The anterior component of occlusal force revisited: direct measurement and theoretical considerations

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Summary

Background: The anterior component of occlusal force (ACF), considered to result from the mesial inclination of teeth relative to the occlusal plane, has been estimated by indirectly measuring contact point tightness (CPT) through interproximal insertion of metal strips. ACF has been observed concurrently with a posterior component, whose theoretical origin is difficult to explain.

Objectives: Evaluate ACF by measuring CPT directly, and integrate current data to propose a theoretical basis for ACF.

Materials and methods: The sample comprised 14 females (age: 22.3±2.8) and 16 males (age: 20.8±2.5). Our device consisted of two force sensors: one for measuring maximum bite force (MBF) (overall thickness: 4 mm), and one for measuring CPT directly (0.2 mm thick), inserted between the lower first molar and second premolar. ACF was computed as the difference in CPT between the biting (at 75 per cent of MBF) and non-biting conditions.

Results: Averages of MBF, CPT, and ACF were 666.67 (standard deviation (SD): 36.06), 6.74 (SD: 1.17), and 20.59 (SD: 4.60) N, respectively. ACF, CPT, and MBF were higher in males by approximately 28, 18 and 7 per cent, respectively. A positive correlation was observed between ACF and MBF ($R^2$: 0.64). CPT was also significantly correlated to MBF ($R^2$: 0.40). Biomechanical analysis indicates that previously offered explanations do not unravel the concurrent increase of CPT at anterior and posterior contact points.

Conclusions: ACF was related to bite force by a logarithmic model. We speculate that CPT increases during biting through a combination of mesial tipping of teeth and mandibular bending.

Introduction

The anterior component of occlusal force (ACF) is considered to arise from the mesial inclination of teeth relative to the occlusal plane. It was first described more than 90 years ago (1) but was convincingly demonstrated by Southard et al. (2–4), who refined the previous methodology (5); the key element was to have the subjects bite on a single tooth, thus controlling the point of force application. ACF has been implicated in mesial migration of teeth and late lower incisor crowding (3,6), although these may be attributed to other factors, such as interproximal fibres, soft-tissue changes, and growth (7). ACF has been estimated indirectly as the difference in interproximal contact point tightness (CPT) between the biting and non-biting conditions. CPT has also been measured indirectly, by the friction of a metal strip as it is pulled between contacting teeth (2,5,6), or by the force required to insert such a strip at the interproximal point (8,9).

Since ACF is a component of the bite force, it is expected that it would be correlated to bite force, and to factors associated with bite
force and masticatory function, such as age, gender, and craniofacial pattern. Indeed, ACF is strongly related to bite force, but no relation was found to cephalometric variables or molar inclination (4). The latter is surprising, considering that molar inclination is assumed to be the basis of this force. In addition, a ‘posterior component’ of force (PFC) has been reported (8,10). This acts concurrently to ACF during biting, increasing CPT posterior to the occluding tooth. It is however difficult to explain how a single occlusal force, acting on one tooth, could increase CPT both anterior and posterior to that tooth, thus raising questions regarding methodology and/or the theoretical basis of ACF.

The aim of this study was to measure maximum bite force (MBF), CPT, and ACF, and to assess the relations between them. We used a direct method to obtain CPT at the contact point between the lower first molar and second premolar. Additionally, we reviewed previous findings and propose a consistent theoretical foundation for ACF.

Methods and materials

The research protocol was reviewed and approved by the Ethics Committee of the School of Dentistry, National and Kapodistrian University of Athens, Athens, Greece (approval date 24 May 2012). Subjects were selected fulfilling the following inclusion criteria: age range 18–25 years, good general health, no missing permanent teeth (excluding third molars), good periodontal status and Class I molar relationship. Exclusion criteria were syndromes, extreme vertical facial types, previous orthodontic treatment, signs and symptoms of craniomandibular dysfunction, caries, open bite, more than 50 per cent overbite, crossbites, and any interproximal spaces between the second molar and canine. In addition, we screened subjects for dental attrition and included only those with Tooth Wear Index (TWI) (11) equal to zero (no wear) or one (normal appearance with just definable wear). Sample size was determined by assuming a minimum effect size of $r = 0.5$ and setting alpha at 0.05 and power at 0.80 (G*Power, www.gpower.hhu.de). These values produced a sample size of 23 subjects; we recruited 30 subjects to ensure drop-outs. All subjects provided written informed consent. The final sample consisted of 14 females [average age: 22.3, standard deviation (SD): 2.8] and 16 males (average age: 20.8, SD: 2.5).

