The effects of cusp and jaw morphology on the forces on teeth and the temporomandibular joint

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Summary
Basic principles of engineering mechanics are used to solve for force vectors in the masticatory system. It was found that incisor guidance/cusp angulation, crown heights and the anterior–posterior location of contact can significantly affect the magnitudes and/or directions of forces acting on contacting teeth and the temporomandibular joint. The results provide insight into the function of the jaws and the diagnosis and treatment of occlusion-related trauma.

Introduction
The forces generated by the masticatory system have long been of interest to dental researchers (Gysi, 1921; Kallenbach, 1931). Tooth mobility and sensitivity, crown fracture and wear, temporomandibular joint (TMJ) and muscle dysfunction, failure of restorations and the resorption of denture-supporting ridges are often indications that the dentition is not in occlusal harmony with muscle-generated forces. Studies of forces on oral structures have focused on the fulcrum function of the condyle, the classification of the mandible as a class I, II or III lever and the lever versus link controversy (Gysi, 1921; Kallenbach, 1931; Robinson, 1946; Seitlin, 1968; Grant, 1973; Barbenel, 1974; Gosen, 1974; Hylander, 1975; Smith, 1978; Tradowsky & Kubicek, 1981). Other works have dealt with the effects of cusp angulation and experimental measurements of bite forces (Hylander, 1978; Floystrand, Kleven & Oilo, 1982; Proffit, Fields & Nixon, 1983; Laurell & Lundgren, 1984).

The laws of static equilibrium can be used to solve the problems of force distribution without involving the kinematics of the jaws (Gabel, 1954). This obviates the need to represent the mandible as a lever or link. Accordingly, a general free-body-diagram (FBD) analysis was used to develop an analytical model of the masticatory system that incorporated several geometric parameters of occlusion. These variables can also be associated with reversible (stabilizing splints) and irreversible (occlusal adjustment, orthopaedic repositioning, orthodontic, restorative dentistry, and orthognathic surgery) treatments of TMJ/muscle dysfunction (Ash, 1986).

Methods
The FBD illustrating posterior bite collapse, a high anterior restoration, the use of an occlusal appliance or an experimental force transducer is shown in Fig. 1 (and Table 1). Input values for the standard mandible, listed in Table 1, were estimated from a
Fig. 1. The geometry and loading of the mandible. (See Table 1 for key).

Cephalogram. Masticatory force vectors, M and P, are those used by Throckmorton & Throckmorton (1985) in their study of masticatory force magnitude effects on TMJ forces.

The solution of the engineering problem was the determination of the unknown force vectors T and J, created by the primary muscles of mastication (M and P) with incisor guidance, A, and jaw morphology defined by a, b, c, d, e and f. The conditions of static equilibrium and the assumption of frictionless contact between smooth, saliva lubricated, tooth surfaces yielded the following:

\[
T_x = \frac{(c+d) M_x + b M_z + (e-c) P_x + f P_z}{a + b + c \tan(A)} \tan(A) = T_y \tan(A)
\]

\[
T_y = \frac{(c+d) M_x + b M_z + (e-c) P_x + f P_z}{a + b + c \tan(A)}
\]

\[
J_x = \frac{[a+b-c \tan(A)] M_x - b \tan(A) M_z - [a+b+e \tan(A)] P_x - f \tan(A) P_z}{a + b + c \tan(A)}
\]

\[
J_y = \frac{-(c+d) M_x + [a+c \tan(A)] M_z - (e-c) P_x + [a+b+f+c \tan(A)] P_z}{a + b + c \tan(A)}
\]

\[
= M_y - T_y - P_y.
\]
A parametric analysis of the changes in vectors T and J due to changes in geometric parameters A, a, c and d comprise the results. In clinical terms, the results show the individual and combined influence of incisor guidance or cusp angulation (A), the anterior–posterior location of contact (a), occlusal plane height (c and d) and vertical dimension of occlusion (c and/or d). Not reported in this paper are calculations showing that T and J were affected by changes in muscle forces M and P.

