal functions in this study.

E. PROGRAM DESCRIPTION

The computer software program of this model was written in FORTRAN IV. The computer system used was a Hewlett-Packard (HP) 1000E-series minicomputer with an HP 7920A DISC DRIVE for storage of data, and an HP 2621A DISPLAY TERMINAL as the major hardware components. Data printing was facilitated by an HP 2607A LINE PRINTER and computer-drawn plots were done using an HP 1350A GRAPHICS TRANSLATER and 1311A GRAPICS DISPLAY SCREEN. Hard-copy of these plots was furnished using a 7210A DIGITAL PLOTTER.

The System Chart, which follows, diagramatically shows the flow of information and how it was handled for input, analysis, storage and retrieval of the data (see SYSTEM CHART).

Initially the anatomical parameters for the given individual, which include the muscle origin and insertion points, and the tooth and joint positions, were entered using an HP 9874A DIGITIZER. These coordinates were entered first from a lateral projection for the vertical and anteroposter dimensions. Then the frontal projection of the right side of the mandible was digitized for the third dimension (mediolateral). The left side of the mandible was generated by the computer as a mirror image of the right thus completing the three dimensional picture. This data was stored on disc for future retrieval, or used directly in the main program.

The physiological variables for the muscle Weight and Scale Factors were entered initially via the main program.

The main program begins with a terminal display of the Main Menu which lists the program options available to the user at this point. These include the following:

- FILE ENTRY/FILE STORAGE - Any existing data file previously stored (on-line) on the disc can be called up or conversely a data file which has just been specified and/or changed can be stored (also on-line).
- VIEW/CHANGE MUSCLE DATA - The orthogonal (x, y and z) coordinates of the attachment points (origins and insertions) for all muscles (left and right) as well as the Weighting and Scaling Factors for the data file under consideration are displayed on the terminal. This display is of the format shown in Table V and is referenced to a zero axis at the right condyle as discussed previously. This also provides the means for the initial specification of the Weight and Scale Factors for each muscle for a particular task and/or file. Any or all of these parameters may be changed by identifying the muscle(s) and

parameter(s) for which a change is desired and entering the new value(s) via the terminal keyboard.

- PRINT MUSCLE DATA - This command gives a printout of the muscle data under consideration via the line printer (see Table V).
- VIEW/CHANGE TOOTH OR LEFT CONDYLE POSITION - This command yields a terminal display of the x, y and z coordinates of the tooth positions and the left condyle position. The format is that shown in Table IV of the RESULTS section. Any or all of these parameters are also changeable as per the muscle data.
- PRINT TOOTH/CONDYLE DATA - The line printer provides a hard copy of the above tooth and condyle data (see Table IV).
- SOFT PLOT ANATOMY: LAT/FRONT/HORIZ - The graphic portrayal of the anatomical relationships for the given individual is plotted on the graphics display screen. The muscle attachment position and alignments, tooth contact points, condyle positions and mandibular outline for either the lateral, frontal or horizontal projections are included as shown in Figure 9 of RESULTS.
- HARD COPY DESIRED PROJECTION - The graphics digital plotter provides a hard-copy of the desired projection of the above data (see Figure 9 of RESULTS).
- TERMINATE - This ends the program at this point.
- CALCULATE - The program enters the main vector analysis of the model. Initially the force vector for each individual muscle along its line of action is derived. This is simply the product of $[X_{mi} \cdot K] \cdot EMG_{mi}$ as discussed previously. From these

vectors (one for each muscle) the three orthogonal x, y and z components of force are derived for each muscle and are used in all subsequent analyses.

At the completion of this initial calculation mode for the muscle vector components a secondary menu, SUBMENU 1, is displayed on the terminal screen. The options at this point include:

- SOFT PLOT MUSCLE VECTORS: LAT/FRONT/HORIZ - The graphics display screen plots each of the individual muscle vectors along their respective lines of action (i.e. from origin to insertion) in either the lateral, frontal or horizontal projections according to the plane specified.
- HARD COPY DESIRED PROJECTION - The graphics plotter provides a hard copy of the desired projection of the above. The format is that shown in Figures 10 to 18A of RESULTS.
- END CALCULATE MODE - The program returns to the Main Menu (eg. if further data changes, or a new file, is required).

Continuation of the calculate mode enters the program in a second phase of calculations where all of the individual x, y and z components of muscle force are combined into single overall components for the system as a whole (as per discussion of Figure 8). These are the total mediolateral (MLR), the total anteroposterior (MAR), and the total vertical (MVR) muscle forces. The general orientation of these overall muscle forces acting on the system in each projection or plane (for the given task) is also derived. Once these determinations are complete another secondary menu, SUBMENU 2, is displayed on the terminal screen:

- SOFT PLOT MUSCLE RESULTANT VECTORS: LAT/FRONT/HOR - The three orthogonal components of the overall muscle forces acting on the system are plotted on the graphics display screen for the projection chosen (see Figure 8 and Appendix II).
- HARD COPY DESIRED PROJECTION
- END CALCULATE MODE - As previous.

Further continuation of the calculate mode requires the operator to specify four variables prior to the determination of the resistance forces at the teeth and joints;

(1) TOOTH# - the desired position of tooth contact.

(2) LTA - the lateral plane tooth angle (α; see Figure 5).

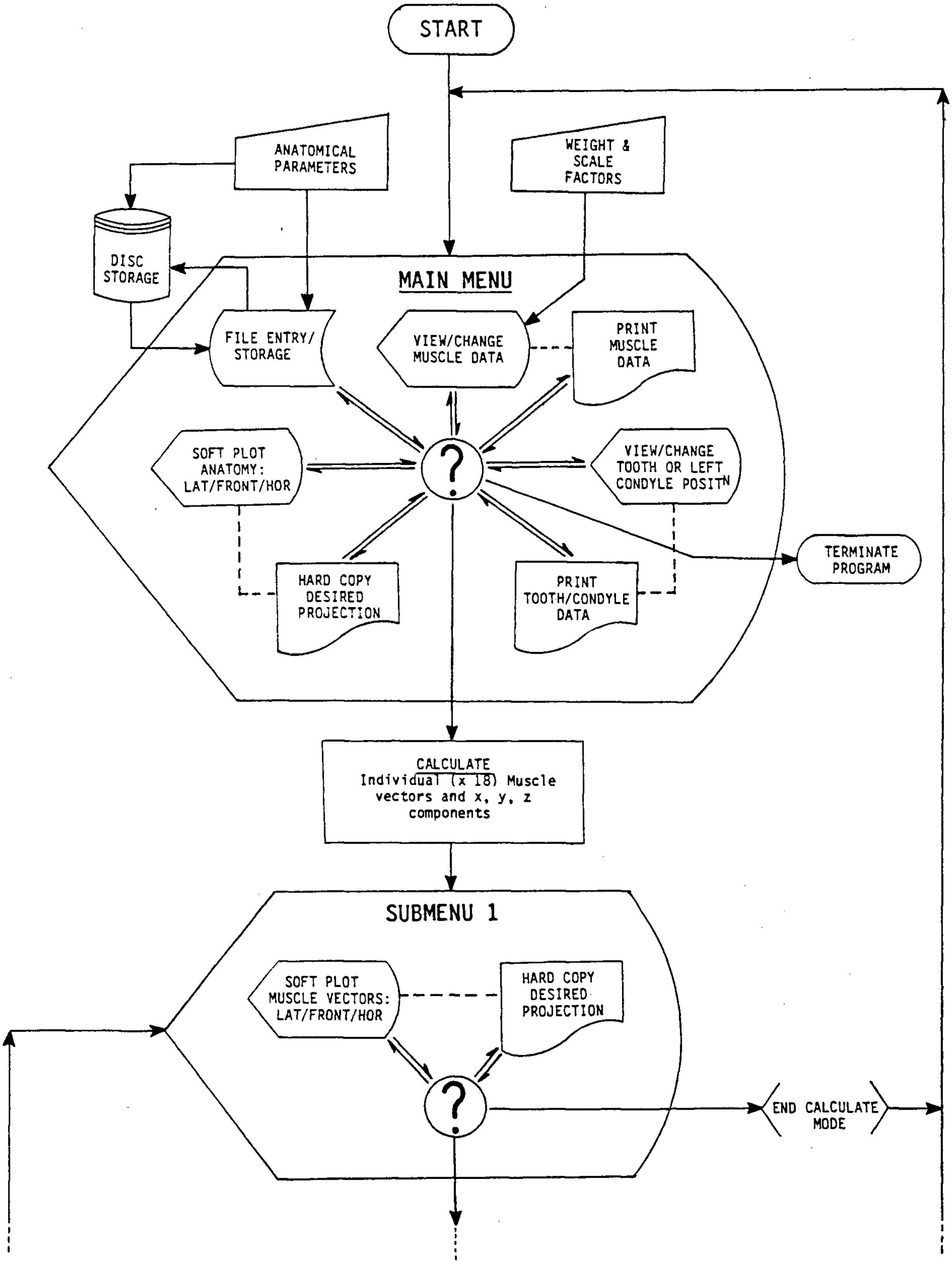
(3) FTA - the frontal plane tooth angle (β; see Figure 6).

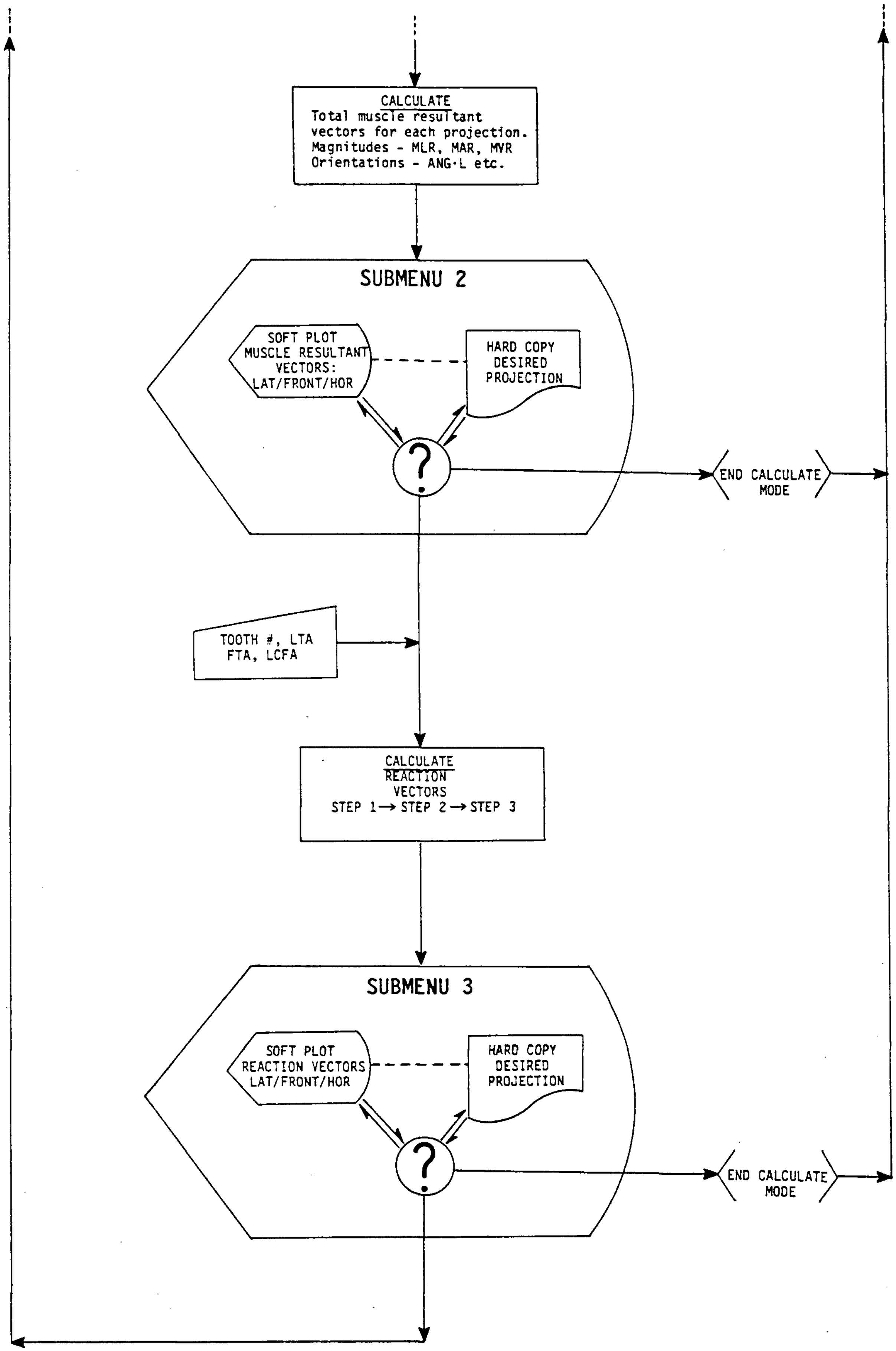
(4) LCFA - the left condylar frontal angle (γ; see Figure 6).

Once these variables are provided the program then determines the reaction force vectors (forces of resistance) at the teeth and right and left joints according to the above specifications due to the given forces produced by the muscles involved. The procedures involved in these determinations are described in STEPS 1, 2 and 3 of the Analysis section. A third secondary menu, SUBMENU 3, is then displayed:

- SOFT PLOT REACTION VECTORS: LAT/FRONT/HOR - The resulting forces of tooth and joint resistance are displayed on the graphics display screen, in the desired projection, for each particular task and input specifications. The actual format of these computer-drawn plots are shown in Appendix II.

SYSTEM CHART. Schematic representation of the flow of the modeling program through the computer system. The MAIN MENU and SUBMENUS 1, 2 and 3 are shown as displays of the options available to the user at each stage of the program. A complete description of the details involved with each step are discussed in the text.




CALCULATE
Total muscle resultant vectors for each projection.
Magnitudes - MLR, MAR, MVR
Orientations - ANG·L etc.
SUBMENU 2
SOFT PLOT MUSCLE RESULTANT VECTORS: LAT/FRONT/HOR
HARD COPY DESIRED PROJECTION
?
END CALCULATE MODE
TOOTH #, LTA FTA, LCFA
CALCULATE REACTION VECTORS
STEP 1 → STEP 2 → STEP 3
SUBMENU 3
SOFT PLOT REACTION VECTORS LAT/FRONT/HOR
HARD COPY DESIRED PROJECTION
?
END CALCULATE MODE

- HARD-COPY DESIRED PROJECTION.

- END CALCULATE MODE - As previous.

Continuation of the calculate mode from this point allows for reconsideration of the muscle vectors and subsequent redesignation of the four input variables should this be desired. This provides a means for comparisons of the effect of changes to one or more of these input variables for the muscle data at hand.

F. PROGRAM USE (IN THIS STUDY)

The computer program is useful only for modeling static isometric tasks undertaken by the jaw system, or in the case of the chewing cycle, where no movement, and hence static conditions are assumed to prevail.

The parameters necessary to derive the force vectors produced by the muscles for each task were derived from data pooled from the literature for a hypothetical "average" individual. It should be reiterated that the parameters ascribed to this hypothetical subject, used in this study, (i.e. muscle anatomical relationships, associated joint and tooth positions, Weighting Factors, task-specific Scaling Factors) were derived only to provide a complete file of the necessary information which could then be applied to the model itself. This was done in view of the fact that all of the necessary data from a single real subject does not exist at this time. Although it is obvious that this pooled data serves only as a first approximation to the real relationships which exist between the various parameters involved it is nevertheless the most comprehensive and complete description of this data presently available.

The modeling program was applied to (1) an intercuspal clench (CO); (2) a bilateral molar clench (BIMOL); (3) a unilateral molar clench (UNIMOL): (4) a unilateral canine clench (UNIK9); and (5) a bite supported (INCISS) and (6) natural incisal clench (INCISN). These were chosen as being representative of the types of static clenching functions undergone by the mandibular system. Application of the model to the three "static" phases of the chewing cycle (near intercuspation) required a more indirect derivation of this data but was undertaken as an example of the potential application and use of the model.

The absence of a means to directly measure the three dimensional orientation of tooth force and/or its actual magnitude made it necessary to initially assume that the angles of tooth resistance force were parallel to that of the applied muscle force. However each task was also modeled for a variety of tooth orientations (±10 degrees approximately) in each plane (lateral angle α; frontal angle β), which included this particular orientation. This was done partly to observe the effect of changes to these angles of tooth resistance, and partly to ensure that a range of these angles was modeled which would include that angle most appropriate with respect to the muscle forces.

Similarly the effect of changing the left condylar angle in the frontal plane was modeled for a variety of orientations for those (unilateral) functions where this alignment may have been other than purely vertical.

RESULTS

The biomechanical relationships between the vectors of force produced by the muscles and the resulting forces of resistance which are generated at the point(s) of tooth contact and right and left joints were analyzed and are presented in three main categories of occlusal function. In each case attachment coordinates and Weight Factors remained constant. Only Scaling Factors and bite point were altered.

The first category included clenching tasks which were bilaterally symmetrical requiring equivalent muscle forces on the right and left sides. These were intercuspal clenching (CO), bilateral molar clenching (BIMOL) and incisal clenching with an "occlusal stop" at the incisors (INCISS), and incisal clenching on the natural dentition (INCISN). "Occlusal stops" refers to a technique of limiting the point(s) of tooth contact by slightly discluding the dentition by means of acrylic separators (see MacDonald and Hannam, 1984).

The second group of tasks was static clenches with occlusal contact limited to one side of the dentition only (right side), including unilateral canine clenching with a stabilizing occlusal stop (UNIK9) and unilateral molar clenching with a stop at the second molar (UNIMOLAR).

The third and final group was the three assumed static intervals near the intercuspal phase of gum-chewing which were also unilateral in the molar region but carried out on the natural dentition (CHEW 1, 2 and 3).

Unlike the unilateral tasks with asymmetric muscle activities the bilaterally symmetrical functions were not complicated by mediolateral considerations. This provided an opportunity to determine an overall magnitude for the total muscle resultant since the two muscle force components (vertical and anteroposterior) were coplanar, lying in the midsagittal plane*. No such determinations were possible for the unilateral tasks for reasons discussed previously (see METHODS).

The individual static clenching tasks involved in each of the first two groups of function are presented and discussed on an individual basis. Comparisons between the tasks involved in each group are discussed subsequently. The three intervals of the chewing function are presented individually but are also discussed as a group.

A. DESCRIPTION OF FIGURES AND ABBREVIATIONS

The figures which follow depict the three dimensional relationships between the vectors of force produced by the muscles and the resulting forces of resistance generated at the point(s) of tooth contact and at the right and left temporomandibular joint condyles.

1. Figures 10 to 18 "A"

These are the computer-drawn depictions of the resultant vectors of each muscle group in the three orthogonal planes of reference for each respective task. Lines of action of each muscle are described in Figures 6 and 9, and Table V. The magnitudes of each vector are determined according to the "Scale Factors" shown in these figures for each

*However, precisely where this resultant vector lies within the two dimensions of this plane cannot be determined.

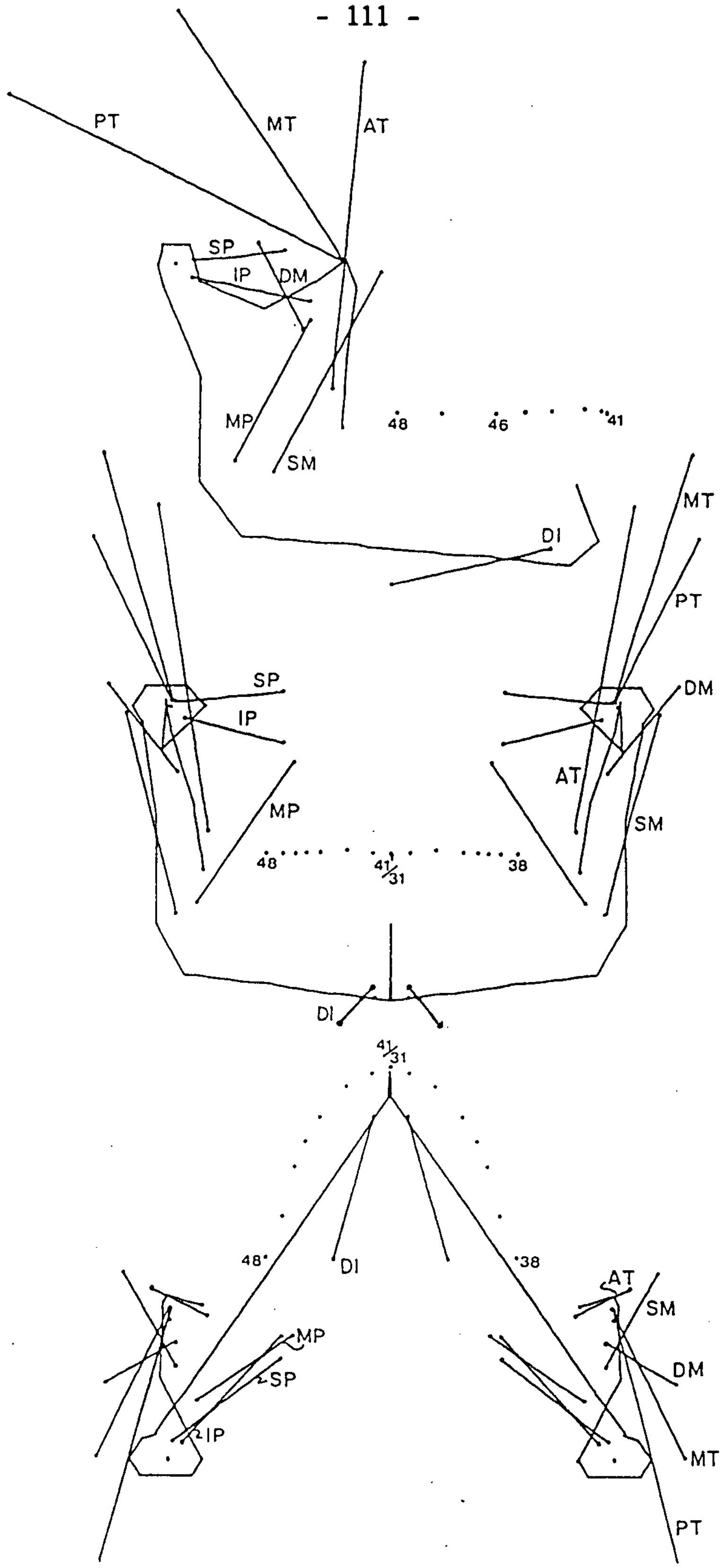


Figure 9. COMPUTER RECONSTRUCTION OF ANATOMICAL VARIABLES. This figure serves as a key to the muscle and tooth force vectors for the three orthogonal planes which follow for each series of tests (see Figures 10 to 18, A). The horizontal plane (lower) is depicted as viewed from below. The spatial cordinates of each are given in Table V (see text for abbreviations).

muscle, as well as the constant "Weighting Factors" (see Table V) as explained in METHODS. The scale values and drawn vectors are proportionate. The combined effect of all the forces generated by the individual muscle groups for each function, whether it be intercuspal clenching or incisal clenching, etc., determines the overall MUSCLE RESULTANT PARAMETERS. These are described in Figures 10 to 18 labeled "B, C, D", etc. It is this overall force generated by the muscles which must be resisted by the teeth and/or joints and therefore to which the input data must be specified to match accordingly (see Program Use, of METHODS section).

2. Figures 10 to 18 "B, C, D", etc.

These figures show the corresponding tooth and condylar reaction force vectors resulting from the specified occlusal function and MUSCLE RESULTANT PARAMETERS. The latter remain constant for a given type of activity (eg. intercuspal, incisal, or unimolar clenching). The parameters within the dashed boxes are the input variables specified by the operator for a particular task (see also SYSTEM CHART). Thus, for any given activity, which has a unique combination of muscle vectors which produce that activity, the effect of changes to any or all of the following variables (and their effect on the magnitude and orientation of the tooth and condylar reaction forces) can be observed:

- The point of application of the tooth resistance force (i.e. tooth position).
- The orientation of the tooth resistance force in both the lateral (LTA) and frontal (FTA) planes.

- The left condylar frontal angle (LCA or LCFA) which is the orientation, in this projection, at which the left joint would be assumed to provide resistance.* Unless otherwise indicated this orientation is arbitrarily assumed to be 90 degrees.

Each combination depicted in these figures represents a single run of the computer. Examples of the actual computer-drawn printout of data are represented in Appendix II. These figures summarize all of the runs for each type of activity and provide the range of reaction vectors for that activity according to the changes in the input variables which are chosen.

a. **"MUSCLE RESULTANT PARAMETERS"**

- MLR, MAR, MVR (NEWTONS) - Orthogonal muscle resultant vector components in the mediolateral, anteroposterior, and vertical directions respectively. These do not necessarily intersect but have very specific positions in three dimensional space. They essentially describe the total lateral, anterior and vertical components of muscle force for each activity (see METHODS for complete descriptions).
- ANG·L (DEGREES) - The angle at which a resultant of the vertical (MVR) and anterior (MAR) components of total

*Although the LCA variable is not necessarily likely to exhibit much, if any, variation in a particular type of activity, at least in this hypothetical individual, this parameter must be specified by the operator in order to operate the program. The reasons for this have been discussed in the METHODS.

muscle force would appear to act if they intersected. This parameter gives a general idea of the overall orientation of muscle force when viewed in the lateral plane.

- ANG·F (DEGREES) - As above but for the frontal plane and muscle components MLR and MVR.

ANG·L and ANG·F serve as first approximations as to the orientation of the overall muscle forces which must be resisted by the joints and teeth in each plane. The effect of changes to the tooth resistance/reaction force orientation (LTA and FTA) is observed for a range of angles which include that of ANG·L and ANG·F. Similarily, the effect of changes in tooth position and joint resistance orientation (LCA/LCFA) can also be observed.

b. "LAT. PLANE RESULTANT VECTOR ORIENTATIONS" (DEGREES)

- RCR - Right Condylar Angle. The angle formed by the projection of the right condylar reaction vector resultant on to the lateral plane (computer derived).
- LTA - Lateral Plane Tooth Angle. As above but for the tooth reaction vector (operator specified).

- LCA - Left Condylar Angle. As above for the left condyle reaction vector resultant (computer derived).

c. "RESULTANT VECTOR MAGNITUDES" (NEWTONS)

- RCR - Right Condyle Reaction Vector Resultant (computer derived).
- TR - Tooth Reaction Vector Resultant (computer derived).
- LCR - Left Condyle Reaction Vector Resultant (computer derived).

d. "FRONT. PLANE RESULTANT VECTOR ORIENTATIONS" (DEGREES)

- RCA - Right Condylar Angle. The angle formed by the projection of the right condylar reaction vector resultant on to the frontal plane (computer derived).
- FTA - Frontal Tooth Angle. As above for the tooth resultant vector (operator specified).
- LCA - Left Condylar Angle (or left condylar frontal angle). As above but for the left condylar resultant vector (operator specified).

e. "JF/TF"

This is the ratio of total joint or condylar reaction force (RCR and LCR) to total tooth reaction force (TR). It is assumed that the forces of resistance occurring at the joints are a residual effect of the production of useful force at the teeth and the former arise only as a stabilizing influence on the system. The ratio between these forces would therefore reflect some element of the efficiency of the system with respect to the distribution of these forces.

B. FORCE VECTOR ANALYSIS

1. Bilaterally Symmetrical Clenching Tasks

a. Intercuspal Clenching (CO) - Figures 10A, B and C

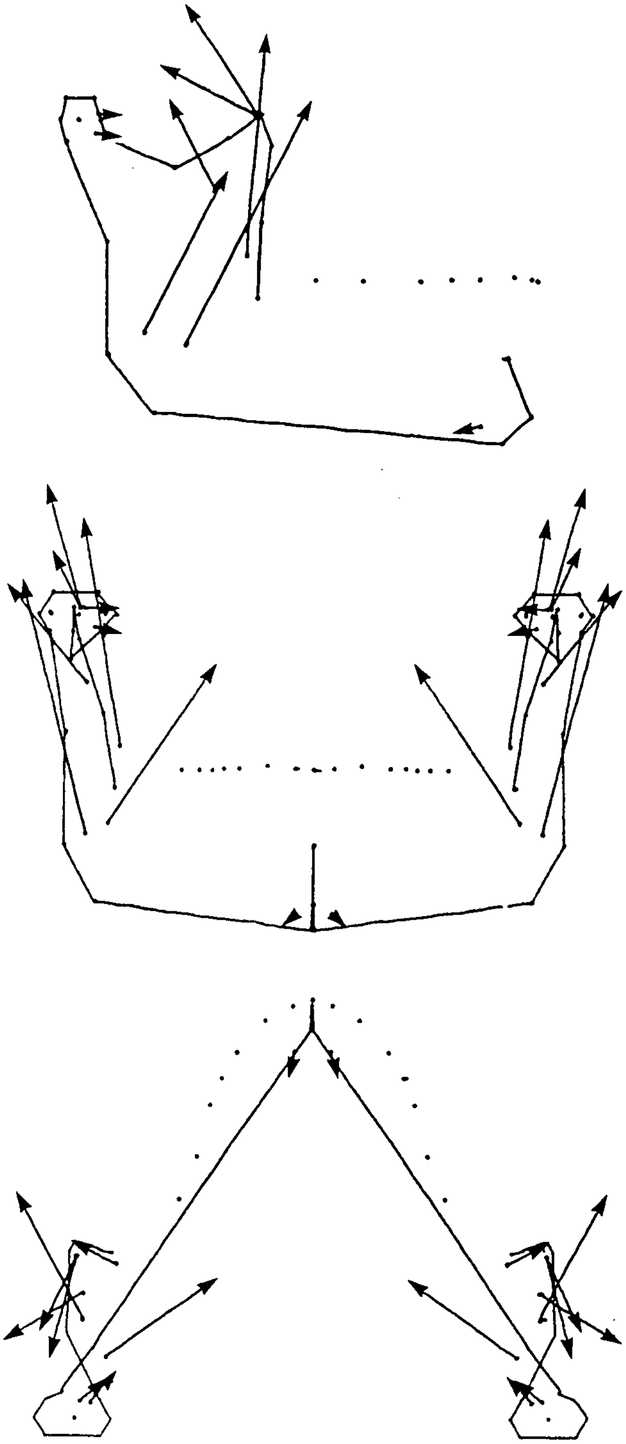
i. Muscle Resultant Parameters

Figure 10A shows the relative activities of the various muscles to be fairly high. The masseters and temporalis groups were at their highest levels for all tasks of this study (see Table II and III for comparisons). Figure 10B and C indicate the magnitude of the two coplanar components of muscle force to be almost entirely vertical with respect to the occlusal plane. The vertical (MVR) component of 1187.6 N was, in fact, the highest value of all tasks analyzed whereas the anteroposterior component (MAR) of 40.9 N was the lowest. The overall muscle resultant force which was oriented at an angle of 88.0 degrees (ANG·L) in the lateral plane, due to these two components, was calculated to be 1188.3 N, which was only slightly greater than the vertical component by itself. In the frontal plane all force vectors lie parallel to the y (vertical) axis (ANG·F = 90.0 degrees) since no mediolateral components exist.

ii. Tooth Position Change - Figure 10B

Since the position of the functional center of intercuspal occlusal contact was not known exactly, although it would lie in the midline, various possible positions of this point were analyzed including the second bicuspid, and the first, second and third molars. The lateral (LTA) and frontal (FTA) plane tooth angles were fixed to match the orientation of the muscle forces (ANG·L and ANG·F) for each run (i.e. 88.0 and 90.0 degrees respectively).

Figure 10A. INTERCUSPAL CLENCHING (CO). Right and left side scale factor values and three dimensional (computer-drawn) depiction of individual muscle vectors.



RT. SIDE SCALE	
SM	1.00
DM	1.00
MP	.76
AT	.98
MT	.96
PT	.94
IP	.27
SP	.59
DG	.28

LT. SIDE SCALE	
SM	1.00
DM	1.00
MP	.76
AT	.98
MT	.96
PT	.94
IP	.27
SP	.59
DG	.28

Most obvious from Figure 10B is the increase in the compressive tooth resistance force at more posterior tooth contacts for the same muscle force, the magnitude varying from 556.2 N at the second bicuspid to a maximum value for all the tasks studied of 866.4 N at the third molar which is an increase of 56%. At the same time 49% less compressive resistance force is required at the joints making the more posterior contact relatively more efficient (JF/TF = 0.37) in terms of the ratio between the joint and tooth forces. The magnitudes of the joint forces at a maximum of 316.0 N per side at the bicuspid and a minimum of 161.0 N per side at the third molar are among the greatest values observed in this study at each of the respective tooth positions. This is a reflection of the relatively greater overall muscle forces involved here. The least efficient position of tooth contact here appears to be the second bicuspid (JF/TF = 1.14) with corresponding increases occurring at more posterior points of tooth contact (see Figure 10B) .