Electronic measuring device

The device consisted of two force sensors and an electronic circuit computer interface. Each sensor was a piezo-resistive element (FlexiForce® A201, Tekscan, South Boston, Maryland, USA) 0.2 mm thick with a circular sensing area of 9.53 mm diameter. We interfaced the sensors using the manufacturer recommended drive circuit at 3 volts and a Parallax microcontroller (Parallax, Inc., Rocklin, California, USA) and collected the output in real time through the USB interface and custom-designed software (Supplementary Figure 1).

The sensor used for measuring bite force was enclosed between two metal strips to protect it from distortion by occlusal loads (Figure 1, Supplementary Figure 2). Each strip contacted the sensor via a spacer that ensured that forces were concentrated on the sensing area only. The metal strips and sensor were surrounded by a soft foam cover to allow the subjects to exert maximum force without restraint (12). Total thickness when biting was approximately 4 mm. The sensor for measuring interproximal force was trimmed according to the manufacturer’s guidelines to prevent deflection during biting. The device was calibrated using known loads.

Measuring procedure

All measurements were performed in the morning, to avoid diurnal fluctuations (13,14), with subjects seated in an upright position in the dental chair (the Frankfurt plane parallel to the floor), to avoid variations of interproximal force due to head positioning (15,16). MBF was measured by placing the sensor between the upper and lower first molars on each side in turn. The side which gave the highest bite force was selected as the test side and three measurements were taken from this side at intervals of no less than 15 seconds.

CPT was measured by placing the interproximal sensor at the contact point between the lower first molar and second premolar on the test side. A wooden wedge was first inserted between these teeth for 30 seconds to temporarily create space for the sensor. The wedge was removed and measurements were taken after allowing a settling time of 2–3 minutes.

CPT was re-measured with the subject biting on the occlusal transducer over the lower first molar on the same side (CPT$_{bio}$). The bite force was dynamically registered and displayed to the subject, who was instructed to keep it at a level equal to approximately 75 per cent of the MBF (MBF$_{pre}$), in order to avoid muscle fatigue and, consequently, force fluctuation. The value of 75 per cent was selected to allow comparison to previous studies (8). At the same time, CPT$_{bio}$ was registered by the interproximal transducer.

This procedure was repeated three times for each subject with a rest of 15 seconds between readings. The difference between CPT$_{bio}$ and CPT was designated $\Delta$CPT and corresponds to the so-called ACF (2,3):

$$\Delta$CPT = CPT$_{bio}$ - CPT

Statistical evaluation

Descriptive statistics were computed for all variables. Normality of distribution was assessed by the Shapiro–Wilks test. One-way repeated measures analysis of variance (ANOVA) was used to test for differences between the three repeated readings. Gender differences were evaluated by the independent t-test. Regression analysis was performed between MBF$_{pre}$ (independent variable) and $\Delta$CPT (dependent variable). All tests were performed with IBM SPSS Statistics 22.

Results

A one-way ANOVA on the repeated measurements for each of MBF, CPT, and $\Delta$CPT showed no significant differences; however, the $P$ value for CPT was equal to the conventional threshold (Table 1). We used the average of the three repeats to represent each subject for all subsequent analyses.

MBF showed evidence of non-normality (Shapiro–Wilks test, $P = 0.028$), which was attributed both to negative skewness ($z$ value $= -2.47$) and high kurtosis ($z$ value $= 3.29$). Three potential
outliers were identified (two low-end and one high-end). Removal of the outliers resulted in a non-significant normality test. We ran all subsequent analyses twice, including or excluding these outliers; we report results for the whole sample and provide other results only when substantially different.