Incisor contact force is displayed in terms of its components T and Ty and magnitude |T| in Fig. 2a as incisor guidance was varied through its geometrically possible range. Similarly, the concomittant force acting on the TMJ is shown in Fig. 2b. Figure 2c shows the corresponding changes in the directions of T and J. (Because of frictionless contact, in all cases, t = A.) The actual force vectors are drawn in Fig. 2d & e in which each vector represents a difference of 5° in incisor guidance and each hatch mark on the vectors is 0.5 units of magnitude. The values of A printed at the tails of the (dotted) vectors are the two extreme values drawn, A = 0.0 and the value of A corresponding to the approximate minimum magnitude of the vector.

Symmetric bilateral posterior tooth contact was modelled by decreasing the value of A = 0.0° represents edge-to-edge incisor contact or flat plane posterior occlusion when the model is generalized to symmetric posterior contact. A > 0.0° defines contact between a maxillary incisor palatal incline and the facial edge of the opposing mandibular incisor or contact between a maxillary cusp distal incline and a mandibular mesial incline. Similarly, A < 0.0° describes a class III incisor relationship or a maxillary mesial incline contacting a mandibular distal incline.

By setting $M_x = P_x = P_y = c = d = e = f = A = 0.0$, the governing equations can be reduced to duplicate lever results:

$$T_x = 0.0, \quad T_y = bM_y/(a+b), \quad J_x = 0.0, \quad J_y = aM_y/(a+b).$$

### Results

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Fig. 2. Force components, magnitudes and directions as functions of incisor guidance: (a) force on the incisor \([\square—\square)\ T_i (\bigcirc—\bigcirc) T_{in} (\bigtriangledown—\bigtriangledown) T]; (b) force on the TMJ \([\square—\square) J_i (\bigcirc—\bigcirc) J_{in} (\bigtriangledown—\bigtriangledown) J]; and (c) force directions. (d) Force vector acting on the incisor; and (e) force vector acting on the TMJ.

Figure 3 shows the results for third molar contact \(a=15\,\text{mm}\), analogous to Fig. 2.

As the contact moved posteriorly from the incisors \((a=60\,\text{mm})\) to the third molars \((a=15\,\text{mm})\), changes occurred in \(|T_i|, |J_i|\) and \(j\) (Fig. 4a & b). Figure 4c–e shows the actual \(J\) vector. (Flat plane and \(\pm 33^\circ\) contacts are used as representative examples of physiological values. More drastic changes occur as contact angulation increases.) Figure 4f is the graph of the simplified lever equations.

Occlusal plane height (OPH) and vertical dimension of occlusion (VDO) changes are shown in Figs 5 & 6. By increasing \(c\) and decreasing \(d\) by the same amount, the plane was lowered. By increasing only \(c\), the VDO was increased due to long maxillary crowns. The same increases in VDO were also achieved with long mandibular crowns (increased \(d\)) and by equally shared changes in the heights of both maxillary and mandibular teeth (\(c\) and \(d\)).
Discussion
The results allow the exploration of some clinical and experimental findings. For instance, posterior bite collapse can lead to maxillary incisor flare. Mathematically this represents a decrease in $A$ from 60-0° to 40-0°, for example, caused by $-T$. The result of flare is a decrease in the horizontal component of force, $T_x$, but an increase in the vertical component, $T_y$, as illustrated in Fig. 2a & d. The progression of flare is then dependent on how the masticatory apparatus handles this changing force. Note also the corresponding effect of the flare on the TMJ (Fig 2b, c & e).