Another way of considering the efficiency of the distribution of the resistance forces is to compare the relative proportion of the total resistance force acting on the system assumed by the dentition with that assumed by the joints. In each run of Figure 10B the orientation in space of the overall muscle resultant and the tooth and joint components (TR, RCR and LCR respectively) were identical (ANG·L = RCA = LCA = 88.0 degrees in the lateral plane and ANG·F = RCA = LCFA = 90.0 degrees in the frontal plane). Therefore the sum of the tooth and joint forces must equal the overall magnitude of the resultant force generated by the muscles which was determined to be 1188.3 N. The proportion of this force taken up by the teeth and joints for each position of the dentition with respect to the total force generated is:

RUN 1	second bicuspid	47% dentition	53% joints
2	first molar	51% dentition	49% joints
3	second molar	61% dentition	39% joints
4	third molar	73% dentition	27% joints

It should be noted that these particular proportions can only be determined when all three elements of force (muscle, tooth and joints) are perfectly aligned (parallel) in space as is the case in Figure 10B. This is because their respective axial vector components are in the same relative proportions as the resultant vectors. Otherwise, comparison of the relative proportion of the respective orthogonal components of these forces must be made, which is tedious to determine and difficult to interpret.

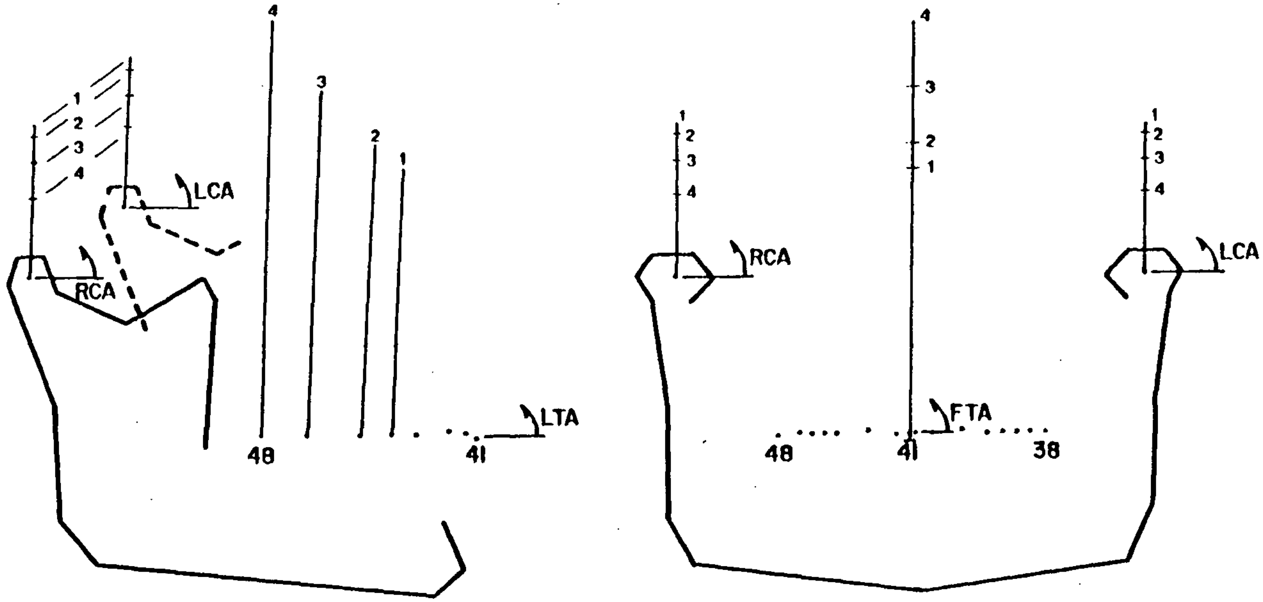
The linear increase in tooth force and respective decline in joint force at more posterior positions is due to the concurrent reduction in the moment arm length of the tooth forces as the bite point becomes more posterior. The moment, or torquing effect of the tooth force at each position, must be equivalent to balance the muscle forces. Thus, a tooth contact at the third molar, which lies a shorter distance from the fulcrum and therefore has a shorter moment arm, requires a proportional increase in tooth force to match the moment produced by the relatively smaller force occurring at the second bicuspid, but which has a correspondingly longer moment arm. Because the fulcrum for the system is assumed to lie at the joints and the task is bilaterally symmetrical neither joint can contribute any moment to the system. The forces at the joints in this case (and the following bilaterally

Figure 10B. INTERCUSPAL CLENCHING (CO)/VARIABLE TOOTH POSITION. Corresponding tooth and condylar reaction force vectors which result for various assumed anteroposterior points of central occlusal stability during an intercuspal clench. This activity is bilaterally symmetrical therefore the frontal plane angles for these forces have no mediolateral components. LTA and FTA are specified according to the overall orientations of muscle force (ANG·L and ANG·H) which likewise have no mediolateral component (eg. MLR = 0; ANG·F = 90°). The left condyle in the lateral plane is shown with dashed outline.

MUSCLE RESULTANT PARAMETERS

MLR =	0.0
MAR =	40.9
MVR =	1187.6
ANG·L =	88.0
ANG·F =	90.0

480 N



RUN	Tooth Positn	LAT. PLANE RESULTANT VECTOR ORIENTATIONS RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS RCA	FTA	LCA*	JF/TF
1	5	88.0	88.0	88.0	316.1	556.2	316.0	90.0	90.0	90.0	1.14
2	6				291.4	605.6	291.3				.96
3	7				232.2	723.9	232.2				.64
4	8				161.0	866.4	160.9				.37

* LCFA

symmetrical tasks) are simply the residue required to balance the linear vertical and anteroposterior muscle forces, since those that are due to the tooth forces (determined by the moments acting on the system) are insufficient to do so. As such, the orientations of the resulting joint resistance forces in these instances (RCA and LCA) also match those of the muscle and tooth forces in the lateral and frontal planes.

If even more posterior positions of tooth contact were assigned the relative proportional increase in tooth force and decrease in joint forces would continue until the tooth force exactly matched the muscle force in orientation and magnitude. At this point no joint forces would exist, because all resistance of the muscle force, both rotational moments and linear forces, would be accounted for entirely by the tooth force. At tooth positions more posterior to this the (compressive) tooth force would continue to increase whereas the joint forces would become tensile in nature and thus opposite in orientation to those observed in Figure 10B.

iii. Lateral Tooth Angle (LTA) Changes - Figure 10C

To assess the effect of changes to the LTA variable (and FTA which follows) the functional center for the tooth contact position was arbitrarily assumed to lie at the first molars, which is slightly posterior to the geometric center of occlusal support.

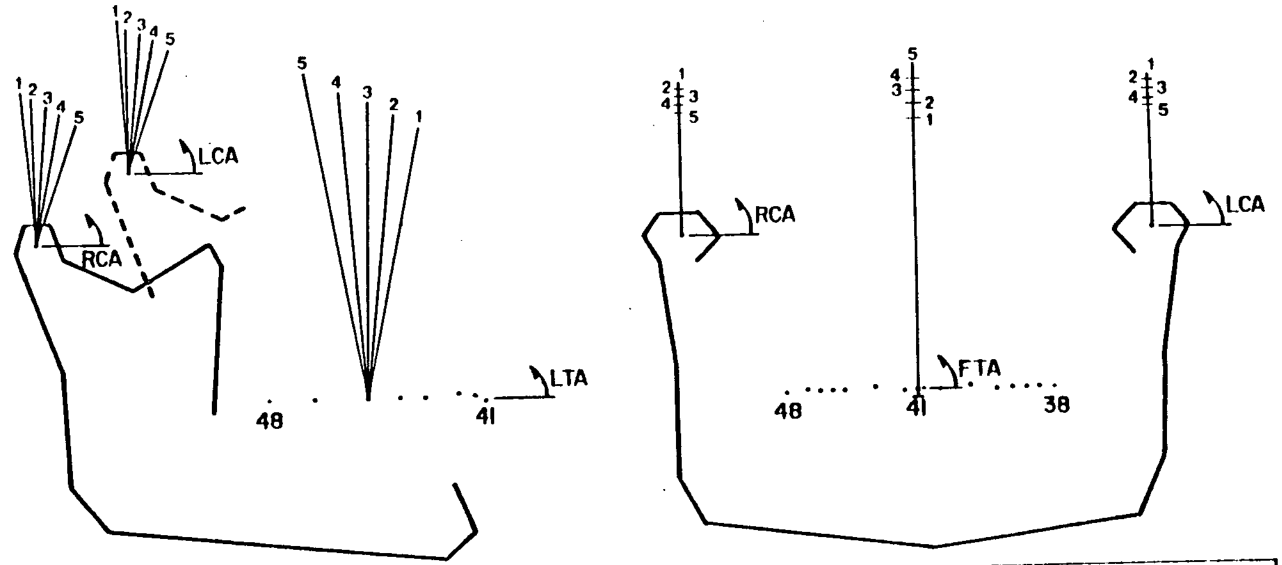
Changes in the orientation of the angle of tooth resistance in this plane from a protrusive to a retrusive direction had two main effects on the resistance forces of the system. First, the magnitude of the tooth resistance force (TR) shows an increase from 574.2 N to 686.8 N, or 20%, due to shortening of the respective lengths of the moment arms for each

Figure 10C. INTERCUSPAL CLENCHING (CO)/VARIABLE LTA. Corresponding tooth and condylar reaction force vectors resulting from changes in lateral plane tooth angle. The range of this change is approximately ten degrees to either side of ANG·L. Frontal angulations have no mediolateral component due to bilateral symmetry.

MUSCLE RESULTANT PARAMETERS

MLR = 0.0
MAR = 40.9
MVR = 1187.6
ANG·L = 88.0
ANG·F = 90.0

480 N



RUN	Tooth Positn	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	6	95.4	80.0	95.4	312.5	574.2	312.4	90.0	90.0	90.0	1.09
2		91.0	85.0	91.0	299.0	592.1	298.9				1.01
3		85.9	90.0	85.9	286.6	615.9	286.5				.93
4		79.8	95.0	79.8	275.9	647.0	275.8				.85
5		72.6	100.0	72.6	267.9	686.8	267.8				.76

* LCFA

orientation. This resulted in a reduction of the joint force from 312.5 N to 267.9 N per joint, or 14%. Therefore, in terms of efficiency since the JF/TF ratio decreases for more retrusive tooth forces, these would appear to be more efficient.

Second, there is a reciprocal effect with respect to the joint force orientations which become more anteriorly oriented with more posteriorly oriented tooth forces. This is due to the change in direction of the anteroposterior component of tooth force. In RUN 1 this component was calculated to be 99.7 N in the posterior direction whereas in RUN 5 it was 119.5 N in the anterior direction. The static linear components of the muscle, tooth and joint forces must balance. This component of right and left muscle, tooth and joint force was 29.4 N anteriorly per joint in RUN 1 and 80.1 N posteriorly in RUN 5 which was a total of 58.8 N and 160.2 N respectively. However the muscle force also contributes an anterior component of 40.9 N (MAR). Therefore for RUN 1 the sum of anteroposterior components is

40.9 (muscle) + 58.8 (joints) = 99.7 (tooth)

and for RUN 5,

40.9 (muscle) - 160.2 (joints) = 99.7 (tooth).

Thus, more posterior components of tooth force require more anterior components of joint force to oppose these forces and maintain equilibrium for a constant muscle force. When the orientation of the tooth force is matched with that of the muscle force as seen in RUN 2 of Figure 10B (LTA and ANG·L = 88.0 degrees; FTA and ANG·F = 90.0 degrees) then the joint force orientations (RCA and LCA) also match.

In general according to the model the orientations of the joint resistance forces due to intercuspal clenching at the first molar are such that one would predict a joint morphology with bearing surfaces directed anterosuperiorly from about 70 to 95 degrees and capable of withstanding up to about 320 N of force.

b. Bilateral Molar Clenching (BIMOL) - Figures 11A, B and C

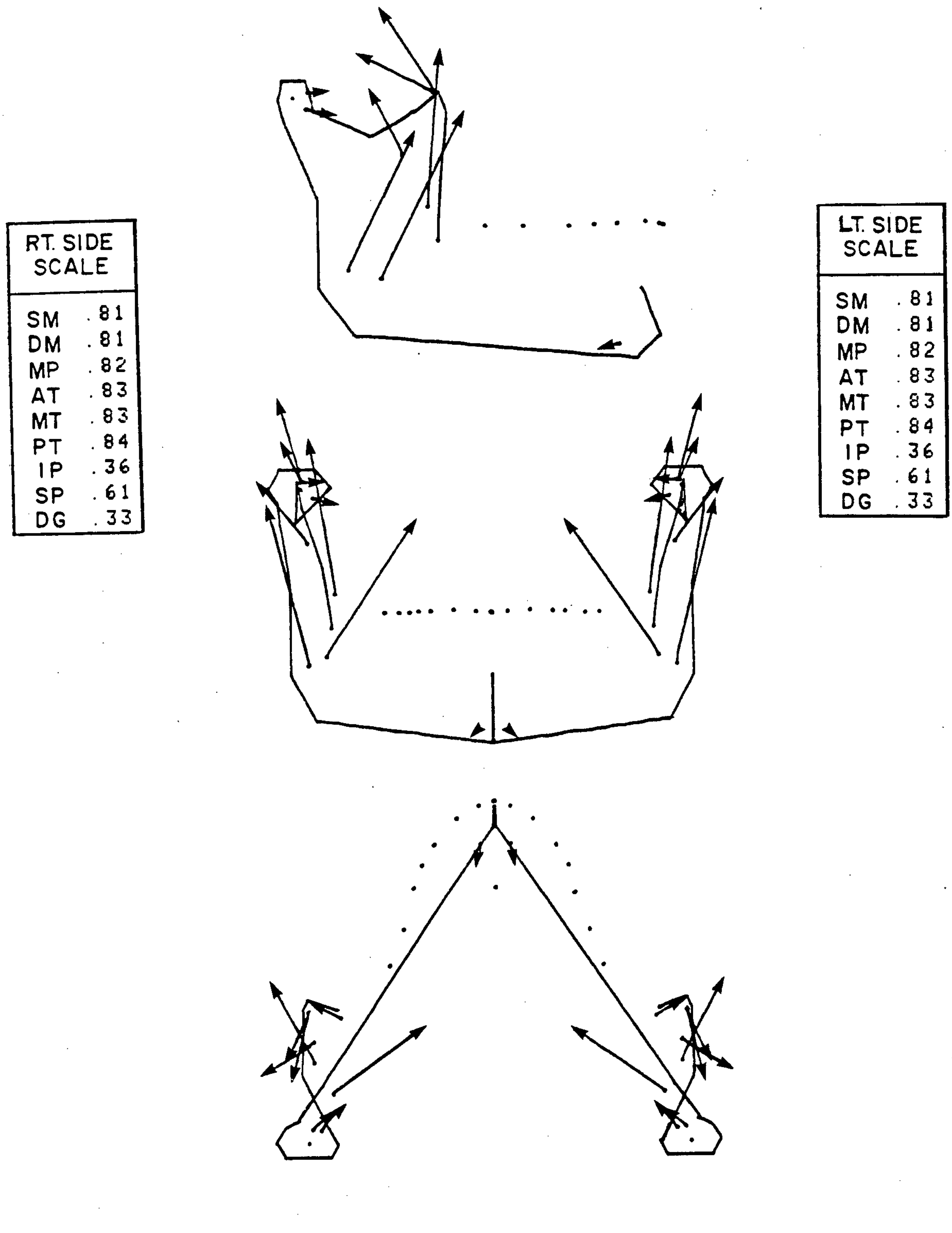
i. Muscle Resultant Parameters

In general, the activity levels of the main adductors of the mandible shown in Figure 11A for this task (which has a stabilizing occlusal stop) was approximately 80 to 85% of their maximal levels. Except for MP and IP this represents a reduction of roughly 15 to 20% compared to the intercuspal clench (CO) activities of Figures 10A (see also Table II). As such there was a corresponding decrease in the overall muscle force generated. Although the anterior component of muscle force (MAR) of 57.0 N represented about a 40% increase over that of intercuspal clenching (40.9 N) the vertical component (MVR) of 1039.1 N was about 13% less than for intercuspation (1187.6 N). This equates to a reduction in the overall muscle resultant, for bilaterally supported molar clenching, calculated to be 1040.7 N, or 12% less than that of intercuspal clenching (1188.3 N). The effect of the increased MAR value for this task was to align the muscle resultant slightly more anteriorly at 86.9 degrees (vs. 88.0 degrees for CO).

ii. Lateral Tooth Angle (LTA) Change - Figure 11B

The bilateral molar clenching task modeled in Figure 11B was initially assumed to occur at the first molar tooth to allow for comparisons of the

Figure 11A. BILATERAL MOLAR CLENCHING (BIMOL). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.



resistance forces with those of intercuspal clenching (see Figure 10C). As can be seen, the magnitudes of both the tooth and joint resistance forces are somewhat less for bimolar clenching than intercuspal clenching, reflecting the decrease in the muscle generated force of this task.

The effect of changes in LTA, shown in Figure 11B, on the magnitude of tooth force and joint forces, and on the orientation of the latter forces are the same as those discussed for the intercuspal clench. That is, a more posteriorly oriented LTA results in correspondingly greater magnitudes of tooth resistance force but a decrease in joint resistance forces. However, over the range of LTA modeled in Figure 11B from 80.0 degrees to 95.0 degrees there was an increase from 495.7 N to 558.6 N in tooth force or 13%, with only a 10% decrease in joint force from 275.9 N to 247.0 N per joint. Over this same range of LTA for intercuspal clenching (CO) there was the same (13%) increase in tooth force (574.2 N to 647.0 N) but a 12% decrease in joint forces (312.4 N to 275.8 N per side). This is reflected in the relatively better efficiency of the intercuspal task of Figure 10C over bimolar function seen here according to the JF/TF ratios.

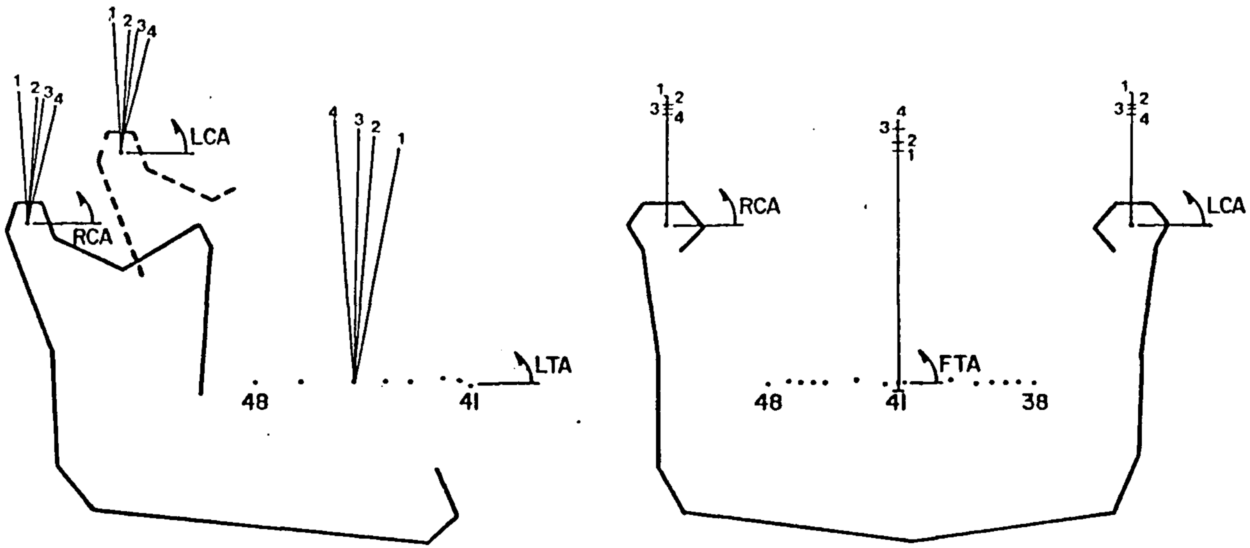
Comparison of the proportion of the calculated total muscle resultant force (1040.7 N) resisted by the teeth (518.3 N) and joints (261.2 N per side) in RUN 2 with muscle-matched orientations shows the resistance forces to be equally divided (50%) between the teeth and joints. Hence the JT/TF ratio of virtually 1.0. Intercuspal clenching at the second molar was slightly more efficient with 51% of the force resisted by the teeth and 49% by the joints (JF/TF = 0.96; see Figure 10B, RUN 2).

Figure 11B. BILATERAL MOLAR CLENCHING (BIMOL)/VARIABLE LTA AT <u>FIRST</u> MOLAR. Corresponding tooth and condylar reaction force vectors for bilaterally symmetrical clenching with tooth contact assumed to occur at the first molars only. The range of LTA variation is approximately ten degrees either side of ANG·L.

MUSCLE RESULTANT PARAMETERS

MLR = 0.0
MAR = 57.0
MVR = 1039.1
ANG·L = 86.9
ANG·F = 90.0

480 N



RUN	Tooth Positn	LAT. PLANE RESULTANT VECTOR ORIENTATIONS RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS RCA	FTA	LCA*	JF/TF
1	6	93.0	80.0	93.0	275.9	495.7	275.9	90.0	90.0	90.0	1.11
2		86.9	86.9	86.8	261.2	518.3	261.2				1.01
3		83.6	90.0	83.6	255.2	531.8	255.2				.96
4		77.7	95.0	77.7	247.0	558.6	247.0				.88

* LCFA

iii. Tooth Position Change - Figure 11C

With tooth contact assumed to lie at the second molars as opposed to the first molars greater magnitudes of tooth resistance force occur for each run. Over the same range of LTA of 80.0 degrees to 95.0 degrees at the second molar (RUN 2 to 5) there is approximately 90 to 115 N more tooth force generated at the second molar (585.9 to 616.3 N; Figure 11C) compared to those at the first molar (495.7 to 558.6 N; Figure 11B). Again the greatest increases occurred with a more posteriorly oriented LTA. The relative increase in TR over this range for first molar contacts, as mentioned earlier, was 13% whereas this increase was 16% at the second molars. In addition, however, there is a concurrent decrease in RCR and LCR of 18% from 232.6 to 191.7 N per side over this range at the second molars (Figure 11C) compared to only a 10% decrease for first molar contact discussed previously (see Figure 11B). Because of this greatly improved relationship between the tooth (TR) and joint forces (RCR and LCR) the JT/TF ratios for second molar contacts are considerably less for second molar contact (Figure 11C) than those for first molar contact (Figure 11B).

The effect of improving this relationship due to changes in LTA at more posterior tooth contacts becomes even more prominent when Figure 11C of bimolar clenching is compared to Figure 10C of intercuspal clenching. Although, as was discussed, the latter situation had a relatively greater magnitude of muscle force acting on the system, comparison of these two figures with two different occlusal contact positions show very similar magnitudes of tooth force. When the runs with corresponding orientations of LTA are compared, bimolar clenching has slightly higher TR magnitudes than intercuspal clenching due to the more posterior tooth position. However this also results in relatively lower magnitudes of RCR and LCR and thus lower JF/TF ratios overall. The total relative increase in TR over the LTA range modeled in Figure 10C (RUNS 1 to 5) for intercuspal clenching at the first molars was 20% and the decrease in RCR and LCR was 14%. That of bimolar clenching at the second molars was a 19% increase in TR (567.9 to 676.3 N) and a 23% decrease in RCR and LCR (249.3 to 191.6 N).

Nevertheless, intercuspal clenching with LTA matched with ANG·L (and FTA with ANG·F) in Figure 10B, shows RUN 3 at the second molar shows TR to be 723.9 N and RCR and LCR 232.2 N each. This amounts to 61% of resistance force at the teeth and 39% at the joints with respect to the total force generated by the muscle resultant (1188.3 N). RUN 3 of Figure 11C for bimolar clenching on the other hand, with TR of only 618.5 N, and RCR and LCR of 211.1 N each, had only 59% of the total resistance force attributed to the teeth and 41% to the joints relative to the muscle resultant of 1040.7 N. This is similarly reflected in the JF/TF ratios of 0.64 vs. 0.68 respectively for the two different tasks. This is a function of the lesser total muscle force acting on the system on the one hand and a slightly more anterior LTA on the other for bimolar clenching with matched data.

Concerning the range of joint force angles in the lateral plane (RCA and LCA) the more anterior tooth contact of Figure 11B shows a closer range of 15.3 degrees (from 93.0 to 77.7 degrees) for LTA of 80.0 to 95.0 degrees (RUNS 1 to 4) compared to 23.1 degrees (95.5 to 72.4 degrees; RUNS 2 to 5) for Figure 11C and a more posterior contact. This is because the more posterior contacts result in a greater TR magnitude due to shorter moment arm

Figure 11C. BILATERAL MOLAR CLENCHING (BIMOL)/VARIABLE LTA AT SECOND MOLAR. Range of LTA variation as per Figure 11B.

MUSCLE RESULTANT PARAMETERS

MLR = 0.0

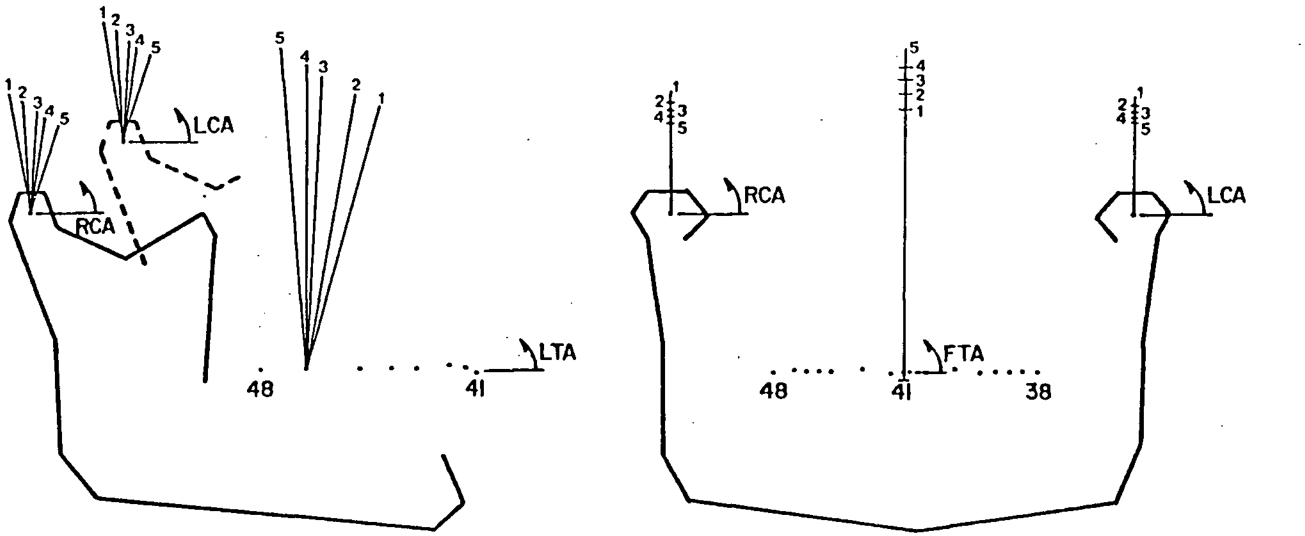
MAR = 57.0

MVR = 1039.1

ANG·L = 86.9

ANG·F = 90.0

480 N



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	7	100.4	75.0	100.4	249.4	567.9	249.3	90.0	90.0	90.0	.88
2		95.5	80.0	95.5	232.6	585.0	232.5				.79
3		86.8	86.9	86.8	211.1	618.5	211.0				.68
4		81.9	90.0	81.9	202.6	637.9	202.6				.64
5		72.4	95.0	72.4	191.7	676.3	191.6				.57

* LCFA

lengths. Thus the anteroposterior components of these forces are relatively greater requiring correspondingly greater anteroposterior components of joint force to balance the system.

Based on the foregoing observations the joint morphology would be predicted to coincide with those attributable to resisting the same magnitudes and orientations of force as predicted from intercuspal clenching.

c. Incisal Clenching With Bite Stop (INCISS) - Figures 12A and B

i. Muscle Resultant Parameters

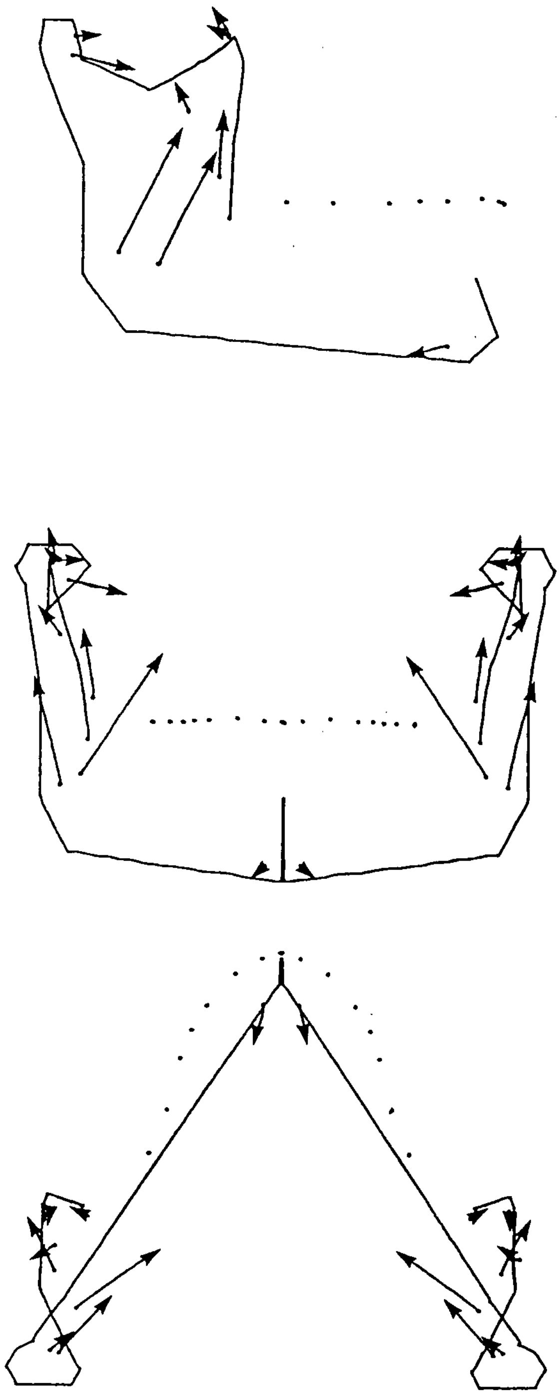
Figure 12A clearly depicts the relatively small muscle forces involved in this task compared with those associated with more posterior function. The total muscle force resultant calculated to be 461.2 N is less than one half that observed for either the intercuspal (CO) or bilateral molar (BIMOL) functions. All Scale Factors are greatly reduced except IP which is at its maximal value for the entire study. Considering the much smaller MVR force component of 432.3 N, it is not surprising therefore that MAR of 160.8 N is a significant component of the overall muscle resultant. The corresponding orientation of this force of 69.6 degrees is much more anteriorly directed than the bilaterally symmetrical molar functions which were near vertical. This muscle force is only 39% that of intercuspal muscle activity and 44% that of bimolar activity.

ii. Lateral Tooth Angle (LTA) Change - Figure 12B

Although the muscle force for incisal clenching is 55 to 60% less than that for the two previous molar tasks, the relative decrease in TR magnitudes

Figure 12A. INCISAL CLENCHING WITH BITE STOP (INCISS). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors).

RT. SIDE SCALE	
SM	.43
DM	.26
MP	.59
AT	.26
MT	.18
PT	.09
IP	.71
SP	.50
DG	.50



LT. SIDE SCALE	
SM	.43
DM	.26
MP	.59
AT	.26
MT	.18
PT	.09
IP	.71
SP	.50
DG	.50

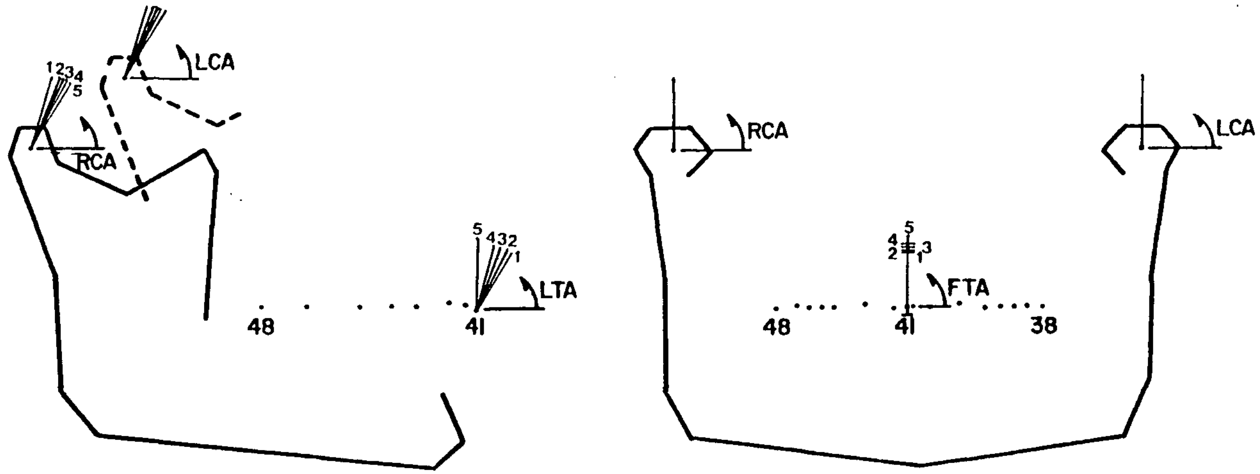
to 141.0 N is much greater. In this instance the increase in the length of the moment arm for the tooth resistances forces necessitates relatively small TR magnitudes. On the other hand the joint forces are still relatively high, being within 55 to 70% of those values for the molar functions (CO and BIMOL) with matched orientations of tooth and muscle forces (ie. RUN 3 of each). Therefore the JF/TF ratios are, in general, very high for these incisal clenches and are than half as high as molar clenches. As such, clenching on the incisal teeth is less than half as efficient as molar clenching in terms of the distribution of resistance forces.