The mean values of MBF, CPT, and $\Delta_{CPT}$ for the whole sample were 666.67 (SD: 36.06), 6.74 (SD: 1.17), and 20.59 (SD: 4.60) newtons (N), respectively (Table 2). Males had significantly higher values than females for all three measurements. MBF was higher by approximately 7 per cent, CPT was higher by 18 per cent, and $\Delta_{CPT}$ by 28 per cent.

Regression analysis between MBF, and $\Delta_{CPT}$ indicated a statistically significant correlation for both the male and female groups (Table 3, Figure 2). The regression plot indicated different slopes between the two groups, verified by ANOVA (Table 3). Removal of the three outliers resulted in a non-significant difference between slopes. Visual inspection of the regression plot and plot of the residuals indicated that the relationship between MBF and $\Delta_{CPT}$ can be better modelled by a non-linear function. We fitted an exponential curve to the whole sample, resulting in $R^2 = 0.6425$ (regression equation: $\Delta_{CPT} = 0.6727 \cdot 0.0045^{\text{MBF}}$, $F(1, 28) = 50.319, P < 0.001$) (Figure 2). This equation fitted the data only slightly better than a linear function (regression equation: $\Delta_{CPT} = -47.589 + 0.136 \cdot \text{MBF}$, $R^2 = 0.640$, $F(1, 28) = 49.791, P < 0.001$). However, the linear function has a considerable negative intercept and therefore does not fit the theoretical model that dictates that $\Delta_{CPT}$ should be zero when there is no occlusal force.

CPT with the teeth not in occlusion was also found to be significantly correlated to MBF ($R^2 = 0.400$, $F(1, 28) = 18.641$, $P < 0.001$).

### Discussion

The few studies that have measured ACF have done so indirectly (2,4–6,8). Our aim was to measure ACF by a direct method and discuss theoretical aspects of ACF and its puzzling counterpart, the PCF (8,10). We begin by considering our methodology and findings, using ACF and $\Delta_{CPT}$ interchangeably, although we consider the latter more appropriate terminology.

$\Delta_{CPT}$ was computed as the difference in CPT between the relaxed and biting conditions, therefore an assessment of bite force was needed. Numerous factors have been related to the magnitude of bite force (e.g., age, gender, number of teeth, craniofacial pattern, bruxism, thickness of the force sensor, perceived hardness of the biting element, bite position, unilateral versus bilateral biting) (17–30). We aimed for sample homogeneity regarding age, dental relationships, TMJ dysfunction, and tooth wear. MBF has been shown to vary with age, increasing until adulthood and decreasing at old age (18,28,29,31,32). Differences in gender have been reported by most investigators, but these are most apparent after puberty or early adulthood (12,18,28,29,31–34). Supplementary Table 1 lists selected studies on samples of comparable age to the one reported here. Our MBF values are within the consensus range. The force sensor was 4 mm in thickness, slightly smaller than in most other studies, for better simulating the intermaxillary distance during masticatory function.

### Contact point tightness

CPT has been measured using the sliding strip method and the insertion/removal method. In the former, a thin metal strip is inserted interproximally and slowly pulled in a buccal or occlusal direction (2,3,5,6). The force required to pull the strip is double the frictional force, which is equal to CPT times the coefficient of friction between metal and enamel:

$$F = 2 \cdot \mu \cdot \text{CPT},$$

where $\mu$ coefficient of friction. A significant drawback of this method is that $\mu$ cannot be measured at each dental contact point, so it is estimated ex vivo. Southard et al. (2) reported a value of 0.145 ± 0.02 for the dry condition, similar to 0.151 estimated by Osborn (5), but in the presence of saliva. These values are approximately three times higher than the result of Acar et al. (6) (0.048; unspecified conditions). Unfortunately, details about the measuring procedure (e.g., surface condition, lubrication) and repeatability of measurements are limited. Data from the tribology literature show that the friction coefficient of enamel may be age dependent and heavily influenced by the presence and composition of saliva (35,36).

