European Journal of Orthodontics 33 (2011) 642–646
doi:10.1093/ejo/cjq127
Advance Access Publication 27 January 2011

Left/right asymmetries and open/closed differences of interdental forces in the mandible

Erwin Jonke*, Wolfgang Manschiebel**, Josef W. Freudenthaler*, Hans-Peter Bantleon* and Hermann Prossinger***
*Department of Orthodontics, Bernhard-Gottlieb University of Dentistry, Vienna, **Private Practice, Paudorf and ***Department of Anthropology, University of Vienna, Austria

Correspondence to: Professor Hermann Prossinger, Department for Anthropology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria. E-mail: hermann.prossinger@univie.ac.at

SUMMARY The aim of the present investigation was to study the variation in interdental forces between mandibular canines and lateral incisors of 19 volunteers (9 males and 10 females) aged 20–26 years for four configurations (mandible open/closed and left/right side). These forces were derived by pulling a stainless steel matrix strip between these teeth, six times per configuration, and registering the time variation with a high-resolution transducer. The repeated median smoothing algorithm was applied to find the maximum of each curve and a bootstrap method estimated the 95 per cent confidence intervals (CIs) for all 76 configurations.

Seventy-six per cent of all paired force differences were found to be significant. Asymmetry phenomena were observed: the interdental forces differed significantly between the left and right sides and also between the open and closed position of the mandible. The interdental forces (4–21 N) showed a pattern modulated by volunteer-specific features: in 91 per cent of the configurations, the interdental forces were larger when the mouth was open. This observed pattern contributes to the instability observed in clinical practice, thus necessitating permanent fixed lower retainer wear.

Introduction

Teeth experience forces not only during occlusion or biting. Forces exist between teeth at their contact points with their neighbours, so-called interdental forces (Southard *et al.*, 1989, 1991; Southard, 1992; Shigenobu *et al.*, 2007). These forces are not axial: the force direction is not along the root direction of the tooth. Research has been undertaken to assess how interdental forces vary with tooth position (Baydas *et al.*, 2004), aetiology (Mochers *et al.*, 2004), tooth width ratios (Bernabé *et al.*, 2004), and asymmetries (Shigenobu *et al.*, 2007). Until now, no study has addressed the issue of whether interdental forces differ when the mandible is in the open and closed position (Figure 1a). The aim of this study was to determine the interdental forces in the canine region of the mandible and to compare their magnitudes: whether they are the same when the mandible is open and when it is closed and whether they are statistically equal in the left and the right canine region.

Subjects and methods

Nineteen healthy volunteers with no history of orthodontic treatment (9 males and 10 females) aged 20–26 years participated in this investigation after signing an informed consent (Austrian Medical Ethics Commission Form No. EK-Nr. 376/2008). All had complete healthy dentitions from second molar to second molar in both jaws. Before the measurements were made, all individuals brushed their teeth for 1 minute with single-use tooth brushes (Happy Morning®; Hager & Werken GmbH KG, Duisburg, Germany) and then gargled a 0.2 per cent solution of chlorhexidine (Chlorhexamed®; GlaxoSmithKline, Bühl, Germany) for 1 minute.

A stainless steel matrix strip (Dentaurum®, 0.05 mm thick, 7 mm wide; Lot No. 326738; J.P Winkelstroeter KG, Ispringen, Germany) was inserted between the left mandibular canine and lateral incisor. While the volunteer was sitting in an upright position with their jaws as wide open as possible, one author (EJ) pulled the strip out from between these teeth at a nearly constant speed. Pulling of the steel strip was repeated five more times and then six times with the jaws closed without biting. In both the open and the closed configurations, the volunteers were asked not to let their lips contact the strip. The procedure was then repeated between the same two teeth on the right side. Between use, the matrix strip was sterilized in a glass-bead heater (STmini®; Hager & Werken GmbH) at 230°C for 20 seconds and then stored in a 96 per cent ethanol solution.

A stainless steel strip pulled between the canine and the lateral incisor results in friction that is proportional to the interdental force, viz.

$$F_{\text{pull}} = 2 \quad F_{\text{interdental}}$$

where μ is the coefficient of kinematic friction, estimated by Southard *et al.* (1989) to be 0.145 ± 0.02 [average ±