In addition, close inspection of the JF/TF ratios for this task in Figure 12B shows the most inefficient run to be with matched data (Run 3), which also has the lowest TR magnitude. 31% of the total force of resistance (141.2 N) occurs at the incisors and 69% at the joints (160.0 N per side). This is quite different from the trends seen up to this point. Previously, as the tooth force became more posteriorly aligned (decreasing posteriorly directed component and/or increasing anteriorly directed component along the y axis) the length of the moment arm for each increment became shorter. This required greater magnitudes of tooth force to maintain rotational stability but also increased the linear components (vertical and anteroposterior) contributed by the tooth forces. This, in turn, left less linear resistance force unaccounted for and thus less joint forces since RCR and LCR are essentially the residual resistance forces needed to balance the linear static equilibrium of the system (see METHODS). Up to now as LTA became more posterior in orientation TR increased and RCR and LCR decreased.

Figure 12B. INCISAL CLENCHING WITH BITE STOP (INCISS)/VARIABLE LTA. Corresponding tooth and condylar reaction force vectors for bilaterally symmetrical clenching on an incisal stop (stabilizer). The range of LTA variation is as per ANG·L and preceding figures.

MUSCLE RESULTANT PARAMETERS	
MLR =	0.0
MAR =	160.8
MVR =	432.3
ANG·L =	69.6
ANG·F =	90.0

480 N



		LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			
RUN	Tooth Positn	RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	JF/TF
1	41	73.8	60.0	73.9	160.5	143.2	160.5	90.0	90.0	90.0	2.24
2		71.6	65.0	71.6	160.1	141.7	160.1				2.25
3		69.6	69.6	69.6	160.0	141.2	159.0				2.27
4		67.2	75.0	67.2	160.1	141.9	160.1				2.25
5		60.2	90.0	60.3	162.1	150.9	162.1				2.15

* LCFA

Incisal clenching however is subject to different geometrical relationships with respect to the LTA increments modeled. This relationship depends on the distance of the point of tooth contact from the fulcrum of the system (joints) both anteroposteriorly (y - axis) and vertically (z - axis). The position of the incisal contact is such that the length of the moment arm for a tooth resistance force oriented at an LTA of 69.6 degrees (RUN 3) is very slightly greater than that for any of the other orientations modeled in Figure 12B. As a consequence, TR at this orientation is somewhat less and RCR and LCR correspondingly greater. Increasing or decreasing LTA orientation from 69.6 degrees decreases the respective moment arm lengths thereby requiring greater TR magnitudes. It would be expected that RCR and LCR values would vary in a reciprocal manner with the highest value corresponding to the lowest TR of RUN 3. Such is not the case however. Actually the opposite occurs, with the joint forces varying with the TR magnitude change, although the extent of this change is very small.

The reason for this can be most easily understood by analyzing RUN 5 (LTA at 90.0 degrees) which demonstrates the greatest TR magnitude for this task (150.9 N). This run also has the greatest RCR and LCR values. At LTA of 90.0 degrees there is no anteroposterior component of force at the tooth contact. However there is an anterior component of force applied to the system by the muscles of 160.8 N (MAR). This can only be resisted by the joints, which means there will be a posterior component calculated to be 80.4 N per joint. The vertical component of joint force is the residual of MVR (432.3 N) minus TR (150.9 N, which is purely vertical), which is 281.4 N or 140.7 N per joint. The resultant of joint force on the right and left sides (RCR and LCR) due to these axial components of force, according to the Pythagorean relationship, is therefore 162.1 N per side. Thus, the relationships between TR, RCR and LCR become quite different for changes to LTA than that previously observed due to different geometrical relationships of the components of the system.

d. Incisal Clenching On Natural Contacts (INCISN) - Figures 13A and B

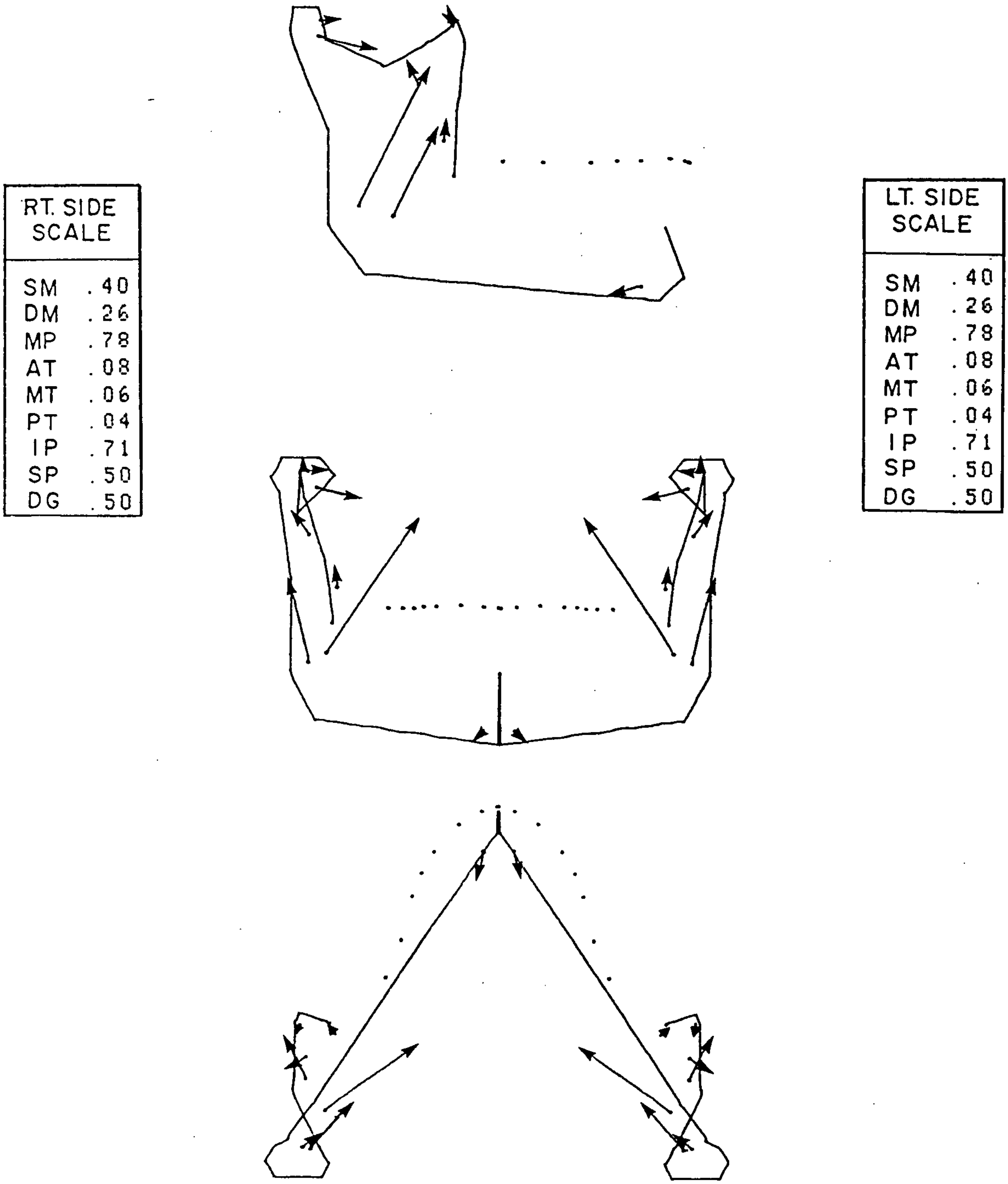
i. Muscle Resultant Parameters

Comparison of Figures 12A and 13A shows that when no stabilizing incisal stops are provided there is a general decrease in activity of the various muscle groups (eg. SM, AT, MT, PT) except that of MP which has increased from 0.59 to 0.78. The vertical component of muscle force (MVR) shows a corresponding decrease from 432.3 N to 395.9 N whereas the anteroposterior component (MAR) has increased from 160.8 N to 194.2 N. This value of MAR is the maximal value of this variable for this study. The orientation of muscle force for this natural incisal clench is therefore much more anteriorly directed at 63.9 degrees (ANG·L). The overall muscle resultant for this task is determined to be 441.0 N, which is only 4% less than that of incisal clenching with stops. Thus, with this (assumed) less stable occlusal contact there is only a slight decline in the overall muscle force generated, but it is more anteriorly directed.

ii. Lateral Tooth Angle (LTA) Change - Figure 13B

Over the range of LTA tested, which was more acute than any tested up to this point, the TR values are significantly less than those for the

Figure 13A. INCISAL CLENCHING-NATURAL (INCISN). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.



stabilized incisal clenching of the previous task. However the magnitudes of RCR and LCR of Figure 13B indicate that very similar forces of joint resistance exist.

For RUN 3 of this task, with LTA and ANG·L matched, 29% of the resistance force is contributed by the teeth and 71% by the joints, which is a somewhat less efficient situation that the corresponding run (RUN 3) of stabilized incisal clenching (30 and 70% respectively) in Figure 12B. The JF/TF ratios of Figure 13B reflect the overall decrease in efficiency of resistance force distribution for this task.

A more direct comparison of the different effect on the distribution of resistance forces due to the different type of incisal contact is given by comparison of RUN 5 in Figures 12B and 13B (LTA = 90.0 degrees in both). Figure 13B shows 134.9 N of force occur at the teeth and 162.7 N per side at the joints. The same occlusal function but with bite stops in Figure 12B shows 150.9 N at the teeth but only 162.1 N at each joint. JF/TF ratios for these two tasks are 2.41 and 2.15 respectively. This difference is apparently due solely to the different activity pattern of the muscles in response to less stable occlusal contact, and thus a less efficient distribution of resistance forces.

As was described for bite stabilized incisal clenching the relationship of joint and tooth forces for natural incisal clenching for LTA changes is not the same as molar clenching. Figure 13B shows the joint forces to increase over the range of LTA orientations tested in RUNS 1 to 5. TR on the other hand decreases to 126.3 N (RUN 4) then increases as LTA increases to 90.0 degrees. Again this is due to different geometry and correspondingly

Figure 13B. INCISAL CLENCHING - NATURAL (INCISN)/VARIABLE LTA. As per Figure 12B but with natural incisal contact.

MUSCLE RESULTANT PARAMETERS

MLR = 0.0

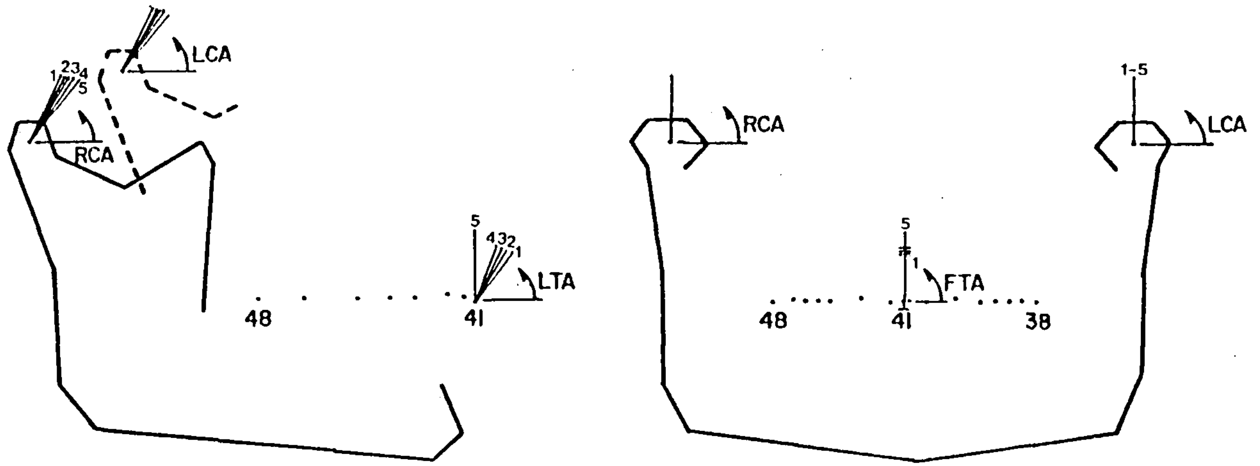
MAR = 194.2

MVR = 395.9

ANG·L = 63.9

ANG·F = 90.0

480 N



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES: RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	FTA	LCA*	JF/TF
1	1	67.6	55.0	67.6	156.5	130.4	156.4	90.0	90.0	90.0	2.41
2		65.5	60.0	65.4	156.7	128.0	156.7				2.45
3		63.9	63.9	63.8	157.0	126.9	157.0				2.47
4		61.5	70.0	61.4	157.9	126.3	157.8				2.51
5		53.4	90.0	53.3	162.7	134.9	162.6				2.41

* LCFA

different lengths of the respective moment arms for each LTA at this tooth position.

According to the predictions of joint resistance forces of incisal clenching, the temporomandibular joints would be predicted to have their load bearing surfaces at the anterosuperior aspect of the condyles. Joint resistance forces occur from about 50.0 to 70.0 degrees with respect to the occlusal plane during this type of function, with magnitudes of around 160 N.

2. Unilateral Clenching Tasks

a. Unilateral Canine Clenching (UNIK9) - Figures 14A, B, C and D

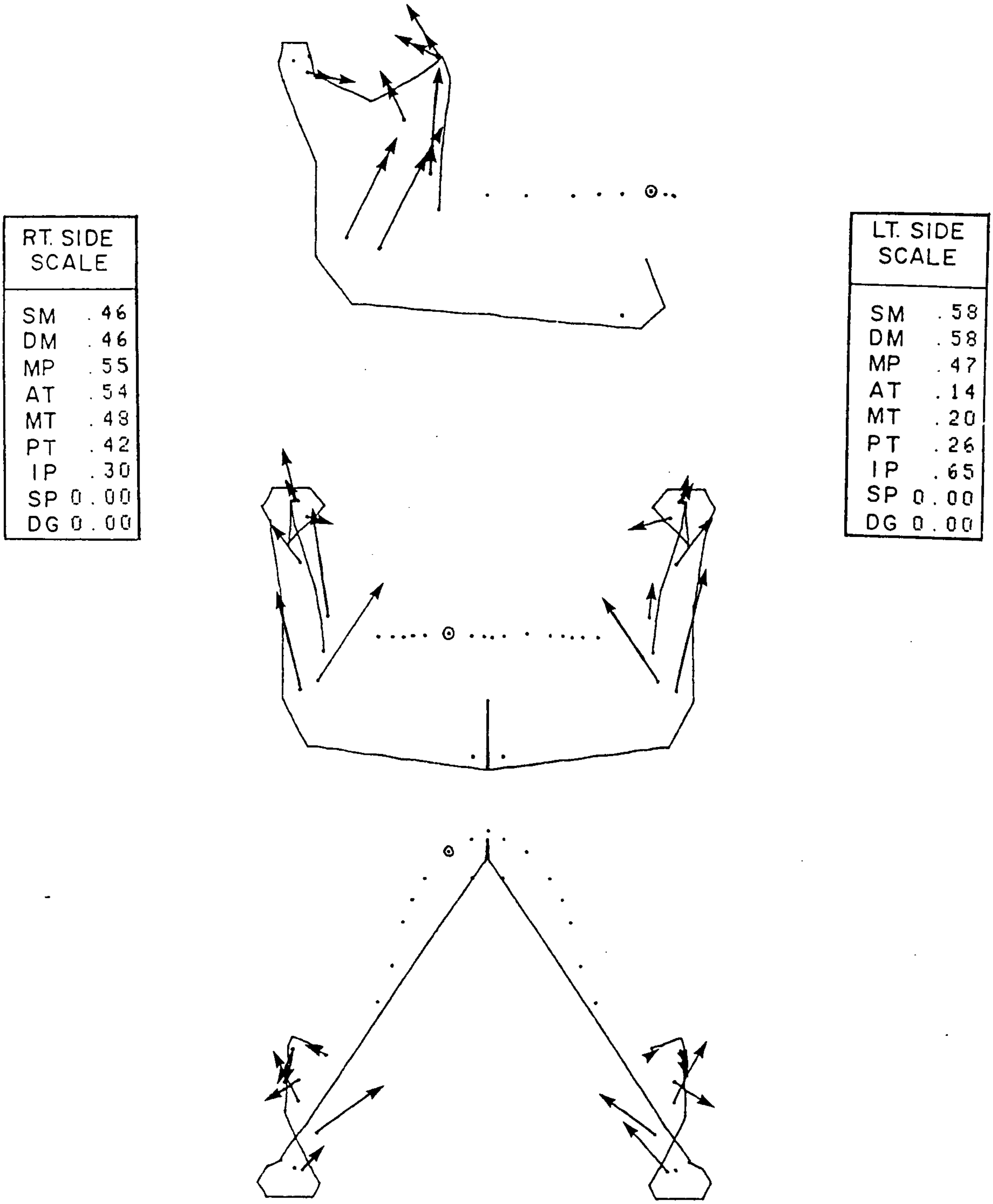
i. Muscle Resultant Parameters

Figure 14A shows the difference in muscle activity between the two sides of the mandible. The point of tooth contact lies at the right canine. The right, or working side MP, and especially the AT, MT and PT are more active than their left, or balancing side counterparts. Conversely the balancing side SM, DM and especially the IP group are more active than those of the working side. In general the activity levels of the various muscle groups are more or less intermediate between those of the bilateral molar and incisal clenching tasks of the previous section (see also Table II of METHODS). Reliable data regarding the activities of SP and DG were not available for unilateral tasks and these groups were therefore excluded from consideration.

The magnitude of the muscle vector components reflect the generally intermediate activity of the muscle groups. MVR of 554.0 N and MAR of 99.7 N are within their corresponding ranges of magnitudes attributed to the bilaterally symmetrical molar clenches on one hand and incisal clenches on the other. ANG·L of 79.8 degrees is less vertical than bimolar or intercuspal clenches with more posterior tooth contact, but more vertical than incisal clenches with more anterior contact.

However for this unilateral task there also exists a lateral component of muscle force, MLR, of 15.8 N directed towards the working (right) side, (indicated by the minus sign). As such it is not possible to determine an overall muscle resultant force magnitude because there are, in this instance,

Figure 14A. UNILATERAL (RIGHT SIDE) CANINE CLENCHING (UNIK9). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.



three muscle vector components (as opposed to two previously) which are not coplanar. ANG·F indicates the overall direction of muscle effort, due to the lateral component, to be 91.6 in the frontal plane.

ii. Lateral Tooth Angle (LTA) Change - Figure 14B

All runs of Figure 14B were done with FTA fixed at 91.6 degrees to match ANG·F of the muscle force data. LTA was matched with ANG·L in RUN 3 at 79.8 degrees. In this matched data run the tooth resistance was 226.8 N and the total joint force was 339.0 N with 171.2 N at the working side and 167.8 N at the balancing side joints. JF/TF of 1.50 indicates canine clenching to be relatively more efficient than incisal (2.27 to 2.47; Figures 12B and 13B) and less efficient than intercuspal (0.96; Figure 10B) or bilateral (0.68 to 1.01; Figures 11B and C) molar clenching regarding resistance force distribution. At more acute LTA orientations there is a decrease in TR, a concurrent increase in RCR and LCR and hence JF/TF increases. The converse is true at less acute LTA's and lower JF/TF ratios result.

Although both RCR and LCR magnitudes vary reciprocally with TR over the LTA increments of change, those of RCR do so to a greater extent than LCR. Over this series of runs in Figure 14B from LTA of 70.0 to 90.0 degrees RCR decreases by about 15 N, from 179.9 to 165.1 N, whereas LCR does so by only 2 N, from 169.5 to 167.5 N. As a consequence, at LTA of 90.0 degrees the left or balancing side joint is more heavily loaded than the right working side, whereas the converse is true at more acute LTA orientations.

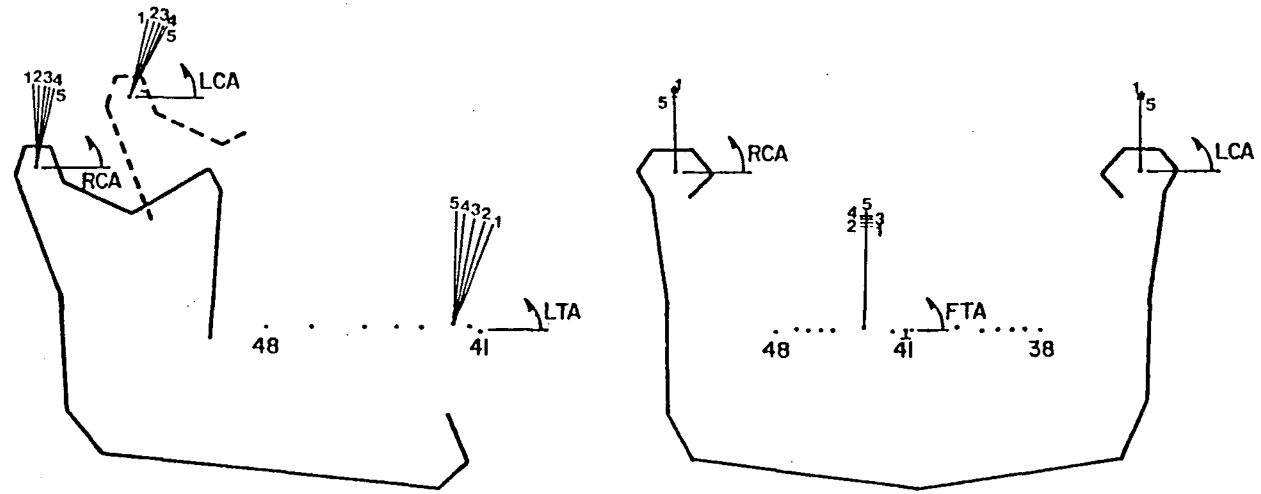
Two further consequences of increasing LTA seen in this series is, first, the familiar effect of producing more acute joint force angles (in thelateral plane) also seen in the bilaterally symmetrical functions previously. Secondly, however, there is an obvious difference between the right and left side joint force orientations. The balancing condyle resistance angles (LCA) are more anteriorly oriented than those of the working side (RCA). This is due to the fact that, in this task, the left condyle does contribute a moment of force to the rotational statics of the system because the bite point and muscle effort are not bilaterally symmetrical. As LTA increases, the tooth force moment arm length decreases, requiring relatively greater TR magnitudes to effect the same rotational moment. In addition, however, the relative magnitudes of the posterior (y) component of tooth force decreases. As such the total posterior (y) component of joint resistance force (of RCR and LCR) must increase to balance that produced by the muscle forces. The reason the left condyle contributes relatively more of this component than the right, and thus has more acute LCA orientations in the lateral plane, is because neither the tooth force (which has fixed orientations and therefore specific x, y and z components) nor the right joint (which is the fulcrum point of the system and can contribute no moments) can offset the rotational moment due to the muscles in the horizontal (occlusal) plane. As LTA increases and the posterior component of tooth force decreases, less rotational moment due to the tooth force is available to offset that of the muscle forces in this plane. This requires

Figure 14B. UNILATERAL (RIGHT SIDE) CANINE CLENCHING (UNIK9) VARIABLE LTA. Corresponding tooth and condylar reaction force vectors for unilateral canine clenching. The range of LTA variation is as per previous figures but FTA is also specified to match ANG·F since the muscle vectors also have a mediolateral component (ie. MRL = -15.8; ANG·F = 91.6) in the frontal plane. The negative value for MLR indicates that the muscle vectors have a mediolateral component to the right. LCFA is arbitrarily specified at 90°.

MUSCLE RESULTANT PARAMETERS

MLR = -15.8
MAR = 99.7
MVR = 554.0
ANG·L = 79.8
ANG·F = 91.6

480 N



RUN	Tooth Positn	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	43	93.9	70.0	77.8	179.9	222.7	169.5	93.2	91.6	90.0	1.57
2		90.4	75.0	75.2	175.2	223.9	168.5				1.54
3		86.8	79.8	72.7	171.2	226.8	167.8				1.50
4		82.6	85.0	69.8	167.7	231.8	167.4				1.44
5		78.1	90.0	66.9	165.1	238.7	167.5				1.39

* LCFA

an increase in this component due to the left condyle, causing more acute LCA orientations in the lateral plane.

It is interesting to note that in RUN 3, with matched data, the mean of RCA and LCA in the lateral plane (86.8 and 72.7 degrees respectively) is 79.8 degrees, which also matches LTA and ANG·L of that run. Similarly, in the frontal plane the mean of RCA (93.2 degrees) and LCA (90.0 degrees) is 91.6 degrees, also matching FTA which was specified at this angle to correspond with ANG·F of the muscle forces in this projection.

iii. Frontal Tooth Angle (FTA) Change - Figure 14C

In this series of runs LTA was specified at 79.8 degrees to match that of ANG·L and the effect of changes to FTA were observed. Note that in Figure 14C there is no run with both LTA and FTA matched to their respective muscle force angles since this run was included in Figure 14B (RUN 3).

In contrast to the effects produced by changes to LTA orientations previously observed, changes to FTA produce very different distributions of resistance forces on the system. First of all, increases in FTA from 90.0 to 100.0 degrees (RUNS 3 to 5) result in an increase in TR. As FTA becomes less acute the moment arm lengths of the tooth forces decrease. This previously has meant the magnitude of TR had to continue to increase to maintain the same net rotational moment due to the tooth resistance force. However, in this series because LTA is fixed at 79.8 degrees the vertical and posterior components of tooth force remain constant. As such, in the lateral plane projection the magnitude of TR "appears" to be identical for each run.

However the increase in FTA (i.e. less acute) seen in the frontal plane requires a change in the relative magnitude of the mediolateral component of tooth resistance force. For changes of FTA from 80.0 to 90.0 degrees this component decreases resulting in the observed decrease in the total (three dimensional) magnitude of TR. From FTA of 90.0 to 100.0 degrees this component increases, resulting in the increase of TR observed over this range. Since the increments of FTA change are equal in either direction from90.0 degrees (RUN 3) there is a correspondingly equal increase in magnitude (but opposite in direction) of the mediolateral component of tooth force at FTA of 80.0 (RUN 1) vs. 100.0 (RUN 5) degrees. As a consequence, equivalent TR magnitudes are observed at these orientations (230.1 N) as well as at 85.0 (RUN 2) vs. 95.0 (RUN 4) degrees (227.5 N).

Another obvious difference in resistance force distribution due to FTA changes is that the orientations of RCA and LCA in the lateral plane vary in an opposite manner relative to one another. As FTA increases from 80.0 degrees RCA decreases, as has been previously observed for LTA changes. LCA in this projection, on the other hand, increases.

In the lateral plane projection there can be no rotational moments due to either condyle, as they are both coaxial with the fulcrum (see METHODS). The tooth resistance force must therefore account for all of the rotational moment acting on the system due to the muscle forces. However, the static linear components (vertical and anteroposterior) of this force (TR) are insufficient to balance those of the muscle leaving the remainder to be accounted for by the joints. Both the orientation of overall muscle force (ANG·L) and the tooth force (LTA) are matched and are essentially parallel in this plane. When such has been the case in bilaterally symmetrical tasks (eg. Figure 10B of CO; Figure 11B, RUN 2 and Figure 11C, RUN 3 of BIMOL; Figure 12B, RUN 3 of INCISS; and Figure 13B, RUN 3 of INCISN) the combined (right plus left) joint resistance forces have been at the same orientation (RCA and LCA) as well. This was because the relative proportions of the vertical and anteroposterior components of joint force must match those of the muscle and tooth forces to maintain static equilibrium. Individually the RCA and LCA of the lateral plane of Figure 14C do not do so. Nevertheless, the combined effect of the two joint forces of this Figure do actually match the muscle and tooth forces as evidenced by the fact that the means of RCA and LCA of each run are virtually that of ANG·L (i.e. RUN 1 = 78.7; RUN 2 = 79.3; RUN 3 = 79.7; RUN 4 = 79.8; RUN 5 = 79.7 degrees). In other words, for RUN 1 of Figure 14C for instance, the anteriorly directed component of right condyle force is effectively reduced by the posteriorly directed component of the left such that their combined net orientation (eg. mean) is 78.7 degrees. The reason not every instance exactly matches ANG·L is due to FTA orientations different from ANG·F which affects the mediolateral component of the right condyle force (and hence RCA). This, in turn influences the magnitude of RCR, its vertical and anteroposterior components and thus RCA in the lateral plane*.

In the frontal plane projection of Figure 14C an increase in FTA from 80.0 to 100.0 degrees results in a decrease of RCA orientations in this plane from 106.4 to 81.6 degrees. Laterally directed tooth forces (eg. RUN 5) do not contribute to stabilizing the likewise directed muscle force (ANG·F = 91.6 degrees). RCA becomes more acute due to a requirement for a more medial component somewhere in the system to balance these combined lateral forces of muscle and tooth. Conversely, medially directed tooth forces (eg. RUN 1) require the opposite conditions. Since the left side joint force angle (LCFA) is fixed at 90.0 degrees it cannot contribute either a medial or a lateral component of resistance force to the system.

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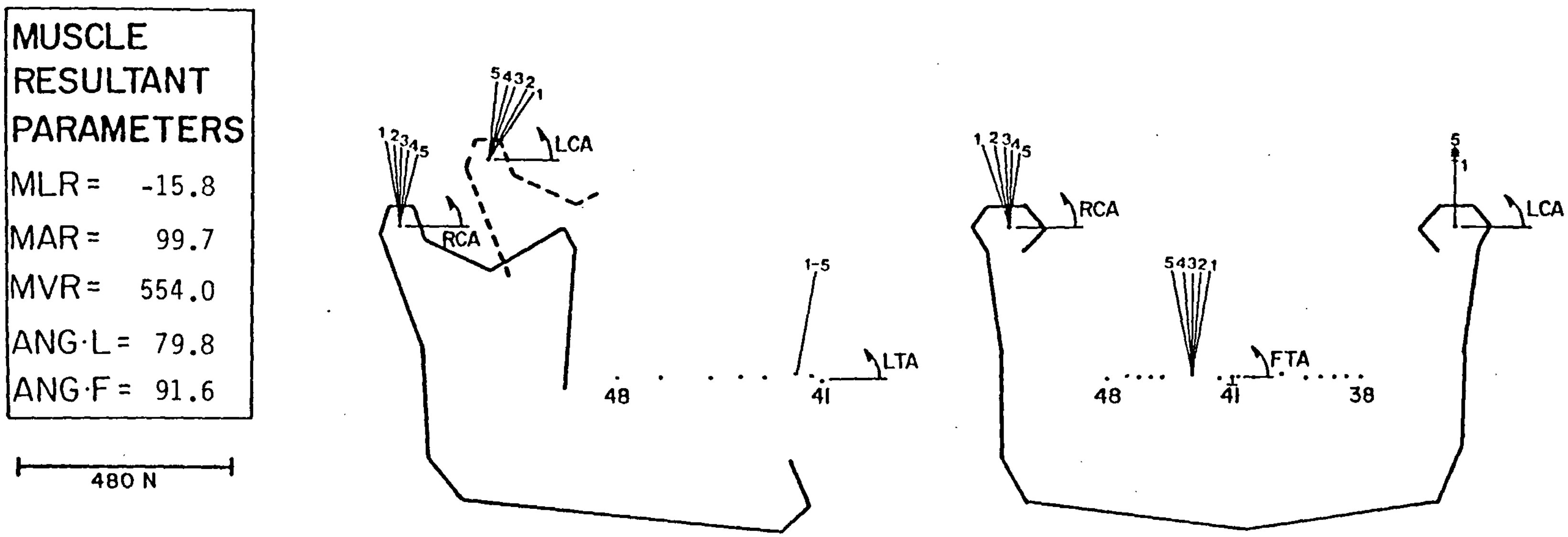
*Another way of considering how the combination of the two joint forces balance the system involves consideration of the horizontal plane which is not depicted here. As FTA increases and the laterally directed (x) component of tooth resistance force decreases (changes direction in fact) there is a decrease in the net rotational moment on the system in this plane due to the muscle and tooth forces. Only an increase in the posteriorly directed component of LCR can balance the system under the given conditions (ie. fulcrum at the right condyle and LCFA of 90.0 degrees) as FTA increases. The magnitude of this component at the left condyle determines both the magnitude and orientation of that at the right condyle then required to balance the <u>linear</u> statics of the system which is also observed in the lateral plane projection. For instance, in RUN 1 (FTA = 80.0 degrees) a relatively large posterior component is needed at the left joint to balance the rotational moments due to MLR (-15.8 N) plus that of TR which essentially adds to that of MLR. However this resulting left joint component is greater than that needed to balance the residual anterior component of muscle force (MAR = 99.7 N) not accounted for by the posterior component of tooth force seen in the lateral projection. Therefore an anteriorly directed component of force is needed at the right joint to balance the system. In RUN 5, however, the posterior component needed to balance the residual rotational moment of the muscle and tooth forces for FTA of 100.0 degrees is much less. So much so, in fact, that an additional posterior component is required at the right joint to maintain the linear static balance.