In anterior contact, the force magnitude in the TMJ is relatively constant from approximately $A = -40-0°$ to 70-0° (Fig. 2b & e). But its direction, $j$, ranges between...
approximately 50–0° (down and back) to −50–0° (down and forward) (Fig 2c & e). In contrast, during posterior contact, the direction remains relatively constant for $A>10–0°$ (Fig 3c & e), but the magnitude changes drastically (Fig 3b & e). For $A<10–0°$, both the magnitude and direction change rapidly. These results emphasize the fact that forces are vectors, and, therefore, TMJ dysfunction could result from variation in the magnitude or direction of $J$, depending on the occlusal contact location and angulation.

Also note that a minimum value for joint loading exists. Equilibrium requires...
that this non-zero force be resisted by the joint through associated muscles, ligaments or the condyle itself.

The results of lever analyses have led to the notion that anterior teeth are protected from large forces by virtue of their location (Gosen, 1974; Loos, 1981), that the forces on teeth increase posteriorly, while at the same time, the force on the TMJ decreases (Fig. 4f). These statements must be qualified. It is true that for a specific contact angulation, the forces on the teeth do increase posteriorly. However, as illustrated in Fig. 4a, a $-33^\circ$ contact, distal to about $a = 45.0$ mm, will always result in higher tooth contact forces than flat plane occlusion. Furthermore, the force magnitude on the TMJ may increase significantly if cusp angulation is taken into account (Fig. 4a). In addition, lever models cannot account for force direction changes illustrated in Fig. 4b.
The OPH and VDO do not appear to be significant determinants of force magnitude in anterior contact and posterior flat plane and +33-0° contact. However, the force magnitudes on -33-0° contacting posterior teeth and the concomitant TMJ forces do change with the OPH (Fig. 5) and the VDO (Fig. 6a). It becomes apparent in these figures that c (which includes maxillary crown height) is a more critical variable than d (mandibular crown height). On the other hand, in the case of posterior flat plane occlusions, d determines the direction of J when VDO is altered (Fig. 6b).

The model showed, in addition, a phenomenon that may have profound clinical implications. A mathematical singularity occurs if the common denominator in the expressions for the force components approaches zero, that is if \(a+b+c \tan (A)=0\). The significance of this is that certain combinations of \(a+b\) (the horizontal distance from the condyle to the contact), \(c\) (the vertical distance from the condyle to the occlusal plane) and incisor guidance/cusp angulation \(A\) can result in extremely high forces on the contacting teeth and the TMJ. This can be seen in Fig 2a & b and Fig. 3a & b in the form of the left and right limits, the asymptotes. Also noteworthy is that \(d\), which includes mandibular crown height, does not enter this calculation.

An examination of the force vector diagrams provides some mathematical and clinical insight into the separate contributions of the geometric parameters (jaw and tooth morphology) and the forces applied by the muscles of mastication. The top borders (the line connecting the tails of the vectors) of the vector envelopes in Fig. 2d & e and Fig. 3d & e have slopes equal to \(c/(a+b)\). As the direction of the vectors approaches this slope, \(T\) and \(J\) magnitudes increase greatly. This is the identical behaviour described in the previous paragraph. Although the specific relationship is not presented in this paper, the distance of the upper envelope border from the origin (the heads of the vectors) is determined by forces \(M\) and \(P\). Similarly, the borders in Fig. 4c–e are determined by contact angulation, \(A\). (Using a different mathematical approach, a similar pattern was obtained by Smith et al., 1986.)

Occlusal appliances, selective grinding, tooth wear and mobility, incisor flare and bite force transducers alter \(A\) and/or \(c\) or \(d\), resulting in changes in the force vectors acting on the teeth and the TMJ. (This observation may partly explain the conflicting experimental results of bite force transducer studies described by Fields et al., 1986. Force transducers measure force magnitudes, but they also prescribe the direction of the measured force, and depending on the mode of attachment, the value of \(c\) or \(d\).) The calculations also indicate that maxillary crown heights are more significant in their effects on force magnitudes than mandibular crown heights, and ordinary lever analyses lead to incomplete and erroneous results.

References
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