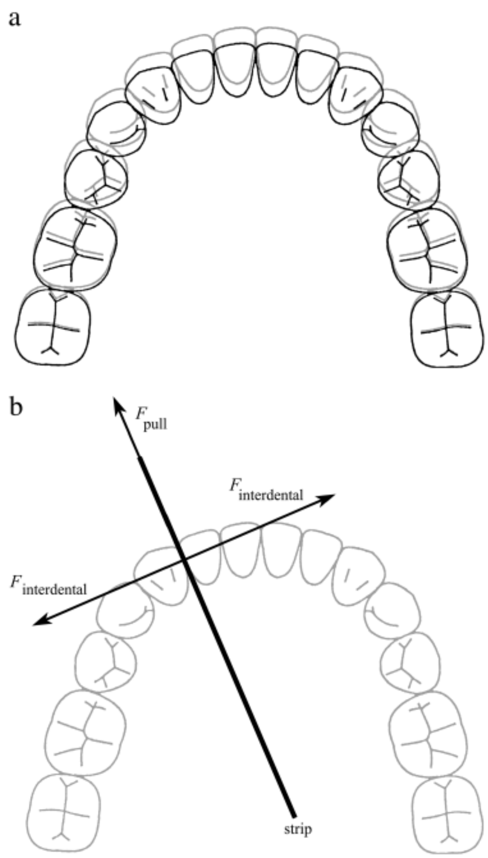

Figure 1 (a) Hypothesized deformation model when the mandible opens and closes. In this model, the dental arch is larger when the mandible is fully opened and shortened when the mandible closes, so the interdental force between the canine and the lateral incisor increases when the mandible opens. (b) The relationship between the interdental forces and the pull measured by the transducer attached to the stainless steel strip.

standard deviation (SD)]. Any differences in interdental forces between the canine and the lateral incisor (Figure 1b) are directly proportional to differences in pull on the strip.

The force registered by the transducer as a (digitized) voltage signal was stored on a hard disk. Two readouts are shown in Figure 2a. Rather than using the maximum reading, a narrow window (width 5 ms) for repeated median smoothing until convergence was used to determine the maximum force. A QQ plot (Crawley, 2007) was used to determine outliers in each of the 76 configurations (19 volunteers × left/right × open/closed).

The bootstrap method of resampling with replacement (Efron, 1981, 1987; Simon, 1998) was used to estimate the 95 per cent confidence interval (CI). Figure 2b shows an example of the procedure for one curve (volunteer 8, mouth open, right half of the mandible). The uncertainty of the estimate of the expectation value is estimated using the bias-corrected and accelerated method (Efron, 1987; Efron and Tibshirami, 1998). The mathematical formula was programmed by one author (HP) in Mathematica® v5.2 (Wolfram Research Inc., Champaign, Illinois, USA). Figure 3 shows how differences can be determined without assuming the existence of an underlying distribution that would otherwise be needed for conventional tests. The 95 per cent CIs estimated with the bootstrap method are graphed about the means. Whenever the resampling means of F_{closed} and F_{open} are unequal, the point lies above or below the (first) median; the difference between these two interdental forces is significant if the 95 per cent CI about these means do not overlap the (first) median.

Results

The findings of this study were threefold: the interdental forces changed as jaw opening ends. These changes were laterally asymmetric—the changes differed between the left and right side. These differences fluctuated asymmetrically between the open and closed jaw position (Figure 4).

The sessions with all volunteers resulted in a total of 456 curves; all were very 'noisy' (Figure 2a), which is why repeated median smoothing was employed. The QQ plot method detected a total of 28 outliers (6.1 per cent).

Interdental forces changed asymmetrically during closing. Figure 4 shows that the asymmetry of the interdental force differences is an important feature of mandiblular kinematics. Of the 38 differences between jaw open and closed, 29 (76 per cent) were found to be significant at the 95 per cent CI (Figure 4). For 25 (86 per cent) of these 29, the interdental force was greater when the jaw was open. However, in the 11 paired differences (i.e. when the left and right differences have the same sign), 10 (91 per cent) mandibles had a greater interdental force when the jaw was open and only one (9 per cent) when the jaw was closed (Figure 4). For one mandible (5 per cent), the interdental force increased on the left side when the jaw opened and decreased on the other. For 11 mandibles, paired differences were observed (therefore, the mandible as a whole showed a behaviour that was larger than the fluctuations ascribable to individual teeth). Nine of these paired differences (82 per cent) had a larger left difference.

For only two of the 19 volunteers (11 per cent), no difference between an open and closed position was observed (i.e. the CI overlapped), either on the left or on the right side. For the five mandibles in which only a difference on one side had a CI that did not overlap the median, four (80 per cent) had a greater interdental force when the mouth was open.

Discussion

Interdental forces in the canine region of the mandible were found to vary among individuals, between the open and closed position, and between the left and right side. These findings have not previously been reported and they raise a number of questions.