Figure 14C. UNILATERAL (RIGHT SIDE) CANINE CLENCHING (UNIK9) VARIABLE FTA. Corresponding tooth and condylar reaction force vectors in this figure reflect the specified variations in FTA which are approximately ten degrees either side of ANG·F. LTA is specified to match ANG·L. LCFA is arbitrarily specified as 90°. As such, no variation in the left condylar vector angle is seen in the frontal plane whereas RCA in this plane does exhibit variation in its orientation as it is computer derived.



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES: RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	FTA	LCA*	JF/TF
1	43	99.8	79.8	57.5	197.5	230.1	170.8	106.4	80.0	90.0	1.60
2		94.5		64.0	183.8	227.5	168.0	101.1	85.0		1.54
3		88.7		70.6	173.7	226.7	167.5	95.2	90.0		1.51
4		82.5		77.1	167.5	227.5	169.2	88.7	95.0		1.48
5		75.9		83.5	165.6	230.1	173.0	81.6	100.0		1.47

* LCFA

This effect also has further consequences on the magnitudes of the right and left joint forces. Over the series of runs tested the magnitudes of the right, or working side condyle resistance force (RCR) exceed those of the left or balancing side (LCR) for FTA orientations of 90.0 degrees or less (RUN 1, 2 and 3). At FTA orientations greater than 90.0 degrees (RUN 4 and 5) the converse is true.

This is due to a progressive (nonlinear) decrease in RCR magnitudes from 197.5 N to 165.6 N as FTA increases from 80.0 to 100.0 degrees (RUN 1 and 5 respectively). LCR, on the other hand decreases from 170.8 N to 167.5 N for FTA increases from 80.0 to 90.0 degrees but then increases to 173.0 N from FTA orientations of 90.0 to 100.0 degrees. The reasons for this require careful consideration of the system three dimensionally and the effect of FTA change to LCA orientations.

First of all, in the frontal projection of Figure 14C, as FTA increases from 80.0 to 100.0 degrees in RUNS 1 to 5 the rotational moment due to the tooth resistance force decreases (due to decreasing tooth force moment arm lengths). Only the left joint force can contribute any more moment to the system to resist that of the muscles not accounted for by the rotational moment of the tooth resistance force. Therefore an increase in the vertical component of LCR results as FTA increases in RUNS 1 to 5. This is apparent in both the lateral and frontal projections. As was mentioned above, because LCFA is fixed at 90.0 degrees only a change in the mediolateral component of RCR is available to accommodate any residual linear components of muscle force not accounted for by that of the tooth force along this axis. Hence the change in frontal plane RCR over the series. Also, due to the increase in the vertical component of LCR as FTA increases, that of RCR decreases.

Secondly, in the lateral projection of Figure 14C as FTA increases there is a concurrent decrease in the posterior component of LCR due to increasing LCA orientations. At same time RCA in this plane is decreasing to maintain the same overall orientation of the combined right plus left joint resistance forces, as has been discussed.

The overall effect of the changes in FTA orientation, from 80.0 to 100.0 degrees, to the three orthogonal (x, y and z) components of right joint force is to produce the progressive decrease in RCR magnitudes seen in Figure 14C. The effect of this change to LCR magnitudes involve only two components, the vertical (z) and the anteroposterior (y). This change in FTA produces an increase in the vertical component of this force as discussed above and a concurrent decrease in the posteriorly directed anteroposterior component. The magnitude of LCR in RUN 3 of 167.5 N is at its lowest value because the magnitudes of both of these components are relatively less than those of either RUN 1 (maximal anteroposterior component) or RUN 3 (maximal vertical component). Therefore the combination of the two respective components of left joint resistance force which are necessary to maintain static equilibrium produce LCR magnitudes which increase for FTA of 80.0 to 90.0 degrees and then decrease from 90.0 to 100.0 degrees (RUN 1 to 5).

Finally, as a further consequence of FTA increase over this series the overall effect on the magnitudes of RCR, TR, and LCR is to produce an increase in the efficiency of resistance force distribution in terms of JF/TF ratios. The more medially directed tooth forces have relatively lower JF/TF ratios. The range of these values are comparable to those observed as at result of LTA change discussed in the previous section.

iv. Left Condyle Frontal Angle (LCFA) Change - Figure 14D

Both LTA and FTA orientations were specified to match ANG·L (79.8 degrees) and ANG·F (91.6 degrees) respectively in this series of runs shown in Figure 14D. Only LCFA orientations were changed from 80.0 to 100.0 degrees. As a result there exists a single vector of TR which remains constant for each run at 226.8 N and the above orientations in space. In the lateral projection the mean of RCA (86.8) and LCA (72.7) is also 79.8 degrees. As was discussed previously this occurs in order to balance both the vertical and anteroposterior forces due to the muscle force acting in this direction (ANG·L) which is not accounted for by TR also acting in this direction (but opposite to the muscle force). The total residual resistance force acting at both joints must parallel these other forces. The distribution of this residue between the two joints is such that the left side has a relatively greater posterior component than the right. In this plane both the right and left joint vertical components are equal in each run regardless of LCFA orientations as are the posteriorly directed components.

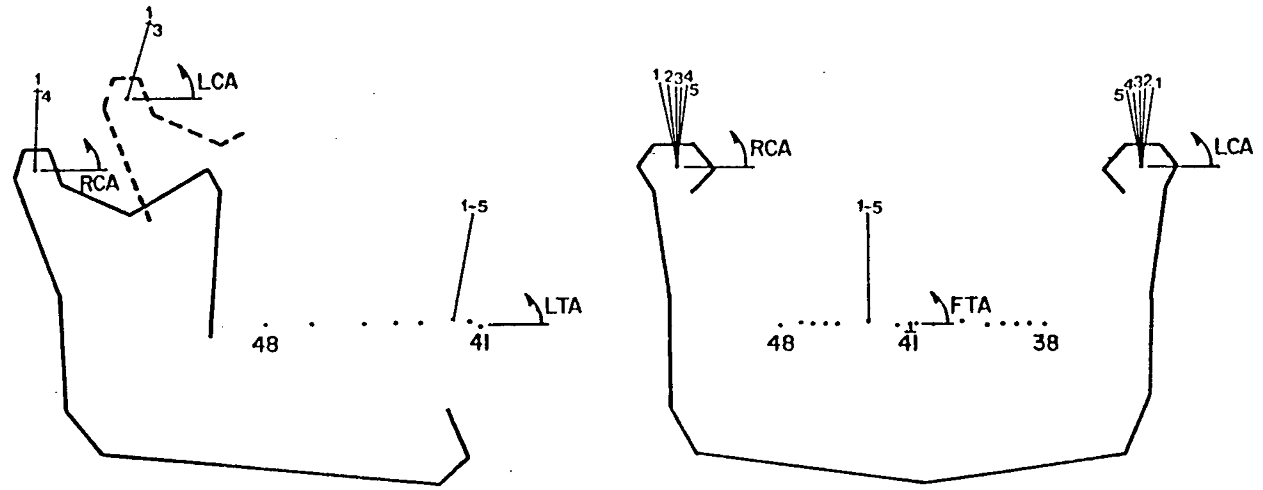
In the frontal projection as LCFA increases from 80.0 to 90.0 degrees (RUN 1, 2 and 3) there is a decrease in the medial (rightward) component of force at the left joint. Since this component of force at this joint does not reduce any of the rightward component due to the muscle force (MLR = -15.8 N) the right joint requires a relatively greater medial (leftward) component to balance the system. At LCFA of 90.0 degrees, however, the left joint does not add any mediolateral component. Thus the medial component of

Figure 14D. UNILATERAL (RIGHT SIDE) CANINE CLENCHING (UNIK9)/VARIABLE LCFA. All variables fixed except the left condylar angle in the frontal plane which varies over the same range as the FTA of Figure 14C. LTA and FTA are specified to match ANG·L and ANG·F respectively.

MUSCLE RESULTANT PARAMETERS

MLR =	-15.8
MAR =	99.7
MVR =	554.0
ANG·L =	79.8
ANG·F =	91.6

480 N



RUN	Tooth Posit^{n}	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	43	86.8	79.8	72.7	175.1	226.8	170.2	102.5	91.6	80.0	1.52
2					172.6		168.4	97.9		85.0	1.50
3					171.2		167.8	93.2		90.0	1.50
4					171.0		168.4	88.5		95.0	1.50
5					172.0		170.2	83.7		100.0	1.51

* LCFA

the right joint (RCA = 93.0 degrees) is simply that necessary to balance the corresponding component of muscle force not neutralized by the medial or leftward component of TR. At LCFA greater than 90.0 degrees a leftward lateral component occurs requiring an opposite balancing component (lateral but rightward) at the right joint. Since the vertical component of force at each joint is identical for each run the magnitude of LCR at 80.0 and 100.0 degrees (170.2 N; RUN 1 and 5) is the same because they both have equivalent (but opposite) mediolateral components contributing to the overall vector. LCFA of 90.0 degrees, with no such added component therefore has the lowest magnitude (167.8 N). The same effect causes the variation in RCR magnitudes but LCFA of 95.0 degrees (RUN 4) produces the lowest value for this vector since the corresponding RCA orientation (88.5 degrees) is the closest to vertical of the right joint forces.

The extent of these changes to RCR and LCR due to LCFA variations are relatively slight and as such there is little change in the JF/TF ratio from 1.50 in this series. However, at LCFA orientations much beyond a range of 5.0 degrees either side of vertical the distribution of resistance forces would appear to be less favorable according to the slight increase in this ratio observed in RUN 1 and 5.

b. Unilateral Molar Clenching (UNIMOL) - Figures 15A, B, C, D and E

i. Muscle Resultant Parameters

Figure 15A depicts the predominance of right (working) side muscle activity during this task. The Scale Factors of SM, DM, MP, AT and PT are significantly higher on the right than the left side. MT is equivalent on the two sides, whereas only IP shows significantly greater relative activity on the left balancing side than its working side counterpart. Except for IP, all of these Scale Factors represent an increase in the relative force produced by each of the various muscle groups compared to those of unilateral canine clenching. IP alone is less active during unimolar clenching than unicanine clenching although the balancing side is more active in both tasks. SP and DG data are unavailable for unimolar clenching and are omitted here.

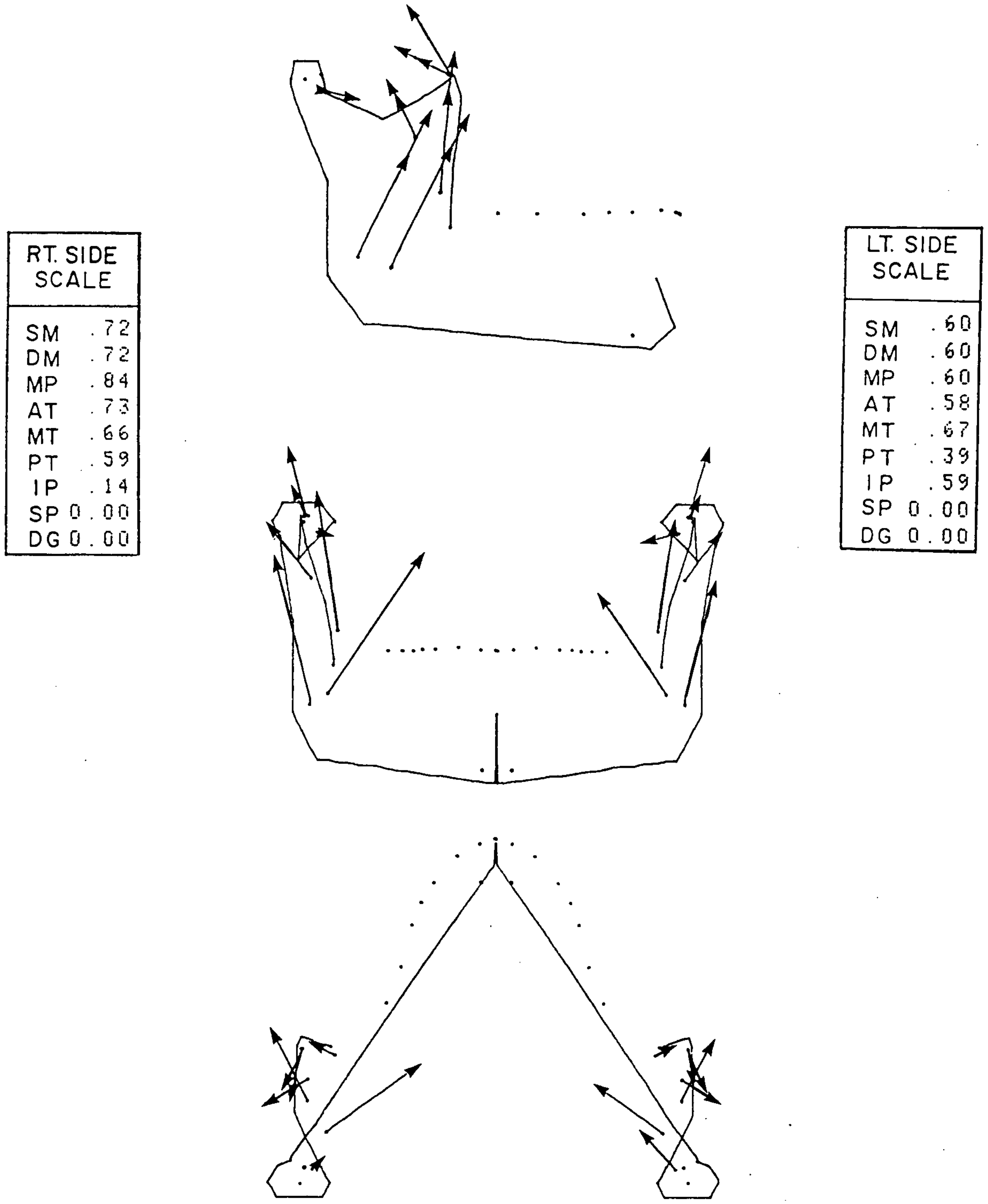
Despite the obvious differences between the Scale Factors of unilateral canine and molar clenching the magnitude of the lateral component of the overall muscle force for the latter task of -15.1 N (MLR) is virtually the same as that of the canine task. This in itself clearly indicates how various different combinations of muscle force can effect the same results. MAR of molar clenching of 87.9 N, on the other hand is somewhat less than for the unicanine task (99.7 N). Nevertheless, unimolar clenching produces a much greater vertical component (MVR) of muscle force at 839.9 N (vs. 554.0 N of unicanine).

The overall orientations of the muscle force produced by the components at ANG·L of 84.0 and ANG·F of 91.0 degrees are similar to canine clenching but in general are more vertical than the latter and much more so than the incisal clenching tasks. Only intercuspal and bilateral molar clenching tasks produce greater vertical ANG·L orientations.

ii. Tooth Position Change - Figure 15B

Although an occlusal bite stop positioned at tooth 47 was incorporated in the derivation of the major muscle groups (eg. SM, MP, AT, PT; see Table

Figure 15A. UNILATERAL (RIGHT SIDE) MOLAR CLENCHING (UNIMOL). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.



II of METHODS), the effect of changes to the position of tooth contact for these same muscle activities was modeled as shown in Figure 15B.

As has been observed previously, more posterior positions of tooth contact result in greater magnitudes of TR. Comparison of the TR value of 454.6 N for first molar clenching in RUN 1 of Figure 15B with corresponding runs for intercuspal (615.9 N; RUN 3, Figure 10C) and bilateral molar clenching (531.8 N; RUN 3, Figure 11B) shows that somewhat less total tooth resistance force occurs during unilateral molar clenching. Similarly the TR magnitude of 545.3 N at the second molar of Figure 15B is also less than that during bilateral molar clenching (637.9 N) of the corresponding run (RUN 3) of Figure 11C. This is, in part, a function of the relatively lower overall muscle force generated during unilateral molar clenches. However it must be remembered that in both intercuspal and bilateral molar clenches the TR force produced is distributed to both sides of the dentition. The tooth forces of Figure 15B occur at the single tooth contact designated on the right side of the mandible. As such it would appear that despite relatively less muscle force, proportionately more tooth resistance force (i.e. per tooth) can be produced for unilateral molar contacts.

In each run of Figure 15B the balancing (left) side joint is more heavily loaded than the working (right) side. For first molar contact (RUN 1) LCR of 258.2 N is approximately twice that of RCR at 138.9 N. As the position of tooth contact becomes more posterior LCR decreases only slightly to 247.8 N at the second molar and 244.3 N at the third. LCA remains virtually constant for all three tooth positions at approximately 78.0 degrees in the lateral plane (90 degrees in the frontal). The right joint resistance force, on the other hand, changes dramatically at the more posterior tooth contacts with respect to both magnitude (RCR) and orientation (i.e. RCA, in both the lateral and frontal planes). At the second molar contact RCR of 64.9 N is only about one quarter that of LCR at 247.8 N and is directed more posteriorly (RCA = 56.4 degrees in the lateral plane) than for first molar contact (RCA = 75.3 degrees).

Tooth contact at the third molar produces the most dramatic change in right (working) side joint force. At this tooth position RCR increases very slightly to 66.0 N but has an upwards as well as posterior component. Hence RCA orientations of 302.9 and 254.3 degrees in the lateral and frontal projections respectively. That is, for the muscle forces described here for a unilateral molar clench and with input variable orientations (LTA, FTA and LCFA) of 90.0 degrees a third molar contact alone creates a tensile force at the working side joint. Up to now only compressive joint forces have been observed. This is due to the fact that more posterior tooth contacts are also positioned more laterally in the frontal plane, which was not the case in the bilaterally symmetrical clenching tasks previously observed.

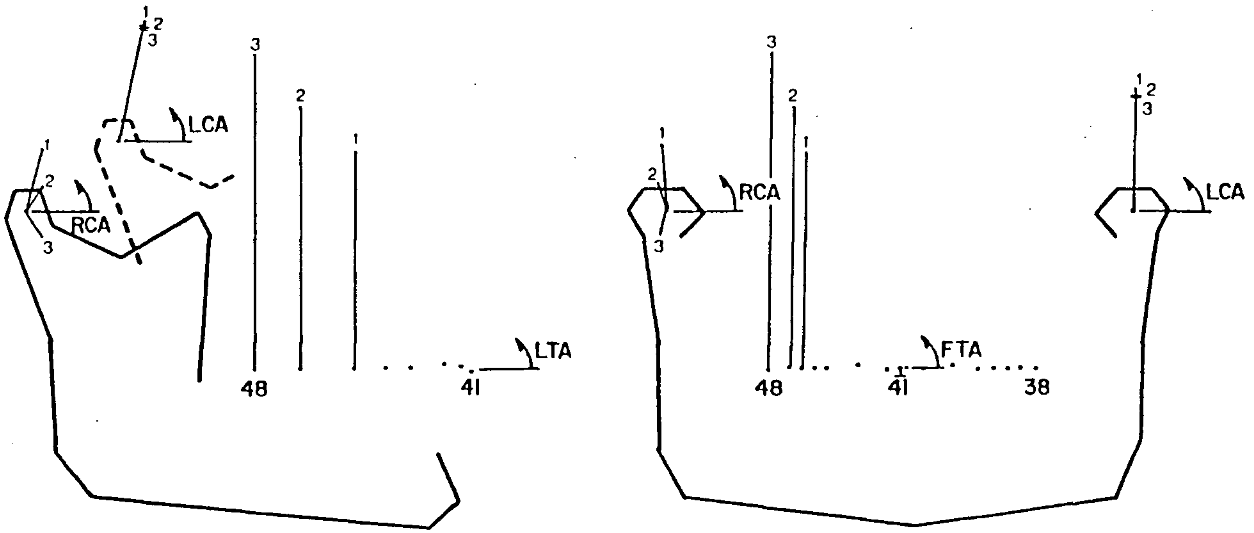
Initially, in the lateral plane, more posterior tooth contacts (with shorter moment arms) require proportionally greater tooth forces (TR) to completely balance the moment due to the muscle force (MAR and MVR). In this plane the moment due to the tooth force alone must account for all of the muscle force moment of rotation. In the frontal plane, however, the rotational moment due to TR (RUN 1) at the first molar (the magnitude of which was determined as that necessary to balance the moments in the lateral plane) accounts for less of the muscle force moment than TR of either the second (RUN 2) or third molars (RUN 3). Therefore the vertical component of LCR seen in this (frontal) projection is greater for first than second or third molar contacts since the first molar contacts must contribute a relatively greater rotational moment to the system than either of the latter.

Although this now satisfies the rotational statics of the system three dimensionally, it does not do so regarding the linear statics. Because the orientations of the input variable angles (i.e. LTA, FTA and LCFA) are all purely vertical, only the right joint in the frontal plane is able to contribute a medial component of force to resist the lateral component of muscle force (MLR = -15.1 N). Thus, for each tooth position there is an equivalent medial component of force at the right joint seen in the frontal projection. However the sum of the vertical components due to the tooth (TR) and left joint (LCR) resistance forces in this plane are insufficient to balance MVR of the muscles. In the case of first molar contact (RUN 1) the necessary additional vertical component must be contributed by the right joint, and it is compressive. For the second molar contact relatively less additional vertical (compressive) force at the right joint is required, due mostly to a proportionally greater TR magnitude in this plane (which was determined as that necessary to balance the rotational statics of the lateral plane). Regarding the third molar position (RUN 3), the relatively greater (vertical) TR force combined with the corresponding vertical component of LCR in this plane (frontal) are greater than that necessary to balance MVR. As such a negative, or tensile stabilizing force results at the right joint to balance the linear statics of the system for a unilateral third molar contact

Figure 15B. UNILATERAL (RIGHT SIDE) MOLAR CLENCHING (UNIMOL)/VARIABLE TOOTH POSITION. Three possible positions of right molar contact are shown. All other variables are arbitrarily specified at 90° to simplify comparisons of tooth position. Therefore the mediolateral component of muscle force (MLR) is reflected in the frontal plane RCA value only.

MUSCLE RESULTANT PARAMETERS	
MLR =	-15.1
MAR =	87.9
MVR =	839.9
ANG·L =	84.0
ANG·F =	91.0

480 N



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	46	75.3	90.0	78.1	138.0	454.6	258.2	96.5	90.0	90.0	.87
2	47	56.4		77.6	64.9	545.3	247.8	106.4			.57
3	48	302.9		77.5	66.0	655.4	244.3	254.3			.49

* LCFA

under the given conditions. Stabilization of the rotational and linear statics in the horizontal plane require equivalent posteriorly directed components of left and right joint resistance forces for all three tooth contact positions as shown in the lateral plane of Figure 15B.

Interestingly, the JF/TF ratios of these runs suggest that unilateral molar clenching can generate not only more occlusal force per tooth with relatively less muscle force than bilateral clenching tasks, but it does so with greater efficiency with respect to the distribution of the remaining resistance forces. Although the second molar position is the most appropriate for the derived muscle data, the first molar position had a JF/TF ratio of 0.87. The corresponding runs of intercuspal clenching (RUN 3; Figure 10C) and bimolar clenching (RUN 3; Figure 11B) had ratios of 0.93 and 0.96 respectively, which are significantly less favorable. Comparison of this ratio for the second molar run of this unilateral task of 0.57 with the corresponding run of the bimolar task (RUN 3; Figure 11C) with a ratio of 0.68 also lends credence to this prediction. Most of this improvement is derived from the fact that the resistance forces of the working side joint during posterior (ie. molar) unilateral clenching are significantly reduced and those of the balancing side are somewhat less while the tooth resistance remains relatively high.

iii. Lateral Tooth Angle (LTA) Change - Figure 15C

The point of tooth contact designated was the right second molar for this series with FTA fixed at 91.0 degrees to match ANG·F and LCFA at 90.0 degrees. An increase in LTA produces an increase in TR and a decrease in both the balancing (LCR) and working side (RCR) joint force magnitudes.

As LTA increases from 75.0 to 95.0 degrees in Figure 15C TR also increases from 485.6 N to 578.2 N, again due to shortening of the moment arms of tooth force in each RUN. Consequently LCR decreases a corresponding amount from 265.1 N to 245.3 N due to a requirement for relatively less vertical and slightly more posteriorly directed components of left joint force to balance the moments of the system (i.e. in the frontal and horizontal planes). Regarding RCR, there is a requirement for reduced vertical components as LTA increases, but relatively more medial (leftward) force is necessary as evidenced by the increasing RCA orientations in the frontal plane from 93.7 to 101.0 degrees. This latter component increase adds relatively little to the overall RCR magnitudes which are all significantly less than those of the balancing joint. However the anteroposterior component of RCR varies greatly over this series and is initially (RUN 1) anteriorly directed but becomes posteriorly directed at greater LTA values (RUN 5). The greatest RCR magnitude of 119.3 N also occurs at the more acute LTA but decreases to a greater extent than LCR with increasing LTA. The lowest RCR is in RUN 4 at 64.0 N. This is simply a consequence of the effects of the changes to the three components of force over the range of LTA which when combined determine the RCR magnitudes.

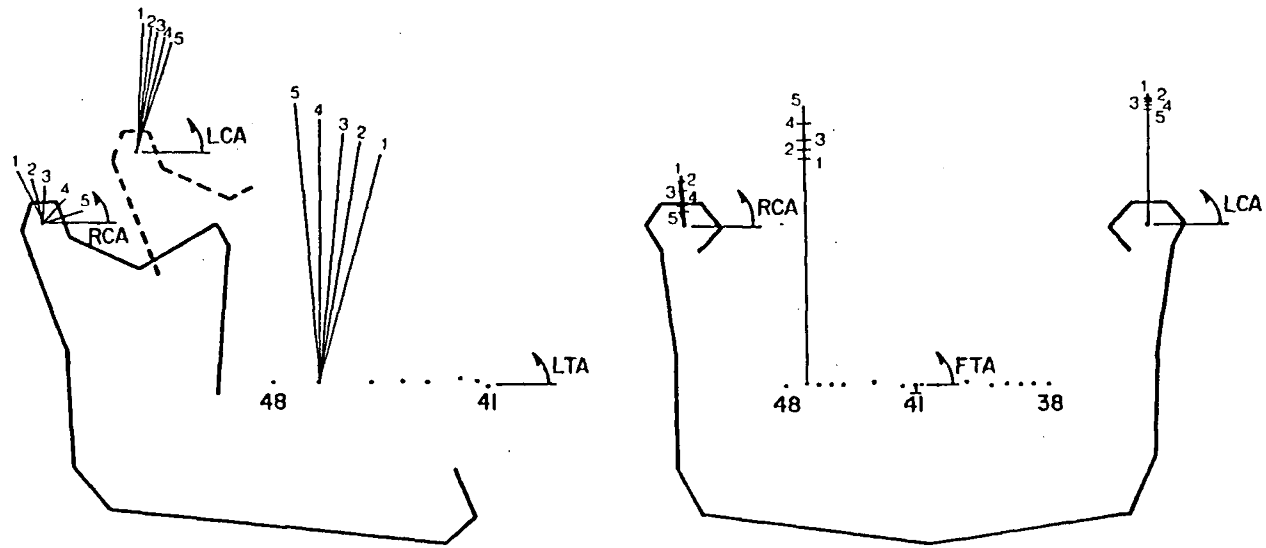
It is apparent that while the change (decrease) in LCA orientation of the lateral plane is only about 10 degrees for this series (86.6 to 75.9 degrees; RUN 1 and 5 respectively) that of RCA is about 100.0 degrees (116.7 to 18.4 degrees for the same runs).

The greater LTA angles with higher values for TR and reduced RCR and LCR magnitudes are more efficient regarding JF/TF ratios which has consistently

Figure 15C. UNILATERAL (RIGHT SIDE) MOLAR CLENCHING (UNIMOL)/VARIABLE LTA. The second molar is specified as the position of tooth contact. LTA is specified as per previous figures. The right condylar angles in the frontal plane (RCA) are not colinear although the relatively small size of the vector projections in this plane makes them almost appear as such. LCFA is arbitrarily specified at 90°.

MUSCLE RESULTANT PARAMETERS	
MLR =	-15.1
MAR =	87.9
MVR =	839.9
ANG·L =	84.0
ANG·F =	91.0

480 N



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	47	116.7	75.0	86.6	119.3	485.6	265.1	93.7	91.0	90.0	.79
2		105.4	80.0	84.4	92.2	500.2	260.0	94.2			.70
3		89.8	84.0	82.4	73.9	515.5	256.0	94.8			.64
4		50.4	90.0	79.1	64.0	545.4	250.0	96.5			.58
5		18.4	95.0	75.9	82.8	578.2	245.3	101.0			.57

* LCFA

been the case in all tasks observed. However the fact that unilateral molar clenching is biologically more efficient is again suggested by the JF/TF of 0.64 for RUN 3, with the input variables matched to those of the MUSCLE RESULTANT PARAMETERS. Bimolar clenching of RUN 3, Figure 11C with similarly matched data did produce more absolute occlusal force (618.5 N vs. 515.5 N) although distributed over both sides of the mandible but also at a cost of 4% more joint force (JF/TF = 0.68).

iv. Frontal Tooth Angle (FTA) Change - Figure 15D

For this series LTA was fixed at 84.0 degrees and FTA varied 10.0 degrees either side of the ANG·F orientation of 91.0 degrees. The effect of this change is qualitatively identical to that observed for the unicanine clench of Figure 14C, although somewhat magnified due to the greater magnitudes of force involved.

Variation of FTA requires equivalent vertical components of TR but adds a variable mediolateral component as FTA increases or decreases from vertical. As such the relatively greater and equivalent TR magnitudes at FTA of 80.0 and 100.0 degrees (523.3 N; RUN 1 and 5) and slightly lower magnitudes at 85.0 and 95.0 degrees result (517.4 N; RUN 2 and 3). RUN 3 (matched) with FTA of 91.0 degrees has the lowest TR magnitude (515.4 N), since it has the smallest extra mediolateral component adding to its resultant length.

This effect also produces the decrease in LCR magnitude and the great change in RCA orientations as FTA increases in the frontal plane. This is because more acute orientations of tooth force (with longer moment arms in the frontal plane) account for relatively more of the muscle moment. Thus less LCR force at the designated LCFA orientation (i.e. vertical) is requiredto make up the difference between the muscle and tooth rotational moments. However the various added mediolateral components of these TR vectors also introduce additional linear forces to the system in the frontal plane which must be balanced. The muscle force in this plane is nearly vertical (ANG·F = 90.0 degrees) and thus has a small lateral (rightward) component (MLR = -15.1 N). Only the right condyle can contribute any extra mediolateral force to balance these components of tooth force since LCFA is fixed. Hence the dramatic decrease in frontal RCA orientations from 133.8 degrees of RUN 1 (large lateral tooth force component and correspondingly large medial joint force component) to 41.7 degrees of RUN 5 (large medial tooth force component and corresponding lateral joint force).

In each run most of the vertical components of the muscle force (MVR) acting on the system are balanced by the sum of the tooth and left joint vertical components of force. However the residual linear vertical force which is attributed to the right joint is much less than that of the left joint forces.

A more acute (laterally directed) FTA also requires a relatively greater posterior component of LCR to balance the moments in the horizontal plane. This produces more acute lateral plane LCA orientations. Conversely FTA orientations greater than 90.0 degrees which have a medially directed component require less posterior, and (in the case of RUN 5) even an anterior component of LCR. Thus LCA increases from 66.7 to 93.1 degrees in the lateral plane as FTA increases from 80.0 to 100.0 degrees in the frontal (RUN 1 to 5). In RUN 1 to 4 the left joint forces shown in the lateral plane have a posterior component (LCA < 90.0 degrees) while RUN 5 (LCA = 93.1 degrees) has an anterior component. The remaining necessary anteroposterior components contributing to the resistance force at the right condyle (RCR) are those required to balance the remaining linear statics of the system. For instance, in RUN 1, FTA of 80.0 degrees requires a relatively large posterior component of left joint force (and a relatively acute LCA orientation) to balance the moment due to the muscle force in the horizontal (occlusal) plane. However, as is apparent in the lateral plane projection, this posterior component due to the left joint force is greater than that necessary to balance the anterior component of the muscle force (MAR). Therefore an additional anterior component results at the right joint at FTA of 80.0 degrees in RUN 1. In RUN 5 the opposite conditions prevail such that the anterior component of force at the left joint adds to that of the linear component of muscle forces. This requires a posterior component of force at the right joint at FTA of 100.0 degrees.