To avoid friction complications, CPT has been measured by inserting and removing a strip along the occluso-gingival direction (8,9,37). The maximum force registered during insertion occurs when the strip separates the teeth and invades the contact point. This force is representative of CPT, but CPT per se cannot be obtained, because the insertion force depends, additionally to the coefficient of friction, on other factors, including the geometry (slope) of the approximating enamel surfaces. If these surfaces are perpendicular to the direction of insertion then it is not possible to insert the strip, even if CPT and friction are zero (Figure 3).

In this study, we exploited the small thickness of piezo-resistive elements to measure CPT directly. Our method also presents with limitations, the most significant being the non-zero thickness of the

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### Table 2. Descriptive statistics of MBF, CPT, and $\Delta_{CPT}$. Results of t-test comparing males and females.

<table>
<thead>
<tr>
<th>Force (N)</th>
<th>Whole sample (n = 30)</th>
<th>Females (n = 14)</th>
<th>Males (n = 16)</th>
<th>t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (SD)</td>
<td>Range</td>
<td>Average (SD)</td>
<td>Range</td>
</tr>
<tr>
<td>MBF</td>
<td>666.67 (36.06)</td>
<td>547.11–751.22</td>
<td>641.40 (34.46)</td>
<td>547.11–694.36</td>
</tr>
<tr>
<td>CPT</td>
<td>6.74 (1.17)</td>
<td>5.30–9.94</td>
<td>6.16 (0.88)</td>
<td>5.03–8.08</td>
</tr>
<tr>
<td>$\Delta_{CPT}$</td>
<td>20.59 (4.60)</td>
<td>12.95–32.07</td>
<td>17.98 (3.26)</td>
<td>12.98–23.45</td>
</tr>
</tbody>
</table>

* t-Test for unequal variances. Mann–Whitney U test resulted in P < 0.0001.
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Table 3. Linear regression analysis. Independent variable: MBF, dependent variable: Slope difference of ϵ. Difference of slopes between genders was statistically significant for the whole sample, but not with outliers removed.

<table>
<thead>
<tr>
<th>Whole sample</th>
<th>Females (n = 14)</th>
<th>Males (n = 16)</th>
<th>Slope difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (R^2)</td>
<td>0.764 (0.584)</td>
<td>0.757 (0.573)</td>
<td></td>
</tr>
<tr>
<td>F (P)</td>
<td>16.850 (0.001)</td>
<td>18.796 (0.001)</td>
<td></td>
</tr>
<tr>
<td>Beta coefficient</td>
<td>0.096</td>
<td>0.231</td>
<td>-0.135</td>
</tr>
<tr>
<td>t (P) testing slopes</td>
<td></td>
<td></td>
<td>-2.437 (0.022)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outliers removed</th>
<th>Females (n = 12)</th>
<th>Males (n = 15)</th>
<th>Slope difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (R^2)</td>
<td>0.798 (0.637)</td>
<td>0.740 (0.548)</td>
<td></td>
</tr>
<tr>
<td>F (P)</td>
<td>17.546 (0.002)</td>
<td>15.754 (0.002)</td>
<td></td>
</tr>
<tr>
<td>Beta coefficient</td>
<td>0.172</td>
<td>0.309</td>
<td>-0.137</td>
</tr>
<tr>
<td>t (P) testing slopes</td>
<td></td>
<td></td>
<td>-1.580 (0.128)</td>
</tr>
</tbody>
</table>

F, F value of the regression; P: probability.

Figure 2. Regression plot of CPT on MBF. Circles: females; crosses: males. The two linear regression lines correspond to the male and female groups. The exponential line corresponds to the whole group.

force sensor. At 0.2 mm, four times or more the thickness of the metal strip used in other methods, it is necessary to separate the teeth for insertion of the sensor, a sometimes difficult and uncomfortable procedure. Additionally, larger separation leads to results that are less representative of the natural situation, where the distance between teeth is zero. Nevertheless, the thickness of 0.2 mm is below the average width of the PDL (37), thus allowing ordinary tooth response to occlusal forces.

Our CPT results compare favourably with those reported in the literature (Supplementary Table 2). Excluding the studies for which CPT cannot be computed (insertion/removal method studies), our results are very similar to those of the Southard group (2,15,16) and Dörfer et al. (13). Others report apparently much lower values (38–40), but these values represent the frictional force; once they are converted to CPT (using: μ = 0.15), a closer agreement is obtained.