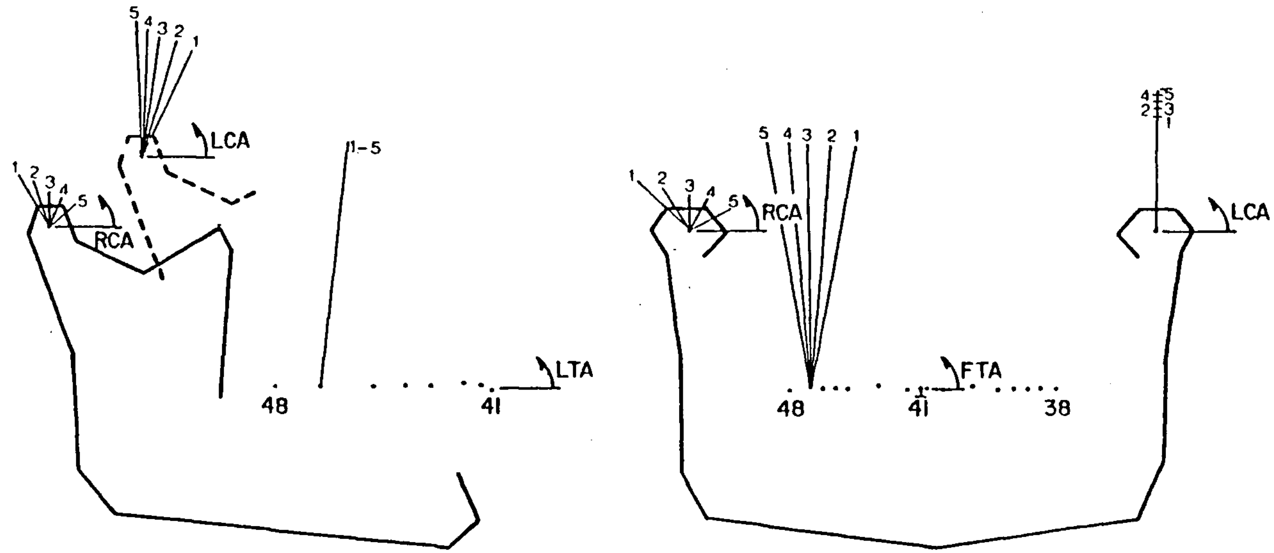
The combination of the three orthogonal components of RCR at the various FTA orientations are such that RCR decreases from 163.6 N at FTA of 80.0 degrees (RUN 1) to a minimum of 70.9 N at FTA of 95.0 degrees. Further increase in FTA to 100.0 degrees increases RCR to 100.1N.

It is interesting that for this task the most optimum distribution of resistance forces occurred in RUN 3 with the input variables matched with the muscle data. Variations in FTA orientations have less favorable consequences on the biomechanics of the system under these conditions.

Figure 15D. UNILATERAL (RIGHT SIDE) MOLAR CLENCHING (UNIMOL)/VARIABLE FTA. LTA is specified to match ANG·L. FTA varies as described in previous figures. LCFA arbitrarily specified as 90°.

MUSCLE RESULTANT PARAMETERS	
MLR =	-15.1
MAR =	87.9
MVR =	839.9
ANG·L =	84.0
ANG·F =	91.0

480 N



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS RCA	FTA	LCA*	JF/TF
1	47	118.4	84.0	66.7	163.6	523.3	236.7	133.8	80.0	90.0	.76
2		109.0		74.2	115.5	517.3	243.2	122.7	85.0		.69
3		89.8		82.4	73.9	515.5	256.0	94.8	91.0		.64
4		70.2		87.4	70.9	517.4	267.1	63.9	95.0		.65
5		41.7		93.1	100.1	523.3	283.9	41.7	100.0		.73

* LCFA

v. Left Condyle Frontal Angle (LCFA) Change - Figure 15E

With LTA and FTA matched with their respective orientations of muscle force the variations of LCFA for this molar clench have similar overall effects on joint force orientation as those seen in Figure 14D of the unicanine task. However both the range of RCA in the frontal plane for LCFA changes from 80.0 to 100.0 degrees and the magnitudes of these resistance forces are relatively greater. This is due to a significantly greater magnitude of muscle force and a tooth contact position much closer to the fulcrum in all three dimensions for this molar clench.

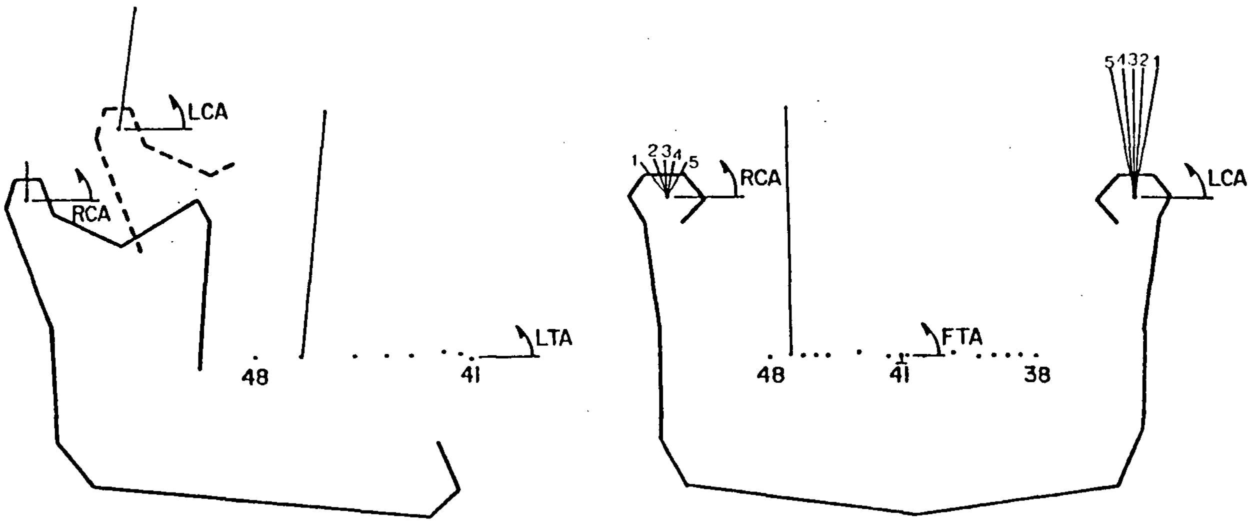
Variation of LCFA above or below 90.0 degrees adds a mediolateral component of left joint resistance to the (constant) vertical component which increases the net resultant of this force. Hence LCR at 80.0 and 100.0 degrees (RUN 1 and 5) is the same at 259.8 N and at 85.0 and 95.0 degrees (RUN 2 and 4) is 256.9 N. No such component exists at LCFA of 90.0 degrees and thus RUN 3 has to lowest LCR magnitude of 256.0 N.

These extra mediolateral components imposed on the left joint force require balancing components at the right joint. Therefore in RUN 1 the medially (rightward) directed component of LCFA requires a leftward medially directed component at the right condyle (eg. RCA = 124.7 degrees). In RUN 5 the opposite set of circumstances require the laterally directed (rightward) component at the right joint (eg. RCA = 62.4 degrees). RUN 3, on the other hand, with no left joint mediolateral component requires no additional balancing component at the right condyle. The slight medial (leftward) component which does exist in this run at the right joint is simply that necessary to balance the lateral (rightward) component of muscle force (MLR =

Figure 15E. UNILATERAL (RIGHT SIDE) MOLAR CLENCHING (UNIMOL)/VARIABLE LCA. LTA and FTA are specified to match ANG·L and ANG·F respectively. LCFA varies over the same range as FTA of Figure 15D.

MUSCLE RESULTANT PARAMETERS	
MLR =	-15.1
MAR =	87.9
MVR =	839.9
ANG·L =	84.0
ANG·F =	91.0

480 N



RUN	Tooth Position	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	47	89.8	84.0	82.4	89.5	515.5	259.8	124.7	91.0	80.0	.68
2					78.9		256.9	111.1		85.0	.65
3					73.9		256.0	94.8		90.0	.64
4					75.4		256.9	77.7		95.0	.64
5					83.1		259.8	62.4		100.0	.66

* LCFA

-15.1 N; ANG·F = 91.0 degrees). The sum of the vertical and mediolateral components of resistance force so produced at the right joint are such that the least magnitude of resultant of this force occurs in RUN 3 (RCR = 73.9 N)and LCFA at 90.0 degrees. Variation from this orientation at the left joint from 90.0 degrees produces increased RCR magnitudes.

Since no change in TR magnitude occurs, the JF/TF ratio is minimal at the LCFA orientation with the lowest combined joint resistance forces which is in RUNS 3 and 4 at 0.64. Beyond this JF/TF increases as shown in Figure 15E. Thus, variation in LCFA from 90.0 degrees produces a reciprocal effect on RCA orientations but in general do not increase the efficiency of resistance force distribution of the system.

3. Unilateral Chewing Tasks

a. Muscle Resultant Parameters - Figures 16A, 17A and 18A

Comparison of Figures 16 to 18 "A" portrays the change in the activities of the various muscle groups (see also Table III of METHODS) during three intervals of the power stroke of right side gum-chewing. The first two intervals are 100 msec (Interval 1), and 50 msec (Interval 2) before Time 0 (Interval 3) which occurred approximately 10 to 15 msec after intercuspation. Each of these intervals is considered to be in static equilibrium with no net movement of the system actually occurring.

In Interval 1 and 2 all of the working (right) side muscle groups are more active than their balancing side (left) counterparts (see Figure 16A and 17A). At Interval 2 all of the working side muscle activities increase to their maximal levels of the three phases considered, as do the three temporalis groups and inferior head of the lateral pterygoid of the balancing side (AT, MT, PT and IP respectively). Only the balancing side masseters (SM and DM) and medial pterygoid (MP) show a decline from Interval 1 to 2 although not to their minimal levels. During Interval 3 (see Figure 18A) all muscle groups of both sides show a decrease in activity from that of Interval 2, with the working side pterygoids (MP and IP) and temporalis groups (AT, MT, PT) at minimal levels of the three phases. The balancing side masseters (SM and DM) and pterygoids (MP and IP) are also least active in this phase. All other levels are more or less intermediate between those of the first two intervals (eg. Working side masseters and balancing side temporals). Digastric is inactive during all three phases.

Comparison of these activity levels with those of the preceding static clenching tasks (see Tables II and III of METHODS) shows that the activities observed during masticatory functions do not necessarily coincide with any particular static function. The various levels of muscle activity seen during chewing and their combinations are unique to each chewing interval. Nevertheless, the combined effect of the various muscle groups in each phase of the chewing power stroke produce overall muscle forces quite similar to those observed in the static molar clenches. The "MUSCLE RESULTANT PARAMETERS" of the three power stroke intervals from Figures 16, 17 and 18 B, C and D are summarized here as are these variables from the unilateral molar clench for comparison.

	INTERVAL				
	1	2	3	UNIMOL	
MLR	-0.4	11.7	15.0	-15.1	(Newtons)
MAR	67.6	54.1	40.2	87.9	(Newtons)
MVR	522.3	676.8	451.3	839.9	(Newtons)
ANG•L	82.6	85.4	84.9	84.0	(Degrees)
ANG•F	90.0	89.0	88.1	91.0	(Degrees)

The muscle effort of Interval 1 in the lateral plane is directed anterosuperiorly at 82.6 degrees with a vertical component of 522.3 N and an anterior component of 67.6 N. In the frontal plane it is essentially vertical having virtually no mediolateral component (MLR = -0.4 N).

The change in activity levels of the muscles in Interval 2, and their combined effect produces an overall muscle effort more vertically oriented in the lateral plane at 85.4 degrees. This is due to an increase in the vertical component of force (MVR) to a peak level for the three phases to

676.8 N combined with a slight decrease in the anterior component (MAR) to 54.1 N. In the frontal plane the change in muscle activities generates a component of mediolateral force of 11.7 N which is directed leftward at 89.0 degrees.

The muscle effort of Interval 3 in the lateral plane is slightly less vertical than Interval 2 at 84.9 degrees due to a further decrease in MAR to 40.2 N and a decline in MVR to 451.3 N from the maximal level in the latter phase. In the frontal plane the increase in MLR to 15.0 N combined with the lower vertical component produces a slightly more leftward muscle effort of the three phases.

These changes in direction and magnitude of the muscle effort are consistent with those to be expected for right side chewing, i.e. maximal vertical effort at 50 msec prior to time zero (or 35-40 msec before intercuspation) with relatively more medially directed effort as the mandible is brought closer to intercuspation.

It was previously observed that more anteriorly positioned clenching tasks produced relatively more anteriorly directed muscle effort. The orientations of muscle force of these three chewing intervals in the lateral plane (ANG·L) from 83.0 to 85.0 degrees coincide with those one would expect from predictions based on the static molar clenching tasks. Unimolar clenching (see Figure 15B, etc.) produced muscle effort at 84.0 degrees in the lateral plane and near vertical in the frontal (91.0 degrees). Similarly the intercuspal clench and bimolar clench produced muscle forces oriented at about 88.0 and 87.0 degrees respectively (see Figures 10B and 11B etc.). Unicanine clenching had this effort at a more acute angle of around

Figure 16A. INTERVAL 1 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW1). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.

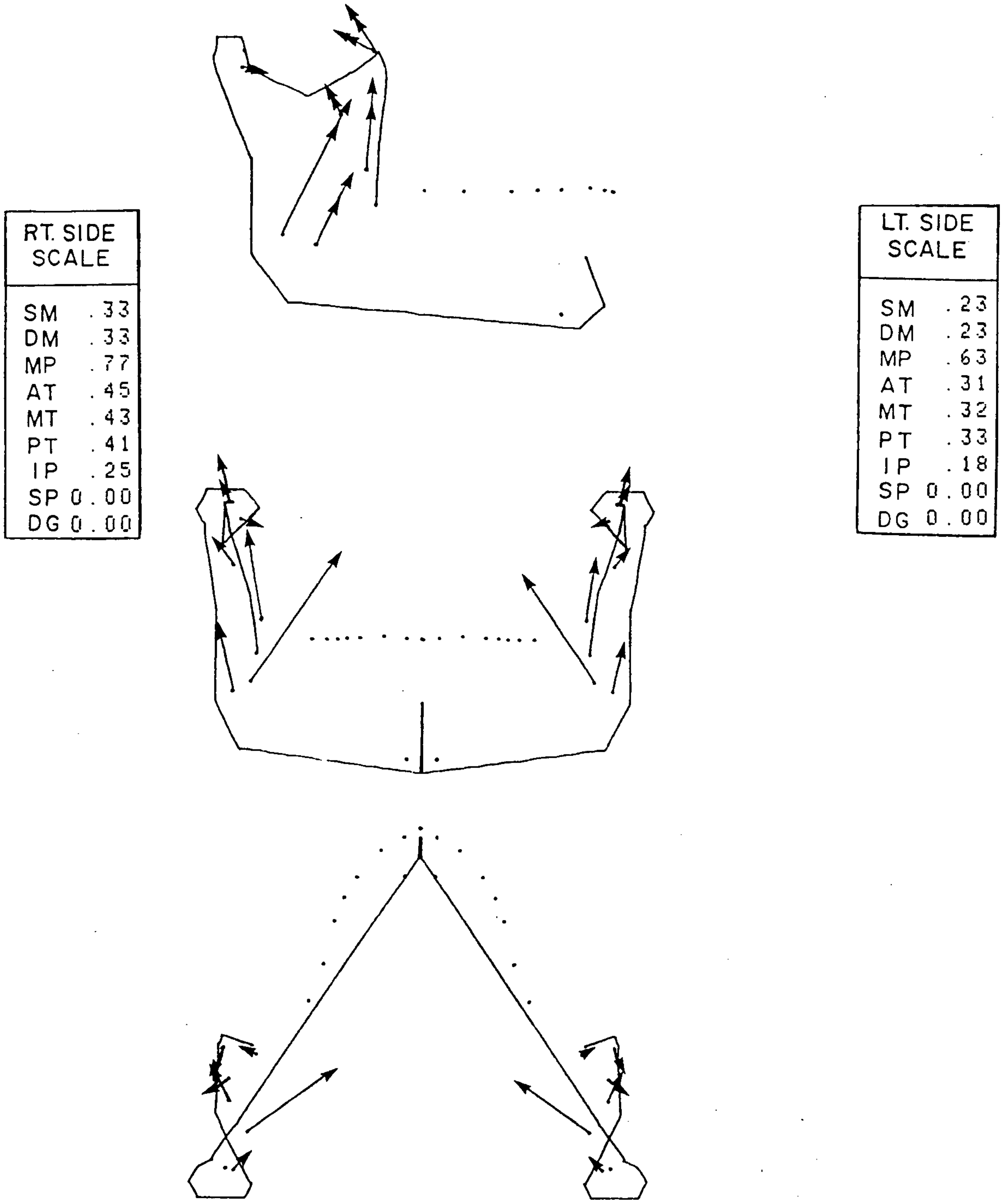


Figure 17A. INTERVAL 2 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW2). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.

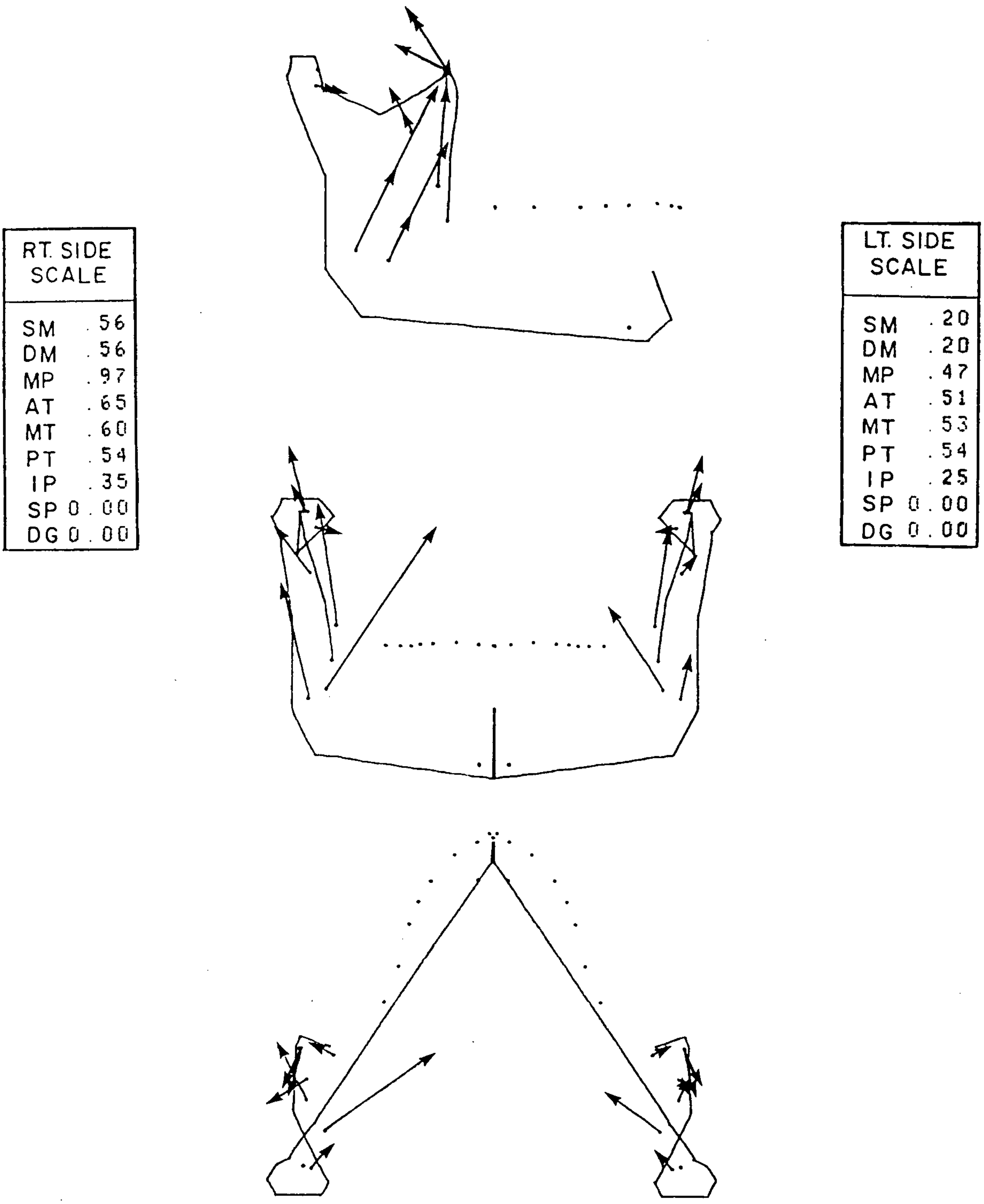
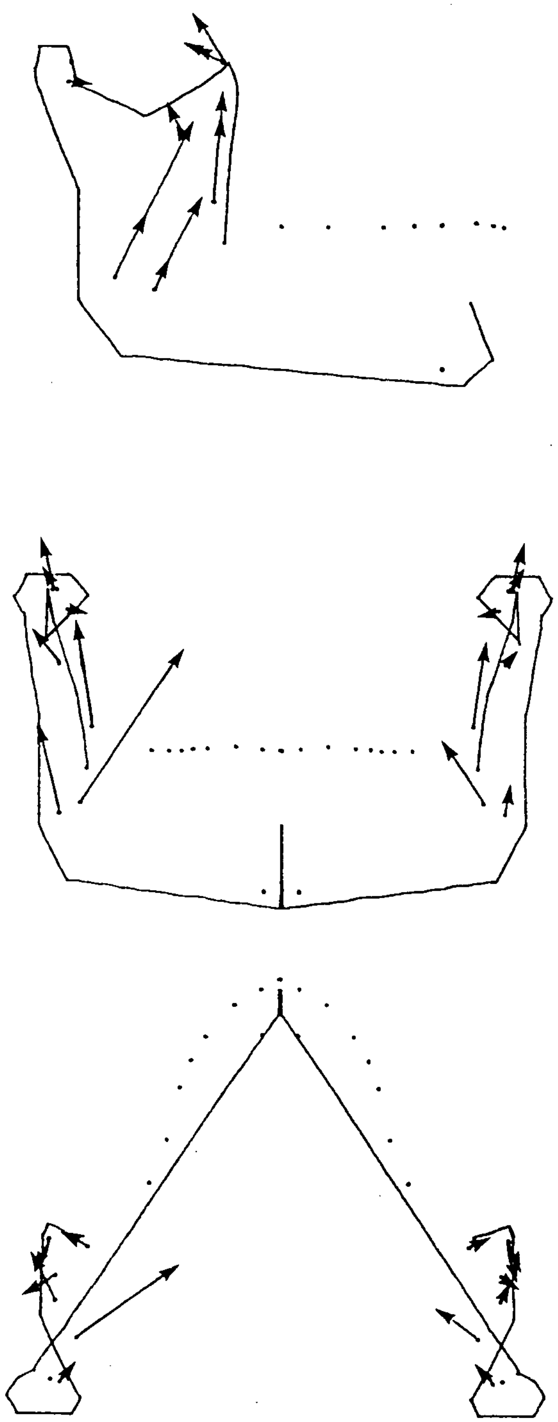


Figure 18A. INTERVAL 3 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW3). Right and left side scale factors and three dimensional (computer-drawn) depiction of individual muscle vectors.

RT. SIDE SCALE	
SM	.36
DM	.36
MP	.75
AT	.45
MT	.37
PT	.29
IP	.15
SP	0.00
DG	0.00



LT. SIDE SCALE	
SM	.09
DM	.09
MP	.29
AT	.36
MT	.36
PT	.35
IP	.15
SP	0.00
DG	0.00

80.0 degrees with the incisal clenches even more so at 64.0 to 70.0 degrees (see Figures 14, 12, and 13B etc. respectively). In all instances the direction of muscle effort in the frontal plane (ANG·F) was very near vertical, as is the case for the three chewing intervals despite the very different individual muscle group activities seen in all tasks. It would seem that many possible combinations of muscle group activities are capable of producing similar overall effects on the system.

b. Lateral Tooth Angle (LTA) Change - Figures 16B, 17B and 18B

In each run of these three figures the position of tooth contact with the bolus is assumed to have been at the right second molar (#47). The range of LTA was modeled from 75.0 to 95.0 degrees, which is approximately ten degrees either side of ANG·L for each interval (82.6, Interval 1; 85.4, Interval 2; and 84.9, Interval 3).

The TR magnitudes over the range of LTA modeled in each interval directly reflects the differences in the vertical muscle forces (MVR) generated for each interval. Interval 1 with intermediate muscle force produces tooth resistance forces of from around 300 to 355 N. Interval 2 which has the greater muscle forces has tooth forces around 390 to 460 N whereas Interval 3, with the lowest muscle forces produced the lowest TR magnitudes from approximately 260 to 305 N.

The joint forces produced for all three intervals were greater on the balancing than the working side. Comparing the runs with tooth orientations most closely matched with those of the applied muscle force (RUN 3 of Figures 16B and C, 17B and C, and 18B and C) the balancing joint was loaded from 100

Figure 16B. INTERVAL 1 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW1)/VARIABLE LTA. All variables specified as per Figure 15C.

MUSCLE RESULTANT PARAMETERS

MLR = -0.4

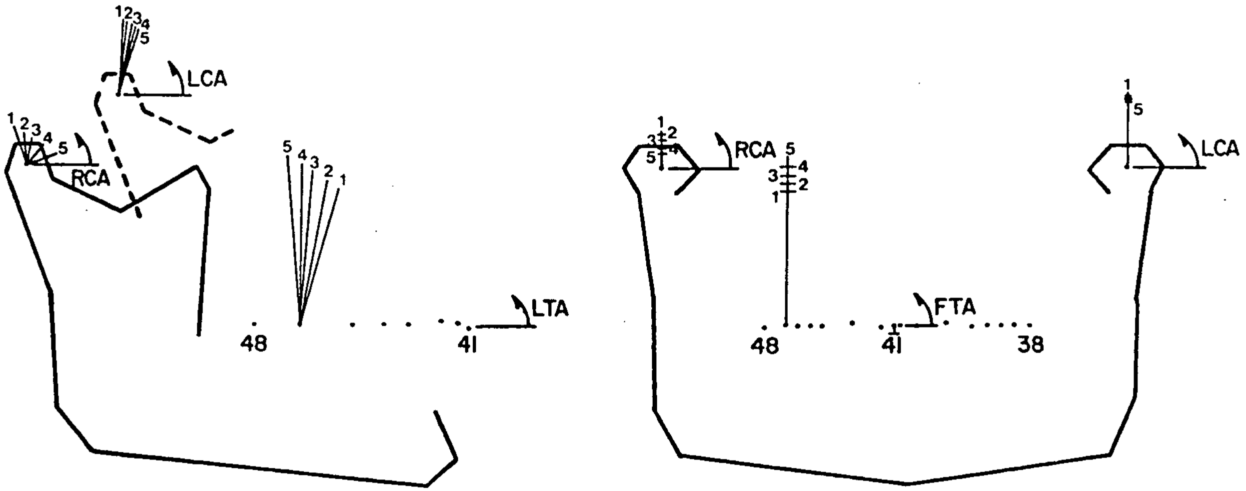
MAR = 67.6

MVR = 522.3

ANG·L = 82.6

ANG·F = 90.0

480 N

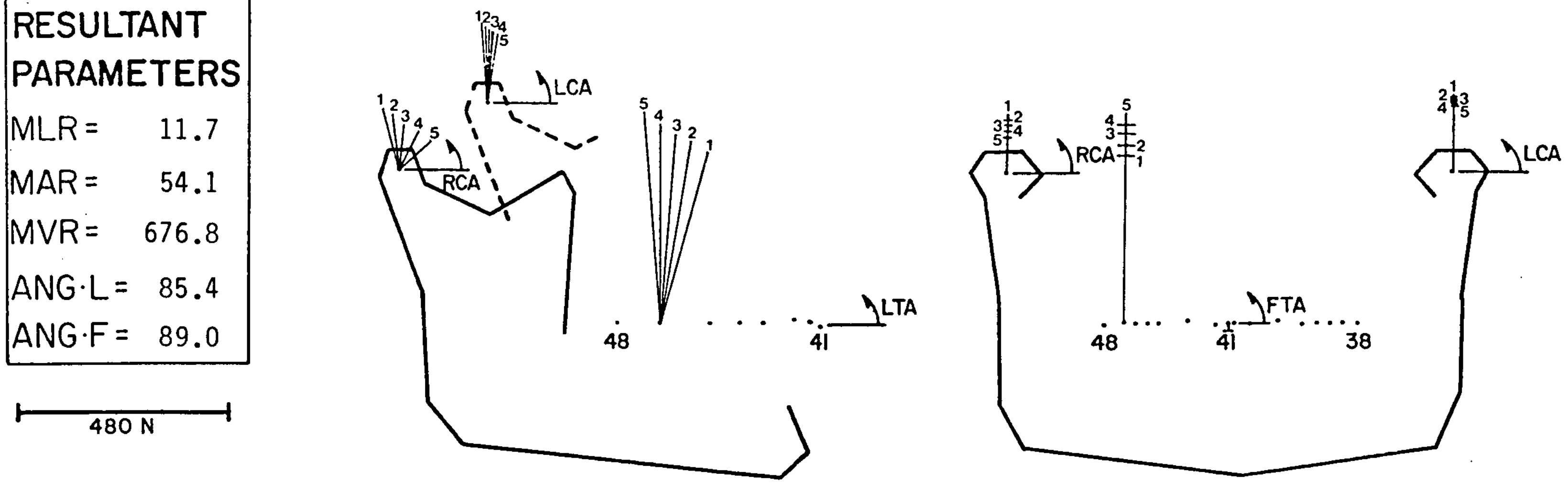


RUN	Tooth Posit^{n}	LAT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES: RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	FTA	LCA*	JF/TF
1	47	106.3	75.0	85.1	81.6	298.8	155.9	90.3	90.0	90.0	.80
2		94.4	80.0	82.7	67.7	307.8	152.9	90.4			.72
3		84.3	83.0	81.1	61.0	314.7	151.1	90.4			.67
4		51.5	90.0	77.0	55.5	335.6	147.1	90.6			.60
5		27.0	95.0	73.5	64.7	355.8	144.4	90.9			.59

* LCFA

Figure 17B. INTERVAL 2 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW2)/VARIABLE LTA. All variables specified as per Figures 15C and 16C.

MUSCLE RESULTANT PARAMETERS	
MLR =	11.7
MAR =	54.1
MVR =	676.8
ANG·L =	85.4
ANG·F =	89.0



RUN	Tooth Posit^{n}	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA*	
1	47	103.0	75.0	95.3	136.5	388.9	169.1	87.8	89.0	90.0	.79
2		93.8	80.0	92.6	119.3	400.6	163.5	87.7			.71
3		80.9	85.0	89.6	105.5	416.3	158.1	87.6			.63
4		63.7	90.0	86.0	98.0	436.8	152.6	87.4			.57
5		43.6	95.0	81.8	101.1	463.1	147.3	87.0			.54

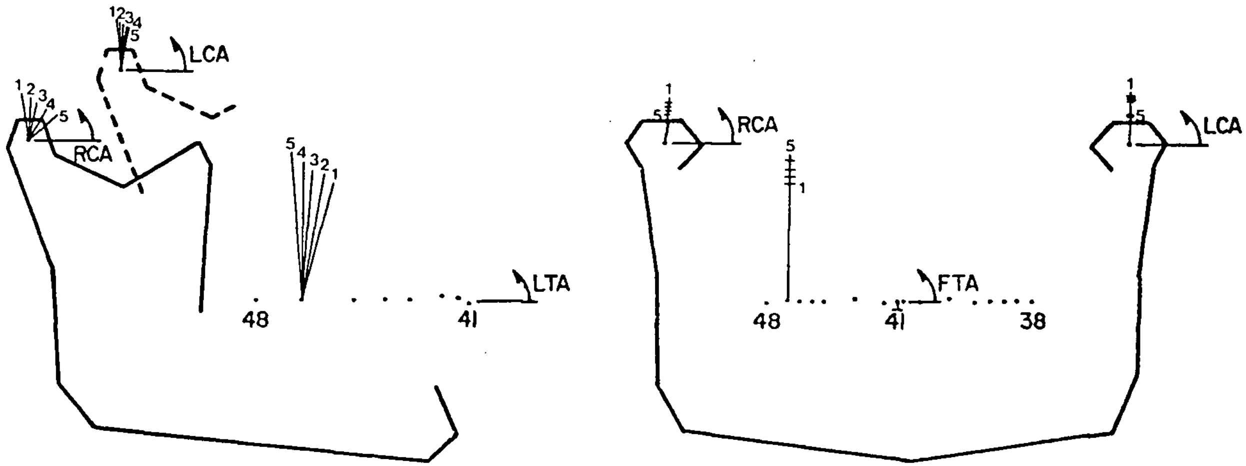
* LCFA

Figure 18B. INTERVAL 3 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW3)/LTA. All variables specified as per Figures 15C, 16C and 17C.

MUSCLE RESULTANT PARAMETERS

MLR =	15.0
MAR =	40.2
MVR =	451.3
ANG·L =	84.9
ANG·F =	88.1

480 N



RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES: RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	FTA	LCA*	JF/TF
1	47	98.3	75.0	96.8	96.7	258.0	107.6	86.2	88.0	90.0	.79
2		89.2	80.0	93.9	86.5	265.7	103.7	86.1			.72
3		77.3	85.0	90.7	78.6	276.2	99.8	86.0			.65
4		62.1	90.0	86.8	74.7	289.8	96.0	85.8			.59
5		44.8	95.0	82.2	76.8	307.2	92.4	85.4			.55

* LCFA

to 160 N and the working side from 60 to 105 N. These are less than those of both the unilateral molar about (75 N at the working side and 260 N at the balancing side) and canine clenches (about 170 N both sides).

The magnitude of the working and balancing side joint forces, however, exhibit rather different relationships through the three phases. Although the changes observed in LCR magnitude of the three chewing intervals coincides with the variation in TR and MVR, those of RCR do not. RCR forces are least in Interval 1, intermediate in Interval 3 and maximal in Interval 2. Comparison of RUN 3 of Figures 16B, 17B and 18B (with LTA and ANG·L matched at the appropriate orientations for each interval) shows RCR (61.0 N) to be 60% less than LCR (151.1 N) in Interval 1, 34% less in Interval 2 (105.5 versus 158.1 N) and only 21% less in Interval 3 (78.6 versus 99.8 N). There is thus an overall increase in the proportion of joint resistance force attributable to the right or working side. This is due to the increase in the lateral component of muscle force (MLR) from Intervals 1 (-0.4 N) to 3 (15.0 N).

Comparison of these results with RUN 3, Figure 15C (matched data) of unilateral molar clenching shows that where MLR was opposite in direction (i.e. -15.1 N) RCR was very much less (71%) than LCR. This has a similar effect on the range of RCA orientations seen in the lateral plane since these angles vary considerably less in the three chewing intervals (approximately 80, 60 and 55 degrees in Intervals 1, 2 and 3 respectively) than for the unimolar clench (100 degrees). LCA orientations, however, are comparable. It is also noteworthy that the three chewing intervals of Figures 16B, 17B and 18B exhibited JF/TF ratios very similar to those seen in the unimolar clenching runs of Figure 15C despite the great differences in the individual contributions of muscle activities between them.

c. Frontal Tooth Angle (FTA) Change - Figure 16C, 17C, and 18C

Variation of the FTA orientations in the three intervals of the chewing power stroke from 80.0 to 100.0 degrees produce the same variation in TR magnitudes seen previously for FTA changes. FTA orientations greater or less than vertical have an additional mediolateral component contributing to the resultant of tooth force in the frontal plane (not observed in the lateral plane). Hence, RUN 3 (muscle matched) of each interval seen in Figures 16C, 17C and 18C, which is closest to vertical in each case has the lowest TR magnitudes. Those of RUN 1 and 5 in each figure are relatively greater and are equivalent to one another since they occur at equivalent divergent angles from vertical (i.e. 10 degrees).

This added mediolateral component of tooth resistance force also produces the change in the frontal plane RCA orientations seen in Figure 16C, 17C and 18C. This is because an additional mediolateral component of joint resistance force at the right condyle is also necessary to balance the system where FTA varies as was explained previously. As the power stroke progresses from Interval 1 to Interval 3 there is an increase in the leftward component of MLR which results in a decrease in the range of RCA in the frontal plane (approximately 88, 74 and 63 degrees for Intervals 1 to 3 respectively). This is also apparent when the muscle-matched RUN 3 of each phase are considered. The frontal plane RCA is 90.4, 87.6 and 86.0 degrees in Figure 16C, 17C and 18C respectively where MLR increases from -0.4 N in Interval 1,

Figure 16C. INTERVAL 1 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW1)/VARIABLE FTA. All variables specified as per Figure 15D.

MUSCLE RESULTANT PARAMETERS

MLR = -0.4

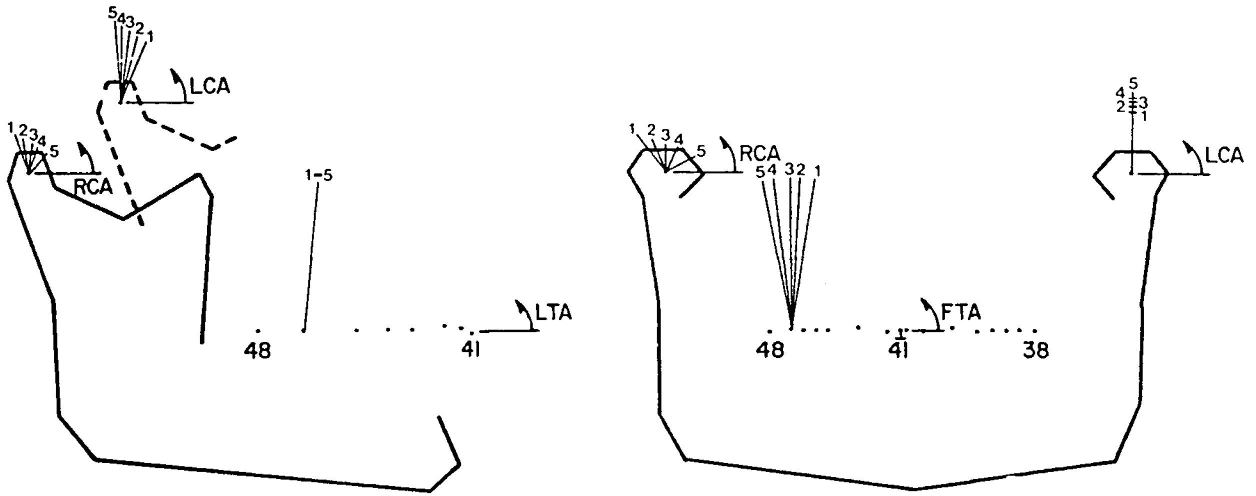
MAR = 67.6

MVR = 522.3

ANG·L = 82.6

ANG·F = 90.0

480 N



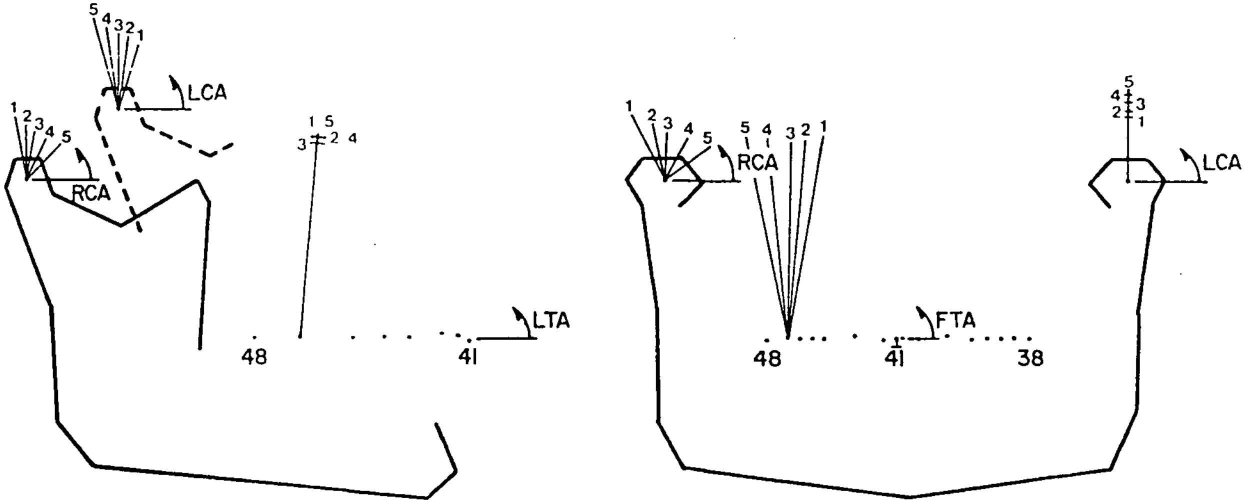
RUN	Tooth Positn	LAT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	LTA	LCA	RESULTANT VECTOR MAGNITUDES: RCR	TR	LCR	FRONT. PLANE RESULTANT VECTOR ORIENTATIONS: RCA	FTA	LCA*	JF/TF
1	47	108.5	83.0	66.4	101.7	319.5	140.9	124.5	80.0	90.0	.76
2		98.3		74.1	76.7	315.9	144.8	111.4	85.0		.70
3		84.3		81.1	61.0	314.7	151.1	90.4	90.0		.67
4		66.1		87.5	61.7	315.9	159.4	62.1	95.0		.70
5		46.0		93.3	78.5	319.5	169.7	46.0	100.0		.78

* LCFA

Figure 17C. INTERVAL 2 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW2)/VARIABLE FTA. All variables specified as per Figures 15D and 16D.

MUSCLE RESULTANT PARAMETERS	
MLR =	11.7
MAR =	54.1
MVR =	676.8
ANG·L =	85.4
ANG·F =	89.0

480 N



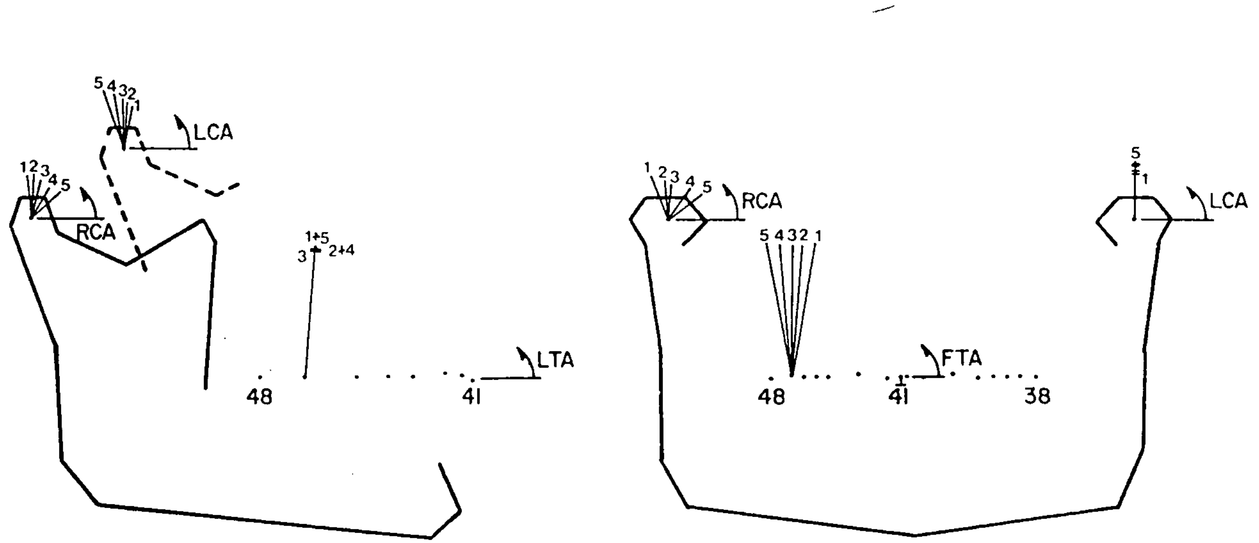
RUN	Tooth Posit^n	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA *	
1	47	100.2	85.0	73.1	143.9	422.6	140.1	115.6	80.0	90.0	.67
2		90.4		82.8	117.3	417.8	148.6	102.1	85.0		.64
3		80.9		89.6	105.5	416.3	158.1	87.6	89.0		.63
4		64.1		98.2	109.1	417.8	175.7	61.5	95.0		.68
5		49.0		104.1	130.3	422.6	193.2	41.4	100.0		.76

* LCFA

Figure 18C. INTERVAL 3 OF UNILATERAL (RIGHT SIDE) CHEWING POWER STROKE (CHEW3)/FTA. All variables specified as per Figures 15D, 16D and 17D.

MUSCLE RESULTANT PARAMETERS	
MLR =	15.0
MAR =	40.2
MVR =	451.3
ANG·L =	84.9
ANG·F =	88.1

480 N



RUN	Tooth Positn	LAT. PLANE RESULTANT VECTOR ORIENTATIONS			RESULTANT VECTOR MAGNITUDES			FRONT. PLANE RESULTANT VECTOR ORIENTATIONS			JF/TF
		RCA	LTA	LCA	RCR	TR	LCR	RCA	FTA	LCA *	
1	47	93.8	85.0	75.5	96.9	280.2	88.5	110.3	80.0	90.0	.65
2		84.0		85.5	82.8	277.1	94.8	96.3	85.0		.64
3		77.3		90.7	78.6	276.2	99.8	86.0	88.0		.65
4		59.7		100.8	84.0	277.1	114.2	58.7	95.0		.71
5		46.6		106.6	99.1	280.2	126.3	46.6	100.0		.80

* LCFA

to 11.7 N in Interval 2, and 15.0 N in Interval 3. Thus as the mandible nears intercuspation the right joint resistance force becomes more medially directed in the frontal plane. In the lateral plane the familiar reciprocal relationship between the RCA and LCA orientations of the joint resistance forces occurs for FTA variation during chewing as well.

The right or working side condylar forces are less than those of the left balancing side (except at very acute FTA orientations; eg. RUN 1 of Interval 2 and 3 where the reverse is true). Comparison of RUN 3 of Figures 16C, 17C and 18C with muscle-matched data is the same as Figures 16B and 17B with respect to the static clenching tasks previously discussed.

Based on the data of RUN 3 with muscle and tooth force orientations matched for each chewing interval this modeling analysis would predict the load-bearing surfaces of the two joint condyles to be capable of resisting up to 160 N of compressive force aligned at 75 to 90 degrees with respect to the occlusal plane.

C. SUMMARY

1. Bilaterally Symmetrical Clenching Tasks

Clenching activities involving the molar teeth generate more overall muscle force than those at the incisors due to relatively greater contribution by each muscle group to molar tasks. The magnitudes of these forces are 1000 to 1200 N for molar clenching but only around 450 N during incisal tasks. For each of the four tasks modeled the muscle force was directed anterosuperiorly. However, greater magnitudes of the muscle forces at more posterior tooth contacts involve relatively smaller anterior components and thus are more vertically directed than tasks involving less total muscle effort at the incisors (eg. ANG·L is 88.0 degrees for CO, 63.9 degrees for INCISN).

Changes in tooth position for the same muscle force result in greater tooth resistance forces at more posterior contacts and less corresponding joint resistance. Posterior contacts are therefore more efficient in terms of resistance force distribution since a greater proportion is taken up by the teeth. Comparison of molar versus incisal clenching also shows this effect even though they involve different muscle forces. Incisal clenching is much less efficient than more posterior (i.e. molar) clenching and involves a considerably smaller magnitude of tooth resistance force. Molar clenching in these analyses produced tooth resistance forces of about 500 to 600 N overall but a maximum of nearly 900 N could potentially have been genetrated during intercuspal clenching at the third molar position (RUN 4; Figure 10B). Incisal clenching on the other hand generated magnitudes of only around 130 N for natural contact and approximately 140 N for more stabilized contact with the stops due to slightly greater muscle forces generated during the latter task.

The relationship between the orientation of tooth force and its magnitude is, to a large extent, determined by the geometry of the mandible and the spatial juxtaposition of tooth contact and fulcrum position. In molar clenching this relation is straight forward as greater LTA values shorten the effective moment arm requiring greater tooth resistance forces to balance the moments acting around the joint fulcrum point. Incisal clenching however has a slightly different geometry in this analysis than molar clenching and consequently a different relationship between tooth orientation (LTA) and magnitude exists. The runs with the intermediate LTA orientations (eg. RUN 3 of both Figures 12B and 13B) had slightly longer moment arms and relatively smaller tooth force magnitudes than more extreme LTA orientations. This in turn has a reciprocal effect on the magnitudes of joint resistance force.

Changes in the LTA orientation also alter the distribution of resistance forces. More posteriorly oriented LTA requires greater tooth forces and subsequently less joint force to maintain static equilibrium. In addition the change in LTA also causes a reciprocal reorientation of the joint resistance forces. As LTA is changed from an anterior to a posterior orientation the joint force becomes more anteriorly oriented for all tasks. Molar tasks with more posterior tooth positions and more vertically directed muscle force have a similarly more vertical orientation of joint force than incisal tasks.

The most appropriate comparison of the efficiency of resistance force distribution (JF/TF ratio) of these tasks is where the orientation of tooth resistance was matched with that of the applied muscle force (ANG·L). In these instances the nature of the tooth resistance most closely corresponds with that of the applied muscle force. The two molar clenching tasks (CO and BIMOL) were much more efficient with JF/TF ratios of approximately 1.00 and 0.65 for first and second molar contacts respectively. Similar runs for incisal clenching had significantly less efficient ratios of about 2.30 and 2.50 for stabilized (INCISS) and natural (INCISN) contacts respectively. The biomechanics of more posterior clenching is thus about two to four times more effective in terms of the resistance forces generated with proportionally more occlusal and less joint forces produced.

In all instances, based on the model predictions of joint force, the bearing surfaces of the joints would be expected to be located at the anterosuperior aspect of the condylar heads and vary between 60.0 and 100.0 degrees relative to the occlusal plane. These surfaces would be expected to be capable of withstanding forces of up to about 300 N per side due to molar clenching. Joint forces due to incisal clenching are on the order of 160 N.

2. Unilateral Clenching Tasks

The vertical component of muscle force (MVR) for unilateral canine clenching of about 550 N is relatively greater than the previously described incisal clenching (around 400 N) but significantly less than either the unilateral molar clenching of 840 N, or the bilaterally symmetrical clenches (1000 to 1200 N). This is consistent with the relatively intermediate position of the canine between the incisal and molar positions anteroposteriorly in the lateral plane. Likewise the anteroposterior component of muscle force (MAR) of 100 N is also greater than any of the molar tasks but less than the incisal tasks. This produces an orientation of muscle force directed less anteriorly (at ANG·L of 79.8 degrees) than the incisal functions (64 to 70 degrees) but more anteriorly than the unilateral molar clench and significantly more so than the two bilateral molar clenches. As such it seems apparent that as the tooth position moves more posteriorly the muscle forces become greater in overall magnitude as well as more vertically oriented, in the lateral plane at least.

In the unilateral tasks changing the position of the tooth contacts more laterally from the midline involves an additional rightward component of muscle force (MLR) of 15.8 N at the canine and 15.1 N at the molar which are very similar despite the significant differences between the two positions mediolaterally. As such both the unilateral canine and molar tasks have very similar orientations of the overall muscle force of about 91 degrees (ANG·L) in the frontal plane although their overall total magnitudes of muscle force differ greatly.

As was the case of the bilateral molar and intercuspal clenching a more posterior tooth position for the unilateral molar task results in greater tooth resistance forces as well as less corresponding joint resistance. However, the balancing joint accounts for only one half to one quarter (80 to 120 N) the resistance force of the balancing side which amounts to around 250 N. This is very similar to those forces occurring at both joints of the two bilateral molar tasks. This reduction in joint loading on the working side of unilateral molar tasks corresponds with a greater tooth resistance force of about 450 to 650 N. Although this is slightly less than that of the bilateral molar clenches the significantly reduced overall joint loads of unimolar clenching provide for much more favorable JF/TF ratios (eg. 0.57 at the second molar), i.e. less total residual joint force is produced for relatively more force per tooth during unilateral than bilateral molar clenching.

Variations in the lateral plane orientation of tooth force (LTA) for unilateral tasks also produce similar effects on the joint forces as seen for bilateral tasks. More posteriorly oriented (eg. more vertical) LTA requires greater tooth forces (480 to 580 N) and subsequently less joint force at both joints to maintain static equilibrium at molar and canine contacts. However, the canine clench differs from the molar clench in this regard in that the variation in magnitude of tooth force for the same range of angular change (20 degrees) is only about 15 N. That of the molar is about 100 N. This is due to the more anterior position of the canine which has less applied muscle force and hence smaller tooth forces of around 225 N. In addition the same increment of LTA variation at the canine produces a relatively small change in the moment arm length. This effect is greatly magnified closer to the fulcrum, i.e. molar positions, which also have additional applied muscle force.

In general the joint forces themselves also become more anteriorly oriented with more posterior LTA orientations. However, this effect is also greatly magnified at the right balancing joint of unimolar clenching where the most divergent joint resistance forces arise due to added mediolateral influences of a more lateral tooth (third molar) contact. These resistance forces at this joint can potentially become tensile rather than compressive at the most posterior contact. Nevertheless, the working side joint loads of the unimolar task remain significantly less than those at the balancing joint despite any changes in tooth force orientation. Canine clenching exhibits joint forces of only around 170 N which are quite similar on the two sides but have the working joint slightly more heavily loaded than the balancing side, for the most part.

The effect of varying the tooth resistance orientation in the frontal plane (FTA) produces a reversal of the relation between balancing and working joint force orientations in the lateral plane. These joint orientations (LCA and RCA) change in a reciprocal manner to one another when the tooth force varies in mediolateral nature (with constant left joint frontal angle, LCFA). In the frontal plane the working side joint forces also vary mediolaterally opposite to the change in FTA when this dimension of the tooth force changes, although the relationships between the magnitudes of loading at the two joints remains the same as above (i.e. WS < BS). Nevertheless, the substantial changes in the relationships of the two joint force orientations for variations of mediolateral tooth force reflect the different mechanics of unilateral compared to bilateral contacts. Again, the difference in extent of this effect on both the tooth forces and the joint forces of unilateral molar versus canine clenching is related to the combination of the magnitude of applied muscle force and proximity of tooth contact to the fulcrum as outlined for LTA changes.

Alterations to the left or balancing joint angle of resistance in the frontal plane (LCFA) has a reciprocal effect on the right or working joint resistance orientation. All other variables being equal more laterally oriented joint force on one side would require a more laterally oriented force on the other to maintain equilibrium. Only minor changes in joint force magnitude occur due to this type of variation.

Comparison of the JF/TF ratios of all clenching data with the tooth force orientations matched with those of the applied muscle force shows unilateral molar clenching to have the most favorable relation of joint versus tooth resistance forces of all the clenching tasks analyzed. The unimolar clenching JF/TF ratio was 0.64 compared to 1.50 of the unilateral canine; 2.27 of stabilized incisal clenching (i.e. with stop); 2.47 of natural incisal clenching; 0.68 at the second molar and 1.01 at the first molar of bilateral molar clenching; and 0.96 at the first molar of intercuspal clenching. In other words, this hypothetical individual is capable of generating more functional tooth force with relatively less residual joint loading when clenching unilaterally at a posterior tooth contact point than either bilaterally and/or at more anterior occlusal contact positions.

According to the modeling analysis of unilateral canine and molar clenching the bearing surfaces of the two joints would be expected to be located anterosuperiorly and capable of resisting up to about 300 N of force oriented at 60 to 100 degrees relative to the occlusal plane (i.e. 60 to 85 degrees at the balancing joint and 75 to 100 degrees at the working joint) for unilateral canine clenching. For unimolar clenching these expected orientations would fall within the same range (i.e. 65 to 95 degrees) for the balancing side joint. However, the right or working side joint exhibits, on the one hand, resistance force orientations of about 20 to 120 degrees in this respect which is well outside this range. On the other hand, the magnitudes of these forces are for the most part substantially less than those occurring at the balancing side. Thus the joint morphology would be expected to be capable of resisting more divergent and even tensile forces although at magnitudes less than one half those of maximal joint forces (i.e. less than 150 N).

3. Unilateral Chewing Tasks

Application of this model to the three static intervals near intercuspation of unilateral molar chewing show that the biomechanics involved are very similar to those which would be predicted on the basis of the static molar clenching tasks despite very different contributions from the individual muscle groups. The magnitude of the overall muscle forces generated are less than the unilateral molar clench but greater than unilateral canine clenching. The vertical component varied from 450 N to about 680 N which occurred just prior to intercuspation. The mediolateral component of muscle force was increasingly directed more medially from virtually zero at the first interval to 15 N at the third interval. This corresponds with expected directions of applied effort as intercuspation is reached. The same component of force (15 N) was shown to exist during the unimolar clench but directed laterally. Nevertheless, the orientations of the muscle forces predicted for the unimolar chewing phases, although based on different data, are also strikingly similar to those of the static unimolar clench. The lateral plane orientation was approximately 85 degrees and about 90 degrees in the frontal plane (84 and 91 degrees respectively for the static unimolar clench).

The range of tooth resistance forces of 260 to 460 N is significantly less than that of unimolar (450 to 650 N) but greater the unilateral canine clenching (around 225 N). Variation of both the lateral (LTA) and frontal plane (FTA) orientations of tooth resistance force on the three chewing intervals produce the same effects on tooth force magnitudes seen previously for the unilateral static clenches. Similarly, the joint forces are greater on the balancing than the working side in all three chewing intervals. However the greater lateral components of muscle force for chewing function reduce the range of RCA orientations for variations of both LTA or FTA compared with those observed for the unilateral molar clench. The magnitude of joint forces of the chewing intervals vary from approximately 60 to 105 N at the working side and from 100 to 195 N at the balancing side.

The JF/TF ratios of 0.63 to 0.67 are very favorable suggesting unilateral chewing is as efficient as unimolar clenching with respect to the distribution of resistance forces. However the mechanics of chewing also indicate less variation of joint force orientations and magnitudes with altered tooth force alignment.

The predictions of load-bearing morphology of the joint condyles for these chewing intervals are well within the ranges of the previous static clenching tasks; specifically 160 N of force aligned at 75 to 90 degrees to the occlusal plane.

DISCUSSION

The reliability of the predictions derived from any model of a biomechanical system are directly related to the number of pertinent variables incorporated. Numerous workers have established the importance of the interrelationships of the anatomical variables, specifically the position of the joints and points of tooth contact with respect to presumed muscle force production (Finn et al., 1980; Bramble, 1978; Smith, 1978; DuBrul, 1980;). However very few studies have incorporated all of these variables simultaneously and in three dimensions (Weijs and Dantuma, 1980) and none of them for humans. This model is unique in its ability to incorporate a wide range of the relevant anatomical and physiological (i.e. muscle) parameters which define a mandibular biomechanical system. This flexibility allows comparisons of the mechanics produced by changes to the physiological variables for the same, or similar, anatomical variables as in the case of different tasks of this study. However, this flexibility will also permit comparisons of the effects of changes to the anatomical variables for similar types of functional tasks.

The necessity of including real values for the physiological parameters which determine the relative forces generated by the individual muscles, and therefore the overall total muscle force resultant vector, provides meaningful insights as to how the mandible functions in real terms. This is similar to the studies of Weijs and Dantuma (1980) and Pruim and his coworkers (1980). In these analyses the determinations of tooth and joint forces was not constrained by limitations imposed on muscle force capabilities because the latter were measured directly. Other models, some very recent work, have incorporated artificial contributions of muscle force by hypothesizing some sort of minimization of muscle and/or joint force to effect occlusal loading (Smith _et al._, 1986; Osborn and Baragar, 1986; Hatcher _et al._, 1986; Barbenel, 1969, 1972, 1974, 1983). Although these models represent those few analyses where most of the pertinent muscle groups as well as three dimensional considerations were incorporated the information derived provides only generalities about jaw biomechanics. The model of the present analysis assumes only that the specific values assigned to the muscles is correct for each task from which predictions of joint force and tooth force, and their orientations, are determined. The "minimization" theory of these other models requires many more assumptions since the algorithm itself determines the muscle data.

A. MUSCLE FORCES

There is little data in the literature from which to compare the overall muscle force resultant magnitudes of this study as very few investigators have attempted to determine this force. Schumacher (1961) determined the theoretical maximum clenching force to be 1528 N (156 kg) according to his cross sectional measurements of cadaver specimens. Although this value is of the same order of magnitude of this study Schumacher assumed a total average force potential of 10 kg/cm^2 compared to only 4.1 kg/cm^2 of this model. correction of Schumacher's value according to this criterion would be only about 620 N which is well below the maximum force observed here. In addition however, Weijs and Hillen (1984a) have pointed out that the specimens of

Schumacher were elderly and with little remaining natural dentition. As such the average force produced by such a group would be expected to be less than that of the younger dentate subjects from whom the data for this study were derived. Van Steenberghe and DeVries determined the maximum muscle force to be 2352 N (240 kg) from the data of Carlsoo (1952). Carlsoo used 11 kg/cm^2) as the force constant for muscle and a similar correction reduces this to approximately 870 N of force. This is also in agreement with the model findings.

Pruim et al., (1980) derived the values of muscle force potential per unit area from a number of subjects and found that although the value varied between about 88 and 175 N/cm^2 (9.2 and 17.7 kg/cm^2) for different subjects they remained relatively constant for each subject. This consistency has been reported by others as well although the mean values seem to be closer to about 30 to 50 N/cm^2 according to Weijs and Hillen (1984a). As such the value of 40 N/cm^2 was used in this study.

A summary of the overall muscle force resultant parameters generated during each of the nine functional tasks is presented in Table VI. As can be seen, the tasks with the more posterior position of tooth contact have, in general, relatively greater magnitudes of the vertical component of muscle force (MVR) with correspondingly smaller anterior components (MVR). Subsequently, the overall orientation of the applied muscle force becomes more vertical at tooth positions located more posteriorly (ANG.L). This relationship holds true despite the fact that each of the groups of tasks has significantly different forces from each of the individual muscles contributing to the overall force applied to the mandible (see Tables II and

TABLE VI - SUMMARY OF MUSCLE RESULTANT PARAMETERS. The values are those from the respective Figure 10 to 18 of RESULTS.

	BILATERAL CLENCHING				UNILATERAL CLENCHING		CHEWING		
Muscle Force Variable	Intercuspal (CO)	Bilateral Molar (BIMOL)	Incisal Stop (INCISS)	Incisal Natural (INCISN)	Unilateral Molar (INIMOL)	Unilateral Canine (UNIK9)	Interval 1 (CHEW 1)	Interval 2 (CHEW 2)	Interval 3 (CHEW 3)
MLR	0.0	0.0	0.0	0.0	-15.1	-15.8	-0.4	11.7	15.0
MAR	40.9	57.0	160.8	194.2	87.9	99.7	67.6	54.1	40.2
MVR	1187.6	1039.1	432.3	395.9	839.9	554.0	522.3	676.8	451.3
ANG.L	88.0	86.9	69.6	63.9	84.0	79.8	82.6	85.4	84.9
ANG.F	90.0	90.0	90.0	90.0	91.0	91.6	90.0	89.0	88.1

III of METHODS). The lateral plane orientations of these muscle forces range from about 64 degrees for natural incisal biting to 88 degrees for intercuspation. Tasks utilizing molar contact positions exhibit these orientations at approximately 80 to 90 degrees depending on the task and tooth contact position. These findings are in very good agreement with those of Prium and coworkers (1980). They also found that the overall muscle force resultant of their two dimensional modeling analysis exhibited a more anteriorly directed orientation at more anterior bite positions. As this position of tooth contact was changed from the first premolar to the first molar and the second molar the muscle vector orientation (with respect to the occlusal plane) increased from 79 degrees to about 83 degrees in the lateral plane (Figure 5, Prium <u>et</u> <u>al</u>. 1980).

Moller (1974) has suggested that the number of occlusal contacts is a significant determinant of jaw muscle activity levels. MacDonald and Hannam (1984) concluded from their studies on various types of occlusal contact patterns and positions that a greater number of contacts and thus contact surface area resulted in a generalized increase in muscle activity. This was especially true at anterior positions. More posteriorly, however, the muscle activity was not affected by either the number or area of contact to the same extent.

Since a significant portion of the muscle activity levels used in this study were derived from the work of MacDonald and Hannam (see Table II of METHODS) the differences in the muscle resultant parameters for similar tooth positions may be at least partly due to the different nature of the occlusal contact. For instance, the greatest magnitude of the total muscle force vector of intercuspal clenching (CO) is 1188 N, which would have the greatest number of occlusal contacts of all tasks modelled. Bilateral molar clenching (BIMOL) however produced overall muscle forces of 1040 N. This latter task was modelled with data derived for clenching on occlusal stops at only two contact points (one on each side of the dentition). Likewise the incisal clench with the occlusal stop (INCISS) had a total muscle resultant of 461 N whereas that of incisal clenching on natural contacts (INCISN) was 440 N. It would seem therefore that greater stability of occlusal contact in the system is conducive to greater overall muscle forces. This is certainly true with respect to the vertical component of muscle force. The greater anterior muscle components (MAR) of the less stable occlusal conditions for the same task may reflect a combination of activities by the individual muscle groups to improve the stability of these types of maximal clenching activities. In this regard, a number of workers have suggested that different jaw muscles may provide different functions with respect to their effects on the resistance forces of the mandible with some, like the lateral pterygoid, relegated to only a stabilizing influence (Hatcher et al., 1986; Osborn and Barager, 1985; Pruim et al., 1980). According to Osborn and Baragar (1985) the major muscle groups of the jaw such as superficial masseter, medial pterygoid and some of the temporalis act as "power" muscles which are arranged such that they can maximize the generation of bite force. However, their action creates forces at the joint which would tend to displace the condyle from the articular eminence. To maintain stability in the system the secondary "control" muscles of the lateral pterygoid and oblique portions of the temporalis (eg. posterior temporalis) come in to play. These workers have reasoned that these control muscles are arranged such that they have very poor moment arms for bite force generation but primarily function to prevent instability in the system, especially at the condyles, in an anteroposterior direction. Thus the more anteriorly directed muscle effort of clenches at more anteriorly positioned tooth contacts (see TABLE VI) may be a reflection of the need for an additional anterior stabilizing component for these types of contact. The activity levels of the lateral pterygoid (IP) in Table II of METHODS directly reflect this trend. The more posterior and stable intercuspal position had the lowest level of IP activity whereas incisal clenching had the highest. The fact that the joint forces generated at more anterior tooth contacts were of substantially smaller magnitudes than more posterior contacts would imply that this extra anterior effort produced by the muscles is more involved with maintaining occlusal than condylar stability.