CPT was higher in males than females by approximately 17 per cent, in almost exact accord with Vardimon et al. (9). Higher values in males are expected since males have higher MBF values and CPT was found positively correlated to MBF. Biologically, the CPT gender difference could arise from a number of factors, including: 1. gender differences in the mechanical properties of the periodontal ligament (PDL) and/or transseptal fibres, and 2. differences in PDL properties arising indirectly, due to different masticatory loading characteristics. Gender and loading have been implicated as factors that may affect the physical properties of the PDL, although the literature is rather scarce (41). Another potential factor is differences in bending of the mandible due to different bone structure and muscle function (see later).

Table 4 shows ACF literature data. Comparison between studies is difficult because of differences in methodology and biting conditions (especially magnitude of bite force). Momentarily ignoring such differences, our results were not statistically different (t-test, P > 0.2) except when compared to the Vardimon et al. (8) study (P < 0.0001) which reported values almost an order of magnitude smaller. We can only attribute such large differences to methodological issues, mainly that the insertion method was used; therefore actual measurement of CPT was not possible.

ACF was higher in males than females. This is expected because MBF was registered at 75 per cent of MBF, which was higher in males. Correlation of ACF with MBF was high. The regression equation that best described the data was of exponential format. Southard et al. (4) report a linear relationship, but there are significant differences between the two studies, in addition to measurement methodology. In ref. (4), the bite force levels were four and pre-specified (50–200 N), all subjects (n = 10) were tested at the same levels and their results averaged, then the regression was computed. In contrast, each of our subjects applied 75 per cent of the MBF and the regression was computed on the data from all subjects. The bite force levels ranged from approximately 415 to 560 N.

Theoretical basis of ACF and PCF

The term 'ACF', an acronym of ‘anterior component of [occlusal] force’, but referring instead to the increase in CPT during biting,
Table 4. ACF measurements at 6–5 contact point, as reported in the literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>ACF (N), average (SD)</th>
<th>Age average (SD or range)</th>
<th>Bite force (N)</th>
<th>Sample size (gender)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southard et al. (2)</td>
<td>24.5*</td>
<td></td>
<td>88.9</td>
<td>15</td>
</tr>
<tr>
<td>Southard et al. (4)</td>
<td>24.7*</td>
<td></td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>Acar et al. (6)</td>
<td>25.2 (20.70)</td>
<td>21 (17–26)</td>
<td>100</td>
<td>13</td>
</tr>
<tr>
<td>Oh et al. (38)</td>
<td>7.67 (5.11)**</td>
<td>22.9 (2.09)</td>
<td>50% of MBF</td>
<td>20 (10 F, 10 M)</td>
</tr>
<tr>
<td>Vardimon et al. (8)</td>
<td>3.25 (2.45)*****</td>
<td>27.05 (3.9)</td>
<td>75% of MBF</td>
<td>60</td>
</tr>
<tr>
<td>Present study</td>
<td>20.59 (4.6)</td>
<td>21.48 (2.69)</td>
<td>75% of MBF</td>
<td>30 (14 F, 16 M)</td>
</tr>
</tbody>
</table>

*Estimated from Figure 7B of Southard et al. (2) and Figure 3 of Southard et al. (4).
**Frictional force to remove strip. Conversion to interproximal force (using a coefficient of friction of 0.15) results in 25.57 (17.03).
***Computed from insertion force; cannot be converted to actual ACF.

is, in our view, a misnomer. Assuming that the masticatory force acts obliquely to the occlusal plane (Figure 4a), the anterior component is parallel to the occlusal plane. This force must be counteracted by an opposite force to maintain static equilibrium of the mandible; the potential areas of application are the TMJ and the biting molar. Therefore, the mandibular molar experiences at most a distally directed force arising from the opposing molar through the bolus or the force transducer. This distal force will decrease rather than increase CPT mesial to the bite position. In this scenario, the maxillary molar will indeed experience a mesially directed force. However, it is not possible for both molars to be forced mesially. It is apparent that ACF cannot be solely responsible for the observed experimental results, where CTP increases in both arches.