The additional mediolateral components of muscle force of Table VI involved in the unilateral tasks, both clenching and chewing, are very small in magnitude compared to the vertical components. Therefore the frontal plane orientations (ANG·F) remain near vertical. However, it is unlikely that this component contributes much to the stability of the resistance forces of the system. It is more probable that it is merely a residual of the combined effort of all the muscles involved in an asymmetric occlusal function. None of the muscle groups has an alignment conducive to stabilizing mediolateral forces at either the teeth or the joints. However, it is interesting to note the increasingly medial component of muscle force of Table VI occuring close to intercuspation (which occurred between Intervals 2 and 3). This would be expected as the mandible progresses through the power phase of chewing towards the more medial position of intercuspation with increasing bite force. Osborn (1982) has suggested that the alignment, or inclination, of the molar teeth in the frontal plane is such as to resist the tilting forces acting on the teeth during the power stroke of mastication. In the frontal plane these resistance forces on the lower molar teeth of the working side would be directed laterally and inferiorly opposite to the direction of applied muscle force observed in this study. Therefore more posterior molar teeth which undergo relatively heavier occlusal loads would be expected to have their long axes aligned correspondingly more medial which is generally observed in human dentitions (Osborn, 1982). Osborn and Baragar (1985) have extended this argument to suggest that the contributions of force from each of the jaw muscles is coordinated by the periodontal receptors in such a way as to produce a bite force aligned with the long axis of the roots of the teeth. Therefore, in order to minimize the torques on the dentition the data would predict the long axes of the respective mandibular teeth to generally correspond with these alignments. Thus, incisors would be relatively more anteriorly oriented with more posterior teeth being closer to vertical as well as more medially aligned. Analysis of the direct measurements of the direction of incisal biting by Hylander (1978) show that these forces lie between approximately 60 to 80 degrees with respect to the occlusal plane. If it is assumed from the above discussion that the orientation of tooth resistance force coincides with that of the applied muscle force then the orientations of the latter from this study agree well with those which would have been predicted from Hylander's data. Osborn (1982), and Baragar and

Osborn (1986), implicate this effect as the reason for the establishment of the curve of Spee which is a consistent feature, in the sagittal plane, of human dentitions. The additional medial component of muscle force generated during the power stroke of chewing would produce a similar torque on the teeth, especially at more posterior positions where relatively more occlusal force can be generated. This would be greatly minimized by medial alignments, especially posteriorly, of the teeth themselves. Such an adaptation would possibly explain the existance of the curve of Wilson in the frontal plane, and as Osborn (1982) has suggested, when all three dimensions are considered, the curve of Monson. It would seem, therefore, that the orientations of muscle force generated by the mandibular system observed in this study may reflect a relatively consistent phenomenon.

It is likely that for at least the natural incisal clenches the activity levels of MacDonald and Hannam (1984) may have incorporated some slight anterior repositioning of the jaw from the intercuspal position in order to effect the proper incisal contact. Although this may not have had a significant affect on the individual muscle activities per se, as concluded by these authors, their combined effects may have produced some possible variation in overall muscle force due to a shift in the working lines of the muscles (Weijs, 1980). Changes in either the relative position of muscle attachment points by as little as 6.5 mm and their orientations by 5 degrees have been shown by Hatcher and coworkers (1986) to produce significant variation in both occlusal and joint loads (up to 20 percent in their study) derived by similar mathematical analysis. The assumptions used in this study, as well as by most other investigators of jaw biomechanics (Weijs and

Dantuma, 1981), that an individual muscle can be considered as a single straight line element from the centers of its attachment areas is a necessary one. However the type of variation observed by Hatcher et al. point out the problems associated with this type of simplification (Throckmorton et al., 1980). Large areas of attachment with variations in density of muscle fiber insertion can affect the position of the true centroid of attachment (Weijs, 1980). As such, the extent of flexibility of this model in accommodating these types of variations and allowing analysis of a wide range of such possibilities becomes an important consideration.

An additional complication not generally considered in modelling analyses is the internal architecture of the muscles themselves. Pennate muscles with dissimilar alignments of groups of fibers within the same muscle can redistribute the applied force over the area of muscle attachments. Weijs and Hillen (1984a) determined that all four of the major jaw muscle groups exhibit some degree of pennation, especially the medial pterygoid and temporalis muscles. These workers have also pointed out that pennation can also contribute to underestimations of muscle cross sectional areas.

Heterogeneity in the firing behavior of groups of fibers within a muscle further complicates this problem (Herring and Grimm, 1979) although to a lesser extent for maximal clenching activities than chewing behaviour (Weijs, 1980; Pruim et al., 1980; Hylander, 1979c). Although such problems can be overcome by detailed consideration of jaw muscle architecture (Osborn and Baragar, 1985; Baron and Debussy, 1979) the reality of modelling human jaw biomechanics and the problems associated with recording muscle activity levels and determining precise attachment points and cross sectional areas limits the incorporation of all of these variables.

Nevertheless, it is noteworthy that the muscle force resultant parameters of Table VI exhibit generally consistent trends with respect to muscle force orientations and magnitudes for both the clenching tasks and chewing phases. The importance of this becomes more obvious when it is remembered that the sources of data used to determine the individual muscle force vectors for these two different types of function were, themselves, very different. The activity levels of the clenching tasks were nearly all derived from studies conducted in our lab (see Table II) whereas those of chewing were from the earlier works of Moller (1966).

B. TOOTH FORCES

Table VII summarizes the tooth force predictions of this study for those instances where the orientations of the tooth resistance force corresponded with the muscle resultant force for each respective task.

It is well established that greater occlusal loads generally occur at more posterior positions along the dental arch where the morphology of the dentition is more conducive to resisting larger loads. When the mandible functions as a bilaterally symmetrical unit, as it does in the CO, BIMOL, INCISS and INCISN tasks of this study, simple lever mechanics have been assumed by a great many workers to govern the forces of the mandible (Tradowsky and Dworkin, 1982; Finn _et al_., 1980a and b; Throckmorton _et al_., 1980; Hylander, 1978; Dubrul, 1974; Gosen, 1974; Turnbull, 1970; Crompton and Hiiemae, 1969; Seitlin, 1968; Davis, 1964; Mainland and Hiltz, 1933;

Gysi, 1920). Most of these analyses have predicted that for posterior points of tooth contact the mandible can generate correspondingly greater tooth forces due to shortening of the relative length of the moment arm at these positions. These predictions have frequently ignored potential changes in muscle activation levels for differing occlusal contacts or functions. Such was the case of the CO task of this analysis where only the position of the assumed center of tooth contact was varied. Consequently the TR magnitude shows a continuous increase from 556.2 N at the second premolar to 866.4 N at the third molar. Osborn and Barager (1985) observed a similar trend using the data of Pruim et al. (1980) to derive muscle activities and force contributions although the magnitudes of occlusal load seem somewhat high. They were 686 N (70 kg) at the incisor, 833N (85 kg) at the first premolar, 1029 N (105 kg) at the first molar and 1715 N (175 kg) at the third.

The only direct measurements of tooth loads near centric occlusion are those of Lundgren and Laurell (1986) who found the total mean maximal bite force under this condition to be only 320 N (± 117). Their study minimized disclusion of the jaws to a mere 1.5 mm at the incisors by incorporating transducers in fixed bridge pontics at four positions in one arch (maxillary). However, the periodontal support provided to the apparatus in these individuals was apparently very much compromised. Therefore it is not surprising such low values for this task were observed. Similarily low forces were found for maximal unilateral biting forces at anterior and posterior positions.

Comparison of the bilateral incisal (INCISS and INCISN) and molar tasks (CO and BIMOL) of this study have shown the muscle activity levels, which

TABLE VII - SUMMARY OF RESULTANT TOOTH RESISTANCE FORCE PARAMETERS. This data is from the modeling runs where the lateral (LTA) and frontal plane (FTA) orientations were designated to correspond with the respective orientations of applied muscle force for each task. The figures from which this data is taken are indicated for reference. Abbreviations are as per previously.

		TOOTH RESISTANCE FORCE PARAMETERS			
Task	Tooth Pos'n	LTA (degrees)	TR (N)	FTA (degrees)	Source Figure
CO	5	88.0	556.2	90.0	Figure 10B, Run 1
	6		605.6		" Run 2
	7		723.9		" Run 3
	8		866.4		" Run 4
BIMOL	6	86.9	518.3	90.0	" 11B, Run 2
	7	618.5	518.3	90.0	" 11C, Run 3
INCISS	1	69.6	141.2	90.0	" 12B, Run 3
INCISN	1	63.9	126.9	90.0	" 13B, Run 3
UNIK9	43	79.8	226.8	91.6	" 14B, Run 3
UNIMOL	46/47	84.0	515.5	91.0	" 15B, Run 3
CHEW 1	47	83.0	314.7	90.0	" 16B, Run 3
2	47	85.0	416.3	89.0	" 17B, Run 3
3	47	85.0	276.2	88.0	" 18B, Run 3

produce their respective overall muscle resultant forces, to be very different as well. Incisal clenching has lower overall muscle resultant forces which were also more anteriorly oriented. It is therefore apparent that the increase in tooth loads more posteriorly must be due to the combined effects of more favorable mechanics as well as more favorable muscle activation levels depending upon the function. Consequently the magnitudes of incisal tooth forces are much less than those of these bilateral molar tasks.

Direct measurements of incisal bite forces by other investigators in Table VIII show notable consistency in the range of mean magnitudes observed from about 100 to 300 N despite a wide range of correlates, subject types and techniques. Finn et al. (1980) compared differences in facial height whereas Helkimo et al. (1975 and 1976) observed a similar range of forces depending on the state of dentition, the extent of tooth wear, or the presence of joint dysfunction. The two studies which do not coincide with the general range of incisal bite forces are those of Osborn and Baragar (1986) and Hylander (1978). Osborn and Baragar however, did not measure the occlusal force directly but mathematically derived it according to their computer assisted model of mandibular biomechanics. They used the muscle activity levels of Pruim et al. (1980) for this derivation. Hylander was not attempting to determine maximal incisal forces but was more interested in their orientations. These were found to lie between 60 to 80 degrees with respect to the occlusal plane (Gingerich, 1979) which agrees very well with the data of this model analysis. The magnitudes of maximal incisal force produced by the model in this study are also consistent with the previous values found in the literature (see Tables VII and VIII). The most prominent factor contributing to less tooth resistance force at the incisors than at more posterior positions was the differences in the overall muscle resultant vectors and not simply less favorable lever type mechanics mentioned earlier.

Pruim et al. (1980) measured the maximal bite forces bilaterally at the first premolar and the first and second molar positions. The mean levels were determined to be 633 N ($\pm$ 210) at the premolar, 965 N ($\pm$ 276) at the first molar but only 756 N ($\pm$ 289) at the second molar. The tooth resistance forces of BIMOL and CO of this study correspond reasonably well with these ranges. However, Pruim and coworkers recorded a substantial and consistent decrease in the activity levels of the muscles (masseter, temporalis and digastric) during contact at the second molar producing the observed decrease in tooth load at this position. They have attributed joint inhibition as the controlling influence on the reduced tooth force at the second molar. They also proposed that more posterior occlusal contacts may have the muscle force resultant very near the bite position requiring more accurate control of the equilibrium. Hence the reduced muscle activities and resulting increase in tooth force at the second molar.

Tradowsky and Dworkin (1982) have proposed that an equilibrium point of mandibular titling exists along the dentition such that the biomechanics of the mandible are different posterior to this position than anterior to it. They found that the mandible tilts to produce tension on the joints at the posterior positions. If such events do occur then they would certainly support, although indirectly, some sort of inhibitory effect from the joints.

TABLE VIII - PREVIOUS INCISAL BITE FORCE DETERMINATIONS. All units have been converted to Newtons of force. The data for different sexes has been combined here and all are assumed to be at maximal effort except where noted.

Authors	Mean (N)	Range (N)	Relevant Factors
Osborn and Baragar, 1986	686	not given	mathematically derived (n = 0)
Finn *et. al.*, 1980	145	not given	long face/skeletal open bite (n = 5)
	286	not given	short face/skeletal deep bite (n = 6)
Helkimo and Ingervall, 1978	190	34-459	non-maximal effort (n = 100) 5 mm opening)
Hylander, 1978	53	28-91	10 mm opening non-maximal effort (n = 10)
	48	19-91	30 mm opening non-maximal effort (n = 10)
	28	22-36	20 mm opening non-maximal effort (n = 10)
Mansour, 1977	209	not given	approx. 5 mm opening (n = 6)
Helkimo *et. al.*, 1976	172	1-44	approx. 5 mm opening 9 (n = 78)
Helkimo *et. al*, 1975	196	not given	normal group (n = 36)
	127		joint dysfunction pretreatment (n = 30)
	147		joint dysfunctions posttreatment (n = 30)
Mansour and Reynik, 1975	100	not given	6 mm opening (n = 1)
Rugh and Solberg, 1972	162	not given	7 mm opening
Ringquist, 1973	293	200-448	6 mm opening (n = 29)
Linderholme and Warnstrom, 1970	206	S.D.=83	15 mm opening (n = 20)
Howell and Manly, 1948	178	130-235	(n = 4)

(Grand Mean of all studies = 170 N)

Furthermore, the results of this present study show that if the orientation of LTA becomes more anterior, for whatever reason, the joint forces not only become reoriented more posteriorly but increase in magnitude as well (eg. Figure 10C, 11B and 11C).

The splint arrangement housing the force transducers of Pruim et al. separated the dentition by about 6 mm from intercuspation at the second molars and about 11 mm at the premolars (Prium et al. 1978). Increasing the vertical dimension has a number of effects. First of all the muscle fibers become elongated reducing the overlap of their fibrils and thereby reducing the active tension of the muscle from its maximum which is at its resting length near intercuspation (Finn et al., 1980). Secondly, as depicted in Figure 19 this will reorient the alignment of the long axes of the mandibular teeth more anteriorly from A to B. If the system attempts to maintain the same alignment of occlusal load with respect to the mandibular dentition this will produce a more anterior orientation of the resulting tooth force (B) and according to the model an increase in joint force magnitude. This joint force will also be aligned more posteriorly. Comparison of Figures 11B and 11C for BIMOL at the first and second molar contacts show that although more posterior contacts have lower joint force magnitudes, the effect of this type of change on the orientation of joint force may be more significant.

Conversely, if the system maintains, or attempts to maintain, the same alignment of occlusal load at the maxillary dentition then tilting the occlusal plane at wider opening would cause the occlusal load to become more posteriorly aligned with respect to the mandibular teeth as well as more posteriorly positioned (C of Figure 19). This changes the mechanics of the

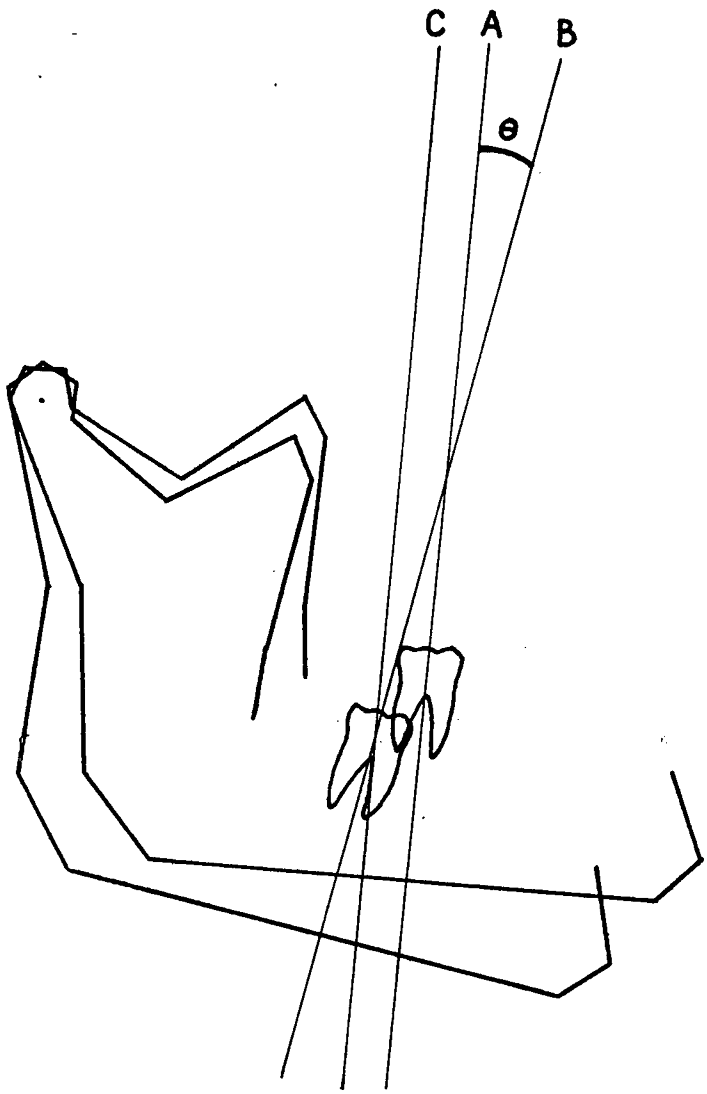


Figure 19. EFFECT OF INCREASING VERTICAL DIMENSION ON TOOTH FORCE. The angle θ denotes the angular change to the system whereas A, B and C indicate potential changes to the tooth force.

whole system to a greater extent. Finn et al. (1980) and Throckmorton et al. (1980) have shown that alterations to the vertical position of the occlusal plane changes the mechanical advantage of the muscles in addition to reducing their maximum potential force development due to fiber elongation. Individuals referred to by these workers as having short faces and a deep bite generally have improved mechanical advantage due to shorter moment arms for bite force and generally longer moment arms for the muscles. Thus, greater bite forces are produced for relatively less muscle effort. Individuals with a skeletal open bite and long facial types have a less efficient mechanical arrangement of their mandibular components and cannot generate nearly as much occlusal force as normal or short facial types (Finn et al., 1980; Proffit et al., 1983a and b; Sassouni, 1969). Consequently under static conditions any device between the teeth which separates them much beyond the intercuspal or rest position effectively alters the mechanical relationships of the system and may reduce the potential tooth force production, especially at relatively more posterior positions of contact.

This effect may not be limited to bilateral mechanics however. Although Mansour and Reynik (1975) noticed a ten percent increase in maximal bite force at the second compared to the first molar there was a decline in the average moment of fifteen percent. They therefore concluded that different mechanical relationships existed at tooth positions distal to the first molar (i.e. Class II compared to Class III lever mechanics). However, consideration of the results of this modelling analysis implicates other possibilities regarding changes to the mechanics of the system due to increasing the vertical dimension. The apparatus of Mansour and Reynik was 6 mm in vertical height. Therefore at the second molar the jaws would have been much more widely opened than at the incisors. As was just described wide opening may cause a reorganization of the mechanics of static biting due to a reorientation and repositioning of the occlusal force with respect to the occlusal plane and the joints. If the overall muscle resultant force remained constant, or nearly so, as compared to a more closed mandibular position the situation seen in Figure 19 may again be representative of the mechanics at play. Note that the position of tooth loading has become more posterior from position A to C due to the inferior jaw position. This same type of interplay was previously observed in Figure 15B. Changing the position of tooth contact more posteriorly in this task was sufficient to produce a tensile force at the ipsilateral joint. If the joint has a regulatory role in mandibular biomechanics as proposed by Pruim et al. (1980) then biting at more posterior positions with increased vertical dimension may produce lower tooth loads due to an inhibitory effect on muscle activation levels.

Mansour apparently took this into account in a subsequent paper (1977) where the vertical dimension was kept constant for measurements of maximal biting force at each tooth position. In this study the mean maximum vertical biting force progressively increased from incisor to third molar. Averaged here between the right and left sides these forces were:

Tooth Position	1	2	3	4	5	6	7	8
Force (N)	209	229	291	485	568	690	735	796

It is of interest to note that although the differences were not statistically significant Proffit et al. (1983a and b) found greater mean occlusal forces to occur at 6 mm than at 2.5 mm of molar separation for both normal and long facial types. The mean values for maximal bite force are given in Table IX although this finding was also consistent for both swallowing and chewing in adults as well as children. This is not consistent with the preceding argument. However, it has been shown by other workers that the maximal bite force which an individual can generate increases with practice (Linderholme and Wennstrom, 1970; Van Steenberghe and De Vries, 1978). The results of maximal biting at the 6 mm position of Proffit and company were recorded after the series of tests at the 2.5 mm position which may have played a part.

In any event the magnitude of unilateral molar clenching of 515.5 N (see Table VII) derived by the model conforms well with the averages and ranges observed by other workers summarized in Table IX. Similarily the unilateral canine forces of this study (226.8 N, see Table VII) compare extremely well with the average magnitudes reported by Mansour (1977) of 291 N and of Van Steenberghe and De Vries (1978) of 279 N at this tooth position. Table X lists the average maximal loads measured by these workers as well as those of other workers at the premolar positions which are included for comparison. The results of the model predict that tooth resistance forces at the more posterior premolar positions would be greater than those at the canine due to more favorable mechanics and a relatively greater overall muscle force vector. The data of this study and Table X also bear this out.

TABLE IX - PREVIOUS UNILATERAL MOLAR BITE FORCE DETERMINATIONS. All measurements described as at the first molar unless noted. Data from different sexes has been combined and all units converted to Newtons of force.

Authors	Mean (N)	Range (N)	Relevant Factors
Lundgren and Laurell, 1986	211	S.D.=77	1.5 mm opening, single posterior point contact (n = 12)
Osborn and Baragar, 1986	1029	-	first molar, mathematically derived (n = 0)
	1715	-	third molar, mathematically derived (n = 0)
Proffit *et. al*., 1983	304	S.D.=196	normal adults at 2.5 mm opening (n = 21)
	350	S.D.=183	normal adults at 6.0 mm opening (n = 21)
	110	S.D.=77	long face adults at 2.5 mm opening (n = 19)
	152	S.D=103	long face adults at 6.0 mm opening (n = 19)
Proffit and Fields, 1983	171	S.D.=188	normal children at 2.5 mm opening (n = 18)
	152	S.D.=139	normal children at 6.0 mm opening (n = 18)
	98	S.D.=58	long face children at 2.5 mm opening (n = 12)
	119	S.D.=101	long face children at 6.0 mm opening (n = 12)
Finn *et. al*., 1983	299	not given	long face, 10 mm opening at "molar" (n = 8)
	706	not given	short face, 10 mm opening at "molar" (n = 6)
Finn, 1978	569	not given	normal face, 10 mm opening
	293		long face,
Helkimo and Ingervall, 1978	471	191-802	non-maximal effort, 5 mm opening (n = 100)
	728	617-882	strong group effort, 5 mm opening (n = 25)
	380	206-461	weak group effort, 5 mm opening (n = 25)

Authors	Mean (N)	Range (N)	Relevant Factors
Helkimo et. al., 1976	400	98-715	5 mm opening (n = 44)
Helkimo et. al., 1975	411	not given	normal group, 5 mm opening (n = 23)
	264	not given	joint dysfunction, pretreatment (n = 30)
	353	not given	joint dysfunction, post treatment
Mansour, 1977	690	S.D. = 38	first molar, approx. 5 mm opening (n = 6)
	735	S.D. = 46	second molar, approx. 5 mm opening (n = 6)
	796	S.D. = 40	third molar, approx. 5 mm opening (n = 6)
Mansour and Reynik, 1975	774	not given	first molar, 6 mm opening (n = 1)
	842		second molar, 6 mm opening (n = 1)
Ringquist, 1973	467	302-679	4 mm opening at "molars" (n = 29)
Rugh and Solberg, 1972	363	not given	7 mm opening at "molars" (n = 19)
Linderholme and Warnstrom, 1970	450	S.D. =107	15 mm opening at "molars" (n = 72)
White, 1967	731	not given	4.5 mm opening at "molars" (n = 83)
Jenkins, 1966	1372	up to 1568!	Inuit subjects
Howell and Manly, 1948	-	405-882	(n = 4)

(Grand mean of all studies = 516 N)

Relatively little data is available as to the tooth loads generated during mastication. What is available is not easily compared owing to differences in food types as well as experimental techniques. Some of the previous analyses suggest that the levels of magnitude for the chewing phases of this study are quite high. Other studies, on the other hand, report findings which suggest the force levels of the model for the data incorporated are appropriate. DeBoever _et al_. (1978) observed less than 20 N of average force during unilateral chewing of a variety of food types in three subjects. Their study utilized a force transducer arrangement incorporated into removable partial dentures. The maximum level observed was about 60 N. Anderson (1956 a and b) used a fixed inlay with attached strain gauges and found chewing forces up to about 140 N, averaging around 100 N depending on food type. Lundgren and Laurell (1986) recorded similar total force levels (109 N) from their bridge transducer apparatus. These magnitudes were totals of force occuring at four simultaneous points of contact at or very near the intercuspal position. A given single point of posterior contact exhibited a mean force of 52 N ($\pm$ 33) which was the greatest of their study. It has been shown that the ability of the mandibular system to produce occlusal force decreases with a decline in numbers of teeth and overall state of the dentition (Helkimo _et al_., 1976). The state of the dentition of subjects in these workers' studies appeared to be significantly compromised. Similar considerations may have contributed to the findings of DeBoever _et al_. as they had a prerequisite for their subject group of at least two adjacent teeth missing. Nevertheless, similar magnitudes of chewing force have also been reported by Graf _et al_. (1974) who

TABLE X - PREVIOUS UNILATERAL CANINE AND PREMOLAR BITE FORCE DETERMINATIONS. As per Tables VIII and XI.

Authors	Mean (N)	Range (N)	Relevant Factors
Van Steenberghe and DeVries, 1978	279	123-588	Canine, 10 mm opening (n = 9) (mean calculated from their data)
Mansour, 1977	291	S.D.=25	Canine, approx. 5 mm opening (n = 6)
Lundgren and Laurell, 1986	126	S.D.=50	"anterior" (premolar), 1.5 mm opening (n = 12)
Mansour and Reynik, 1975	347	not given	first premolar, 6 mm opening (n = 1)
Rugh and Solberg, 1972	294	not given	first premolar, 7 mm opening (n = 19)
Linderholme and Wennstrom, 1970	372	S.D.=111	"premolars", 15 mm opening (n = 72)

measured these forces at the first molar in three dimensions. They found the axial (vertical) loads to be greatest with mediolateral components secondary. There was both an initial laterally directed (facial) load which became medially directed as the axial force increased, agreeing with the FTA orientations assigned to the three chewing phases of this study. However, Graf, et al. noted a pronounced posteriorly directed component, which is opposite to the anterior component of LTA of this study initially assumed as the tooth force orientation to parallel that of the overall muscle vector resultant. This finding takes on greater significance when the effect of altering LTA is considered. As these results have consistently shown, when the tooth force orientation in the lateral plane becomes more posterior the magnitude of this force increases for the same muscle effort. At the same time the total magnitude of joint force resistance decreases. In terms of the amount of useful tooth force compared to residual joint force (JF/TF ratio), a more posterior alignment of the tooth force, as found by Graf et al. is more sound in terms of mechanics. However, just how it would be possible for the mandibular system to reorient the angles of tooth force to maximize this type of mechanical benefit without reorienting the direction of muscle force is not clear.

The only studies which have reported tooth resistance forces of magnitudes comparable to the chewing intervals of this study are those of Helkimo and Ingervall (1978) and Gibbs et al. (1981). The former investigators indirectly measured these force levels for simulated chewing and reported a mean level of 246 N with a range from 67 to 532 N at the molars. Likewise, Gibbs et al. used an indirect technique of sound transmission to find a mean maximum chewing of up to 360 N for hard foods and 240 N for soft foods. Unlike Helkimo and Ingervall the latter workers determined these forces at the intercuspal position where the greatest forces are generally agreed to occur in chewing (eg. Moller, 1966). These findings also corroborate the results derived by this model. However, they reflect the total amount of occlusal force at all points of contact in the dentition. The modelling results are determined according to a single point of tooth contact. Both sides of the dentition have been shown to be involved in distributing the force of occlusal loading during chewing (Lundgren and Laurell, 1986; DeBoever _et al_., 1978; Graf _et al_., 1974). Therefore the results of this study may more accurately reflect the amount of tooth force if the dentition was only able to contact at a single point. When the resistance forces at the teeth become distributed over a surface of contact, or multiple asymmetric contacts, the mechanics may differ (Bramble, 1978).

C. JOINT FORCES

At the present time there are no other studies which have determined reliable estimates of the actual magnitudes and three dimensional orientation of the joint forces in humans during static function (Smith _et al_. 1986). The information which is available is mostly based on analyses of incomplete variables or highly artificial parameters. Unlike the models which have been presented for the rabbit (Weijs and Dantuma, 1980) and the rat (Weijs and Dantuma, 1975) virtually all the previous modelling analyses of human jaw mechanics have incorporated arbitrary, or at best, artificial magnitudes of individual muscle forces and often neglect asymmetrical considerations of jaw function (Gysi, 1921; Mainland and Hiltz, 1933; Craddock, 1951; Roydhouse, 1955; Gingerich, 1971 and 1979; Barbenel 1969, 1972, 1974 and 1983; Osborn and Baragar, 1986). Even those analyses which do consider unilateral functions are of little comparative usefulness for these same reasons (Hekneby, 1974; Smith, 1978; Smith et al., 1986; Hatcher et al., 1986). It is sufficient to say that there is general agreement among previous investigators using modelling approaches that resistance forces do occur at the joints. Their studies have generally shown that in order for the statics of the system to balance and remain in equilibrium the joints must contribute some degree of loading depending upon the position of tooth resistance. Indications from these previous model analyses would also imply that this is the case for virtually any applied muscle force. The results of the present study show clearly that for the static functions modelled the joints are indeed loaded, and to a greater or lesser extent depending upon the specific task.

Simple lever mechanics have been the basis of most of the previous models of jaw mechanics of humans as well as a variety of other creatures, at least in the two dimensional sagittal plane. Predictions from this type of analysis produce greater magnitudes of joint force at more anterior positions of tooth resistance. However this is based on the assumption of a constant muscle force applied to the system. Such a situation occurs in the intercuspal (CO) clenching of Table XI which summarizes the joint resistance force data when tooth force and overall muscle resultant force were aligned parallel. In this task the muscle force remained artificially constant for changes to tooth position. Because the tooth resistance force decreases

TABLE XI - SUMMARY OF RESULTANT JOINT RESISTANCE FORCE VECTORS. Joint resistance force orientations and magnitudes for the runs of each task with tooth and overall muscle force vectors aligned parallel as in Table X.

		Lateral Plane Resultant Vector Orientations (degrees)		Resultant Vector Magnitudes (N)		Frontal Plane Resultant Vector Orientations (degrees)		
Task	Tooth Pos'n	RCA	LCA	RCR	LCR	RCA	LCA	Source Figure
CO	5	88.0	88.0	316.1	316.0	90.0	90.0	Figure 10B, Run 1
	6			219.4	291.3			" Run 2
	7			323.2	232.2			" Run 3
	8			161.0	160.9			" Run 4
BIMOL	6	86.9	86.9	261.2	261.2			" 11B, Run 2
	7			211.1	211.0			" 11C, Run 3
INCISS	1	69.6	69.6	160.0	160.0			" 12B, Run 3
INCISS	1	63.9	63.9	157.0	157.0			" 13B, Run 3
UNIK9	43	86.8	72.7	171.2	167.8	93.2	90.0	" 15C, Run 3
UNIMOL	47	89.8	82.4	73.9	256.0	94.8	90.0	" 14B, Run 3
CHEW	1	84.3	81.1	61.0	151.1	90.4	90.0	" 16B, Run 3
CHEW	2	80.9	89.6	105.5	158.1	87.6	90.0	" 17B, Run 3
CHEW	3	77.3	90.7	78.6	99.8	86.0	90.0	" 18B, Run 3

anteriorly the joints must contribute more resistance force themselves in order for the system to remain in equilibrium.

Generally, however, the present results have also shown that a change in tooth contact position produces a change in the overall muscle resultant vector. The more anterior positions of tooth contact produce less rather than more overall joint resistance, as comparison of joint forces during bilateral molar tasks with those of incisal functions indicates. This is due to the decrease in muscle activity levels at more anterior positions. As a consequence the present results do not support simple lever mechanics as an approximation of mandibular jaw function without adequate consideration of the overall muscle resultant force as well.

The work of Pruim et al. (1980) appears to be the only previous study predicting human joint force magnitudes from an analysis which included individual muscle vector determinations. They found that the maximal joint forces during maximum clenching at the first premolar were of nearly the same magnitude as when clenching at the first molar, despite the fact that the muscle forces of the former were reduced. They concluded that a more anterior position of tooth contact can therefore produce greater joint forces, similar to the predictions of simple lever mechanics. However they also concluded that the primary determinants of the joint and tooth resistance forces are the activity levels of the muscle groups. The average magnitudes of these joint forces derived from their data (n = 7) are approximately 540 N per joint for the first premolar position, 545 N for the first molar, and 300 N for the second molar position. These varied from about 400 to over 1100 N per joint. Correction of their intrinsic muscle force value from 13.7 N/cm^2 to 4.0 N/cm^2 of this analysis puts their range between about 114 to 314 N per joint corresponding well with this study.

As has been mentioned in the previous section Prium *et al.* attributed the reduction in muscle activity to joint inhibition at the first premolar. Their results imply that the level of joint force during maximal clenching on their apparatus at the first molar may have been the maximum allowable by the regulatory factors controlling jaw biomechanics. The reduction in tooth force which these workers observed at the more posterior second molar produced a corresponding decrease in joint force as well. Pruim *et al.* attributed this to a need for more control over the mechanical equilibrium due to close proximity of the overall muscle force resultant to the bite position. Their subjects all found bilateral clenching on the second molar uncomfortable, implying that perhaps a tendency may exist for instability in the joints to occur for this type of function. The reduction in overall muscle effort has been suggested as an attempt to lessen this instability.