A promising alternative is the vertical component of the bite force (Figure 4b). If this component acts mesial to the centre of resistance (CRes), then the teeth will tip mesially, increasing CPT and producing the observed ‘anterior component’. There, however, three points to consider. First, the inclination of the molar under loading was not found related to the magnitude of ACF (4). Second, mesial tipping requires the point of force application to be mesial to CRes. It is estimated that the molar would have to be inclined mesially more than 20 degrees to ensure that all occluding points of the crown are mesial to CRes. Normal values of molar tip are below 10 and 2 degrees for the lower and upper molar, respectively (42). Third, an increase in CPT anterior to the bite position due to mesial tipping should cause a decrease of CPT posterior to the bite position, but experimental data show a PCF acting concurrently with the anterior component. The first study that demonstrated PCF is probably the work of Conroy (10), later confirmed by Vardimon et al. (8), although seemingly oblivious to the preceding work. These investigators provide rather unclear explanations for the existence of the posterior component: depression of the loaded tooth relative to the neighbouring teeth (10) or ‘by the partition along the mesial and distal cusp slopes of the bite force’ (8). Depression of the loaded tooth would tend to pull the immediate neighbouring teeth towards it, and thereby away from other teeth, thus decreasing rather than increasing CTP along the arch. The explanation involving ‘partitioning’ of the bite force is difficult to understand, especially when the bite force is concentrated on a single cusp tip.

We think that the puzzle of ACF and PCF may stem from the historical attempt to explain the mesial migration of teeth and late incisal crowding (1); a mesial force was needed and the increase of CPT during biting was assumed to represent a tendency of teeth to move anteriorly. However, investigations measuring ACF actually measure increase in CTP, not absolute mesial tooth movement. Is there a mechanism that could compress teeth towards one another along the whole semi-arch, both anterior and posterior to the bite position? A potential answer is mandibular bending (Figure 4c) (10,43).

Mandibular bending has been measured in vivo and computed in silico using finite element methods (FEM) (44–48). Most of the recent literature has concentrated on mandibular flexure during mouth opening, which results in constriction of the mandibular dental arch and has clinical implications for implant-based prostheses (43,49–52). Significant bending also occurs during biting and includes twisting of the mandibular corpus and bending in the sagittal plane (47). On the working side, compression is observed at the superior part of the alveolar process and tension at the lower mandibular border (53). Such bending could increase CTP at all interproximal positions of the working side.

Based on the above we consider that ‘ACF’, used to represent the CPT difference between the rest and biting conditions, is a misleading and potentially confusing term. There is currently no clear evidence to show that the change in CPT is due to an anterior component of bite force; on the contrary, such a notion is inconsistent with experimental data. We suggest that CPT change is due to 1. the vertical component of the bite force, acting anterior to the CRes of the mesially inclined teeth, and 2. bending of the mandible in the sagittal plane, which tends to approximate all teeth of the working side. The relative importance of each of these factors remains to be elucidated. Bending of the mandible has been considered previously but dismissed (4). One of the reasons was that bending would result in CPT increasing beyond open contact points, a situation not observed experimentally. However, such evidence is limited to a handful of subjects not described in detail (2,6). Previous studies have demonstrated tooth movement on the contralateral side of the arch even in subjects with missing teeth, and even when clenching the muscles without actually biting (43). Indirect evidence is provided by the observation that teeth posterior to the bite position also tend to tip mesially (54).

Limitations

There are limitations to this research, in addition to the thickness of the force transducer that was mentioned above, including: 1. $\Lambda_{\text{ctf}}$ was measured using a bite force that was 75 per cent of the maximum, thus exceeding the expected range during normal mastication, 2. only one measurement session was available per participant, so repeated measurements were not available for testing repeatability.

Conclusions

CTP was measured using a direct method. ACF, or more appropriately $\Lambda_{\text{ctf}}$, was related to bite force by a logarithmic model. We
speculate that CPT increases during biting through a combination of mesial inclination of teeth and bending of the mandible.

**Supplementary material**

Supplementary material is available at *European Journal of Orthodontics* online.

**References**