Osborn and Baragar (1985) have suggested that the "control" muscles of their analysis are responsible for maintaining stable joint loading on the load-bearing surfaces of the condylar head and articular eminence. Reduced overall muscle effort, when this instability occurs, permits these weaker muscle groups (i.e. lateral pterygoid and posterior temporalis) to maintain the position of the condyle surface on the inclined plane of the eminence without displacement.

The equilibrium point of Tradowsky *et al.* (1981 and 1982) was essentially the same as Prium *et al.* However, the former investigators concluded that tilting of the mandible occurs about the dental equilibrium point. This would implicate the possibility of joint unloading during such bilateral clenches. Ito _et al_., (1986) have recently measured this change in condyle position for bilateral molar clenching. Their results suggest that the condyle may move slightly inferiorly during this task. The joint forces of bilateral molar clenching derived from the model do not support this finding, however. Both intercuspal and bimolar tasks had joint force orientations such that if any movement were to occur the joints would tend to move superiorly at approximately 70 to 100 degrees relative to the occlusal plane, depending on the angle of tooth force (LTA). The intercuspal clenching tasks of Ito _et al_., on the other hand, do suggest this direction of joint loading as well. It should be pointed out, however, that Ito _et al_., did not consider the effects of bending or distortion of the mandible under their isometric conditions. Considering that the amount of joint movement during these functions was only about 0.03 to 0.07 mm it would seem possible for the displacement they measured, to be merely an artifact of bone bending.

Although very minor amounts of displacement occurred for the bilateral posterior or intercuspal clenches of Ito _et al_. the incisal clench did exhibit significantly more movement. This condition was very similar to the stabilized incisal clench of this study (INCISN). Their results indicate a movement of about 0.6 mm at an angle of approximately 67 degrees, assuming their coordinate system is aligned relative to the occlusal plane. This compares very favourably with the same orientation of joint force from this study (see Table XI). However, Ito and company concluded that temporo mandibular joint loading increases when posterior tooth support is removed. They proposed that where posterior support is present it effectively protects the joints from heavy loading forces by redistributing more of the total resistance force to the dentition. The results of the present model disagree with this as relatively greater joint resistance forces occurred for the posterior points of tooth contact, especially CO. However, this discrepancy again points out the fact that the model only considers single point contacts at the teeth, and not actual surfaces or multiple contacts. Such is certainly not the case of intercuspal clenching, especially with an interocclusal splint (Ito et al., 1986). Therefore the joint resistance forces of intercuspal clenching (CO) from the model analysis are really predictions of the joint and tooth loads as they would occur if the muscles were as active as intercuspal clenching but only a single position of tooth contact were present. As has been shown by this study a change in occlusal contact pattern produces a change in the overall muscle force resultant due to differential activities of the individual muscle groups (MacDonald and Hannam, 1984a and b; Moller, 1966). Therefore changing the position of tooth contact in the intercuspal task without also producing a different overall muscle force seems unlikely. The predictions of joint and tooth resistance forces of the CO task are therefore of limited value.

However, the notion that joint inhibition may limit muscle activity levels and the overall muscle resultant force, which thereby also limits occlusal resistance forces, may be important (Wook and Tobias, 1984). If the dentition does, in fact, contribute to a reduction of the load at the joints then a very worn occlusal scheme with reduced vertical dimension would reposition the condyles more superiorly as well. This would be expected to produce increased forces at the joints. In order to compensate for this the joints would be expected to undergo adaptive changes due to this increased loading. Observations of tooth attrition and joint morphology suggest this may occur (Hinton, 1981; Seward, 1976). Similarly, a reduction in the numbers of teeth, especially posteriorly, have been shown to produce the same effect (Osberg et al., 1970; Moffet et al., 1964). Pathosis such as that manifested by Temporomandibular Joint Dysfunction Syndrome is one well known outcome of a dentition with compromised posterior support (Roberts, 1974), or occlusal disharmonies (Storey, 1981; Seitlin, 1968) which alter the mandibular mechanics from that genetically dictated as most efficient.

Unilateral functions, or at least those with more limited tooth contact, are perhaps more appropriately analyzed by this model. Unilateral canine clenching produced joint resistance forces which were very similar on the two sides despite some differences in muscle activities. However the unimolar clenching exhibited much more diversity in muscle activation between the two sides as well as generally higher levels, especially on the working side (see Table II). The model predictions consistently show that the balancing side joint exhibits greater compressive forces than the working joint during the unilateral molar clench as well as during the three intervals of chewing analyzed. The extent of the difference varies according to the difference in muscle forces. Similar findings have been reported by a number of other workers using theoretical considerations (Hatcher et al., 1986; Smith et al., 1986; Smith, 1978; Walker, 1978; Hylander, 1975; Gysi, 1921). Unfortunately there are no estimates of actual joint force magnitudes for humans anywhere in the literature for comparison.

The work of Ito et al. (1986) provides the only indication of the differential loading of the two temporomandibular joints during unilateral functions from direct observation of humans. They found the balancing condyle to move in an anterosuperior direction (about 40 degrees from their data) whereas the working side condyle moved inferiorly as well as posteriorly (about 215 degrees) for unilateral molar contact. This suggests the balancing condyle was loaded under compression similar to UNIMOL and the chewing data of the model. The working condyle, however, was distracted or loaded under tension. This finding is consistent with clinical and experimental observations by other workers (Hawthorn, 1984; Koivumaa, 1961). Smith et al. (1986) utilized a mathematical "minimization" model of human joint loading similar to those previously discussed (Osborn and Baragar, 1985; Barbenel, 1974). Using artificial muscle forces they also found joint loads to be minimal with vertically directed bite forces at the second molar. Positioning the bite force at the third molar produced a distracting or tensile force but at the balancing, as compared to the working side joint. Although this seems confusing in relation to the findings just discussed it must be understood that Smith et al. were defining only the minimum possible joint loads for any combination of arbitrary muscle forces. When this is taken into consideration the side of this type of loading becomes irrelevant in their study. In any case, their analysis showed that the human temporomandibular joints were loaded in tension by more than 5 percent of the bite force magnitude.

Unilateral biting at the third molar position of Figure 15B produced this very situation with the working side joint experiencing about 10 percent of the bite load. These findings highlight a very important point. The ratio of joint to tooth resistance force for this task at the third molar was the lowest of all runs observed in this study (other than the intercuspal clench at the third molar which, as already stated, may not be a realistic situation; see Figure 14B). This further suggests that the ability to utilize muscle forces of the opposite side during unilateral functions provide maximal mechanical efficiency during mandibular function. Studies of primate jaw mechanics by Hylander (1979b and 1977) and Beecher (1977) have shown that much of the advantage of a fused symphysis is the ability to apply contralateral muscle force to a unilateral bite position. Secondarily, however, is the advantage of a concurrent reduction in the resulting residual joint forces, observed here.

Similar conclusions have been drawn by other workers as well. From experimental analyses of the rabbit Weijs (1980) and Weijs and Dantuma (1981) concluded that, "during natural mastication the muscles of both sides act in a proportion ensuring the largest bite force possible without pulling the articulating surfaces of the working side joint apart" (Weijs, 1980; p. 716). Hylander (1979c) and Hylander and Bays (1978 and 1979) measured subcondylar bone strain in monkeys and found that compressive reaction forces occurred during isometric molar biting at or anterior to the second molar. The magnitude of the joint forces was less at molar than premolar contacts. More posteriorly however, at the third molar, the working side joint was either unloaded or loaded under tension (Hylander, 1986). The ability of the mandible to coordinate the mechanical relationships to maximize bite force while minimizing joint forces, at least on the working side may, therefore, be a universal feature of mandibular mechanics (Greaves, 1978) where a fused symphysis exists. This would substantiate the earlier suggestion that perhaps the orientation of tooth resistance force is actually aligned more posteriorly than that of the overall muscle forces. If such is the case then the greater tooth resistance force occurs with reduced joint forces. This reduces the JF/TF ratio implying better biomechanical distribution of resistance forces (see Figures 15C). The joint force also becomes reoriented more anteriorly.

Based on the predictions of this model the bearing surfaces of the joints resisting compressive loads would be expected to be positioned at the anterior and superior aspects of the head of the condyle in the sagittal, or lateral plane. A reciprocal arrangement would be expected for those surfaces of the articular eminence. There would also be a requirement for the joint morphology to be able to resist distracting or tensile forces of lesser magnitude, as well. In the frontal plane, over the range of tooth force orientations tested the compressive load-resisting surfaces would be expected to extend from the mediosuperior to the laterosuperior aspects.

It is generally agreed that the morphology of the temporomandibular joints is a reflection of jaw function and therefore loading patterns (Carlsson, 1979; McNamara, 1972; Turnbul, 1970). With regard to compressive forces normal joints have been shown to have the thickest load-bearing type of tissues located at the anterior and superior aspects of the condylar head and posterior and inferior surfaces of the articular eminence and tubercle

(Hansson et al., 1976; Moffet et al., 1964). Other surfaces (i.e. roof of the joint fossa and posterior aspect of the condyle) are not histologically adapted to withstand the same extent of loading. Moffet and his coworkers also found that these areas exhibited a much greater propensity for remodelling of the osseous components in response to the assumed predominant loads at these surfaces. The temporomandibular ligament as well as the joint capsule itself are regarded as the components limiting distraction or tensile forces of the joints (Rees, 1954). The predictions of joint function from the model therefore appear to correspond well with the morphology of the temporomandibular joints.

The only reliable report of joint force orientation for human static function is that of Pruim et al. (1980). The average orientation from their data for bilateral clenching functions was approximately 74 degrees with respect to the occlusal plane which substantiates the results from the model. The range of joint forces predicted was approximately 60 to 100 degrees with a mean orientation for the bilaterally symmetrical tasks of about 77 degrees from Table XI. Those compressive joint forces predicted by the model to have orientations greater than about 90 degrees in the lateral plane suggest the possible involvement of the roof of the joint fossa for support. This would be a condition for which the fossa is not designed according to the information just described. The apparent incongruity may be explained by the fact that for the functions modeled, except for intercuspation, one would expect some amount of jaw opening to be involved. This translates into a rotational change in the apposition of the condylar head to the articular eminence. The nature of this change would depend on the extent of opening, but an increase in jaw opening would effectively reorient any joint forces more anteriorly. For instance, the results are all depicted as if the mandible remains stationary but the rest of the cranium, including the articular eminence, would become reoriented more posteriorly for wider opening.

Another consistent finding in morphological studies of the temporomandibular joints is the fact that the lateral aspect of the joint components, especially the disc, exhibit indications of greatest wear and attrition (Hansson, 1986; Hansson et al., 1979 and 1977; Hylander, 1979c). It has been assumed by most workers that this aspect of the joints undergo greater compressive loads during functional as well as parafunctional activities. The effects of varying the frontal plane orientation of tooth force (FTA) in the model have shown that more medial alignments produce more lateral joint forces at the working side. Since this orientation of the balancing side joint forces has usually remained fixed for changes in FTA no obvious reorientations of this force are evident (see Figure 15D). Nevertheless, the model has also shown that for static functions where all other factors are equal a change in frontal plane orientation more laterally at one joint produces a similar reorientation at the other, and vice versa (eg. see Figure 15E). Perhaps the nature of the dynamic forces which determine the distribution of resistance forces in these types of function are such that there is a tendency for laterally oriented joint forces to be produced at one condyle. If this is at the working side there would be a similar lateral component at the balancing side but of greater magnitude. It may be that the interplay of condylar translation, condyle and disc position, jaw opening and direction of muscle effort combine to produce the types of loading which have a predilection to produce this type of resistance force orientation at one or the other joints.

D. STRENGTHS AND WEAKNESSES OF THE CURRENT MODEL

Inherent in any model of biological function is the need to be able to manipulate and control the potentially vast and complex interplay of the many variables involved. Ideally, a biological model should be flexible enough to permit the incorporation of all relevant factors influencing the system under study. Unfortunately, the reality of the situation is such that certain assumptions must be made regarding which variables are most important and how they should be incorporated in the model. Firstly, the enormous mathematical complexity in analyzing dynamic mechanics dictates the limitation to static functions, or assumed near-static conditions during dynamic functions such as intercuspation in chewing. Although it may be possible to apply this model to incremental analyses of purely dynamic conditions the validity of the assumptions necessary may be questionable. Secondly, the mathematical solution of resistance force distributions for each task of this study is dependent upon designating the left condyle frontal angle (LCFA) of resistance. This reduces the resistance force variables to a statically determinant number. Third, the positions of tooth (teeth) and joint contact through which the resistance forces act is assumed to be single point rather than surfaces or multiple points. Again this is to simplify the mathematics involved in static analysis.

The muscle parameters are determined according to their lines of action between single points of attachment. The position of these points may be an oversimplification for some groups especially where pennation of muscle fibers exist. In this study the nine pairs of muscle vectors were assigned to specific muscle groups such as the medial pterygoid, or subgroups of other muscles such as the three portions of temporalis, and two each of the masseter and lateral pterygoid. There is no reason, or need, to limit the mumber of muscle subgroups strictly for the sake of the model itself, however. The model will easily accommodate the assignment of the nine pairs of coordinates to any portion of any muscle chosen. Inclusion of additional pairs of muscle coordinates beyond the nine used in this study is also possible. The element which limits the ability of the model to incorporate great numbers of muscle subgroups as found in a pennated muscle, is the ability to accurately determine precise points of attachment. Furthermore, the muscle parameters are determined according to their weighting value given to the muscle group or subgroup (i.e. physiological cross section) as well as their scaling values (i.e. activity levels) for a given functional task. The ability to provide or measure these values also determines the number of muscle subgroups which can be incorporated and reasonably modeled (eg. Osborn and Baragar, 1985). The nine pairs used in this study are currently feasible for determination of these parameters by means of techniques such as magnetic resonance imaging (MRI), CT scanning, and electromyography.

This model was designed for application to living subjects from whom such data can reasonably be derived as well as estimates of interocclusal forces. All that is necessary is the input of actual values for these variables from given individuals. Validation of the predictions of this study by experiment are therefore currently feasible at least so far as muscle morphology, muscle use, bite points and occlusal forces are concerned.

E. FUTURE DIRECTIONS

Application of this model in its present form will allow the indirect determination of the biomechanical relationships which exist in any given individual during any static function or task. Comparison of jaw biomechanics of different individuals based on quantitative rather than qualitative parameters is possible. Comparison of different craniofacial types would provide a reference from which predictions of functional differences due to alterations in the mechanics of the system could be made. For example, the effect of changes in these relationships could be predicted for alterations to the dentition via occlusal or orthodontic intervention. The effect of surgical procedures to correct morphological abnormalities could also be modeled from a functional point of view. In addition, functional disturbances to the masticatory system can be simulated. This may shed light on the biomechanics as causative, or contributing factors, or their role in appropriate treatment strategies, for example occlusal splint construction.

Finally, the model provides a very powerful tool for comparative analysis of anthropological material. The model has already been used in comparative studies of the relationships between jaw form of various mammalia with very different feeding behaviors and mechanics. Application in this wide field of study illustrates the model's diverse potential as an experimental and conceptual aid to research.

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APPENDIX I

Anatomical points of origin and insertion for the 12 muscle groups which comprise the masticatory elevator muscles as described by Baron and Debussy (1979, pp. 547-8) and depicted in Figure 1a and b.

Masseter

(a) Superficial Masseter

ORIGIN - "at the junction of the anterior and middle thirds of the posteroinferior (masseteric) border of the zygomatic bone. It occupies the top of an eminence which should not be confused with Paturet's sub-jugal eminence situated more anteriorly and to which Zlabek's tendon attaches (Paturet, 1951, p. 95)."

INSERTION - "at the pre-angular bony projection which corresponds to the anterior limit of Cihak and Vlcek's masseteric eminence (1962)."

(b) Intermediate Masseter

ORIGIN - "at the small bony spur near the squamoso-zygomatic suture at the posterior end of the masseteric border of the zygomatic bone."

INSERTION - "the geometric center of a rhomboidal area corresponding to Weidenreich's masseteric fossa."

(c) Posterior Deep Masseter

ORIGIN - "the geometric center of the longitudinal fossa in the posterior half of the inferior border of the zygomatic process of the squama."

INSERTION - "at the geometric center of a triangle corresponding to Cihak and Vlcek's (1962) zygomatico-mandibularis musculi fossa. This triangle situated between the coronoid process and the condylar process is limited by a soft ridge forming a V with curved branches called the crista musculi zygomatico-mandibularis."

(d) Anterior Deep Masseter

ORIGIN - "the top of the superior border of the superior surface of the zygoma (almost in the middle)."

INSERTION - "the geometric center of a pentagon centered on the body of the coronoid process."

Medial Pterygoid

(e) Anterior Medial Pterygoid

ORIGIN - "the center of the inferior (palatine) surface of the pyramidal process of the palatine bone adjacent to the maxillary bone."

INSERTION - "the top of the bony projection in the center of an elliptical space in the preangular region."

(f) Posterior Medial Pterygoid (Superficial Layer)

ORIGIN - "deep in the pterygoid fossa, in the center of a vertical segment joining the top of the inter-pterygo-scaphoid ridge to the pterygoid notch."

INSERTION - "the center of a crescent-shaped area situated in the preangular region. It corresponds to the second-to-last eminence near the gonian (angle)."

(g) Posterior Medial Pterygoid (Deep Layer)

ORIGIN - "the center of the posterior border of the lateral pterygoid plate of the pterygoid process, near the posterior pterygoid spine (Civinini's spine, Paturet, 1951, p. 329)."

INSERTION - "the center of a 1 cm long ridge, parallel to the mylohyoid groove and situated between the dental notch and the angle."

INSERTION - "at the top of the coronoid process."

Temporalis

(h) Anterior Temporalis (Zygomatico-Mandibularis)

ORIGIN - "the geometric center of a trapezoid made by the following points (Paturet, 1951, pp. 117, 329):

- stephanion (on the superior temporal curved line where it crosses the coronal suture)
- upper point of the inferior temporal curved line

- top of the sphenoidal eminence (tuberculum sphenoidale)
- posterior end of the sub-temporal ridge (at the junction of the sphenoid and temporal)"

INSERTION - "the center of a horizontal segment passing through the top of the retromolar triangle and linking the two ridges to the anterior border of the coronoid process."

(i) Middle Temporalis

ORIGIN - "at the geometric center of a large rectangle limited by:

- the spheno-occipital suture, anteriorly
- the inferior temporal line on the outer surface of the parietal bone, superiorly,
- the sub-temporal ridge of the squama, inferiorly,
- the linking of the posterior segments to the superior and inferior segments of the muscular origin, posteriorly."

INSERTION - "at the top of the coronoid process."

(j) Posterior Temporalis

ORIGIN - "in the parieto-temporal fossa situated behind the area of [i], at the center of a line linking the central points of the antero-inferior and postero-superior segments in this fossa.

INSERTION - same as [i].

Lateral Pterygoid

(k) Superior Lateral Pterygoid (Sphenoidal Head)

ORIGIN - "the center of the segment between the sub-temporal plane of the greater wing of the sphenoid and the superior third of the lateral surface of the lateral pterygoid plate of the pterygoid process."

INSERTION - "the center of the anterior border of the articular surface of the condylar process. This point is meniscal."

(l) Inferior Lateral Pterygoid (Pterygoidal Head)

ORIGIN - "the center of a rectangle which occupies the inferior two-thirds of the lateral surface of the lateral pterygoid plate of the pterygoid process and the points adjacent to the maxillary eminence and the pyramidal process of the palatine bone."

INSERTION - "the center of a small depression occupying the anterior slope of the articular process of the condylar process."

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APPENDIX II

The following figures are representative of the actual three dimensional computer printout for each run of every task. Each of the following five pages corresponds to RUNS 1 to 5 respectively of UNILATERAL MOLAR CLENCHING at the second molar position depicted in Figure 15C of RESULTS. The lower diagram depicts the horizontal view of the mandible viewed from below.

LTA and FTA of previous figures are here designated as simply TA corresponding to their appropriate plane or projection ANG·L and ANG·F values are likewise indicated but the muscle vectors themselves are not depicted in these printouts for reasons discussed in METHODS.

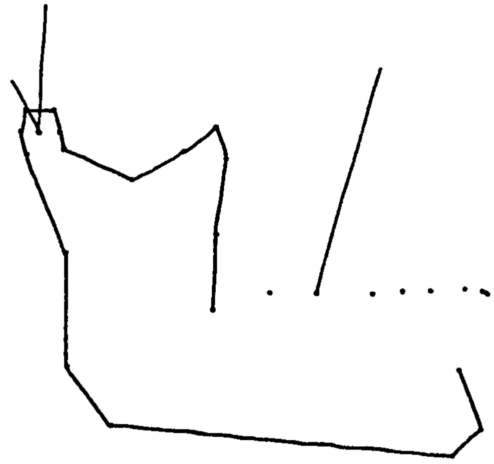
UNIMOL RUN 5

LCR= 265.1
LCA= 86.6

RCR= 119.3
RCA= 116.7

TR = 485.6
TA = 75.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 84.0

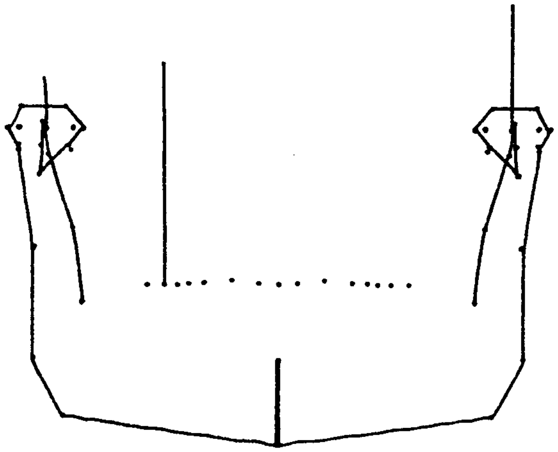


LCR= 265.1
LCA= 90.0

RCR= 119.3
RCA= 93.7

TR = 485.6
TA = 91.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 91.0

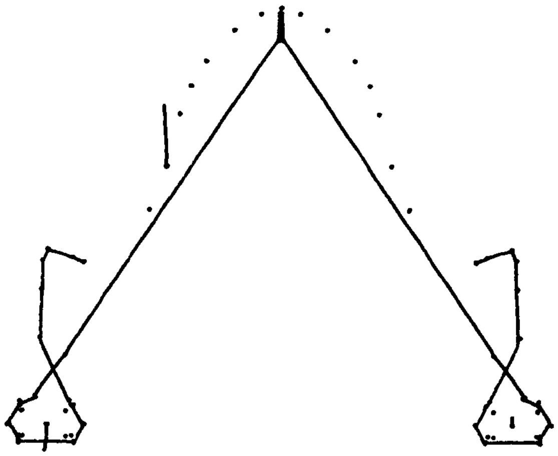


LCR= 265.1
LCA= 90.0

RCR= 119.3
RCA= 262.6

TR = 485.6
TA = 93.7

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 99.8



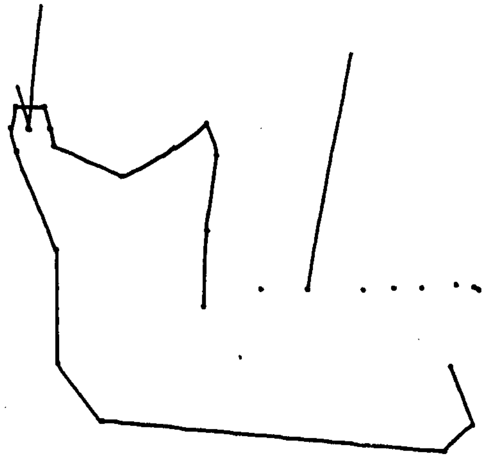
UNIMOL RUN 4

LCR= 260.0
LCA= 84.4

RCR= 92.2
RCA= 105.4

TR = 500.2
TA = 80.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 84.0

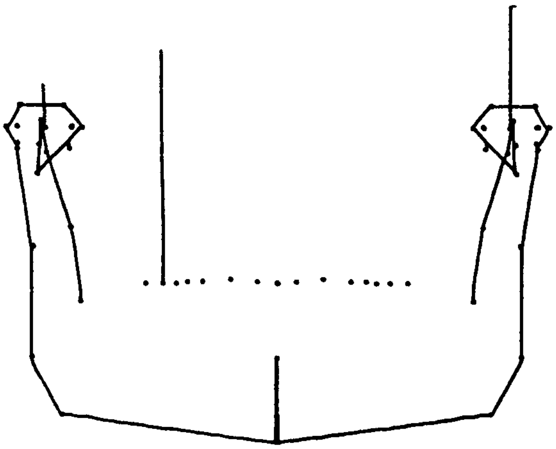


LCR= 260.0
LCA= 90.0

RCR= 92.2
RCA= 94.2

TR = 500.2
TA = 91.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 91.0

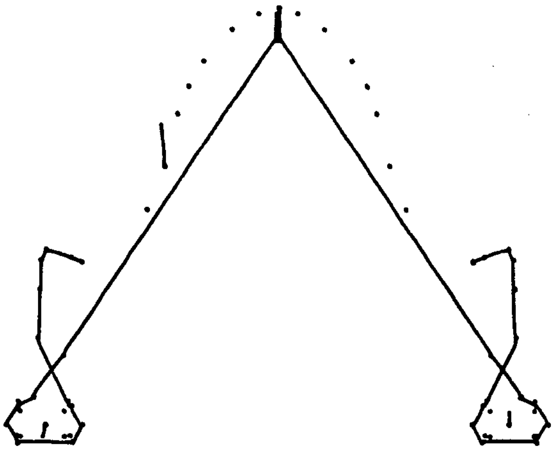


LCR= 260.0
LCA= 90.0

RCR= 92.2
RCA= 255.1

TR = 500.2
TA = 95.7

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 99.8



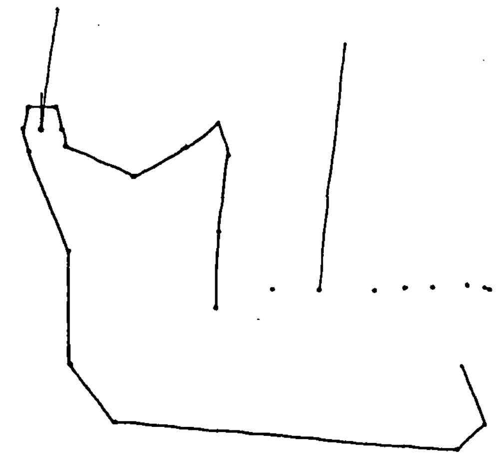
UNIMOL RUN 3

LCR= 256.0
LCA= 82.4

RCR= 73.9
RCA= 89.8

TR = 515.5
TA = 84.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 84.0

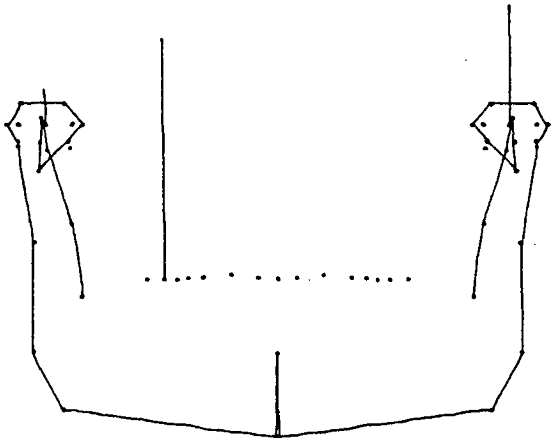


LCR= 256.0
LCA= 90.0

RCR= 73.9
RCA= 94.8

TR = 515.5
TA = 91.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 91.0

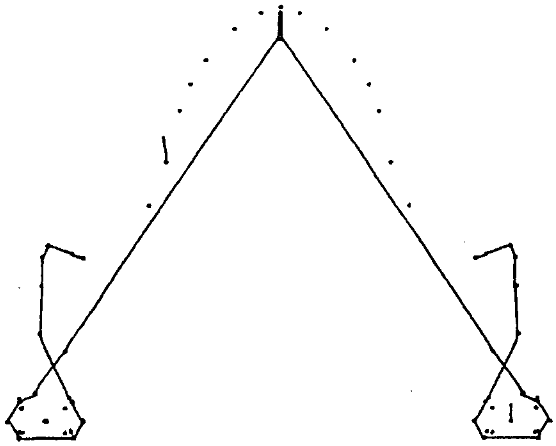


LCR= 256.0
LCA= 90.0

RCR= 73.9
RCA= 177.8

TR = 515.5
TA = 99.4

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 99.8



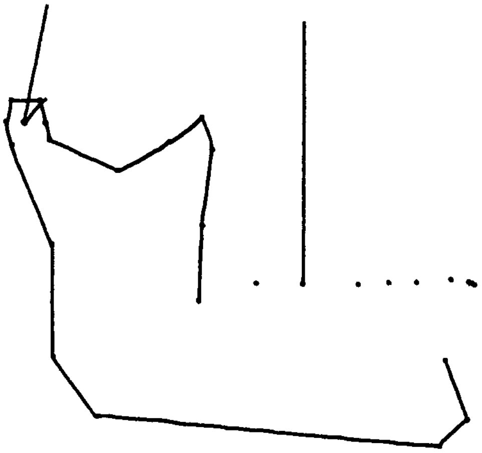
UNIMOL RUN 2

LCR= 250.0
LCA= 79.1

RCR= 64.0
RCA= 50.4

TR = 545.4
TA = 90.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 84.0

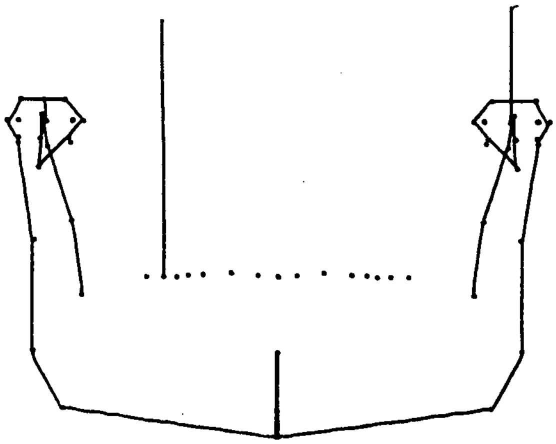


LCR= 250.0
LCA= 90.0

RCR= 64.0
RCA= 96.5

TR = 545.4
TA = 91.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 91.0

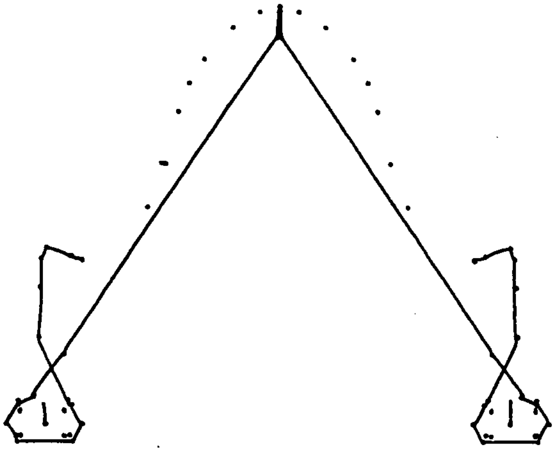


LCR= 250.0
LCA= 90.0

RCR= 64.0
RCA= 97.9

TR = 545.4
TA = 180.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 99.8



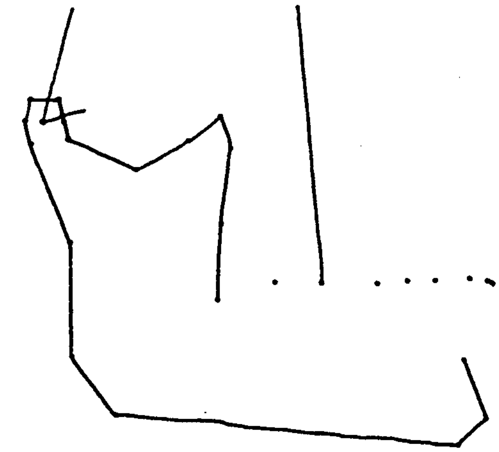
UNIMOL RUN 1

LCR= 245.3
LCA= 75.9

RCR= 82.8
RCA= 18.4

TR = 578.2
TA = 95.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 84.0

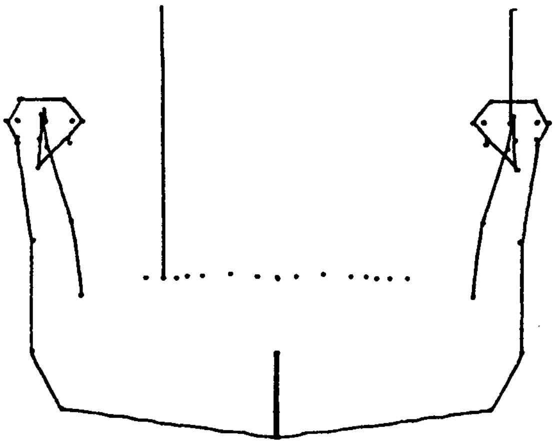


LCR= 245.3
LCA= 90.0

RCR= 82.8
RCA= 101.0

TR = 578.2
TA = 91.0

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 91.0



LCR= 245.3
LCA= 90.0

RCR= 82.8
RCA= 93.7

TR = 578.2
TA = 258.7

MLR= -15.1
MAR= 87.9
MVR= 839.9
ANG= 99.8