The difference in interdental force between the open and closed position implied that the mandible is non-rigid. Solar *et al.* (1994) investigated the biomechanical deformation of the mandible during opening and closing with a finite element model (FEM) and observed that the mandibular teeth

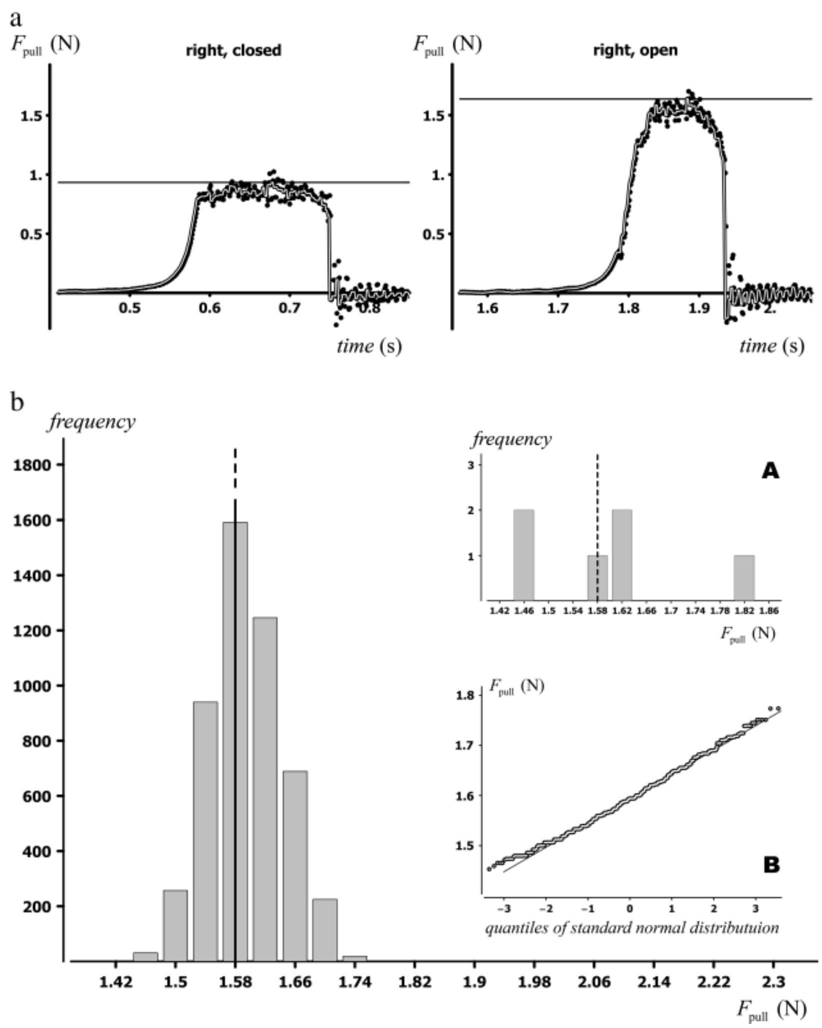

Figure 2 (a) The force as a function of time when a stainless steel strip is pulled through the proximal space between the lower right lateral incisor and the lower right canine of a volunteer (second trial open mandible and second trial closed mandible). The kinematic friction experienced by the strip fluctuates considerably. The ribbon line superimposed on the data points is the graph of the repeated median smoothing (with a window width of 5 ms) until conversion. The maximum values found by this smoothing are drawn as horizontal lines (closed mandible: 0.933 N and open mandible: 1.637 N). In this trial, the interdental force is larger when the mandible is open. (b) The outcome of estimating the 95 per cent confidence interval (CI) of the mean using the bootstrap method for this volunteer, open mandible, right side. The main graph shows the histogram of estimated means after 5000 resamplings. The average of the estimated means is drawn as a solid vertical line at the position 1.594 N (standard deviation after resampling = 0.049 N); the dashed vertical line is the estimated mean of the six measured maxima shown in the histogram of inset A. The asymmetry of the histogram frequencies is used to estimate bias in the bias-corrected asymmetry (BC_a) method of estimating the CIs graphed in Figure 3. Inset A: the histogram of the six maxima of the repeated median smoothing until convergence, as demonstrated in Figure 2a. The estimated mean of the six maxima, shown as a dashed vertical line is 1.594 N. Inset B: the QQ plot of the 5000 estimated means obtained by the method of resampling. The majority of these points are in the linear region of the QQ plot: the regression function is linear to a significance level $P < 2 \times 10^{-13476}$ with adjusted $R^2 = 0.99563$ (Bonferroni correction is not necessary when the probability is so low). The slight deviation from linearity is used to estimate the acceleration in the BC_a method for calculating the CIs in the bootstrap method.

moved approximately 0.14 mm between canine and lateral incisor because the bone is non-rigid. Their study attempted to distinguish between deformation of the mandible and subsequent tooth movement due to flexibility of the periodontal ligament without relating the directions of the movements to interdental forces and mandibular deformation. However, in their FEM, they could not determine any asymmetry as their methodology was not designed to identify this. A variation in anterior crowding is insufficient to explain why interdental forces vary between the open and closed mouth in such a consistent manner (Figure 3).

Southard *et al.* (1989) were the first to measure the interdental forces and define the anterior component of the occlusal force. The methodology used in the present study looked for indicators of mandibular deformation effects at the canine. In this region, interdental forces are neither anteriorly nor laterally directed. Any established base estimation of deformation would then be modulated by tooth movement of the incisors, which is of interest to orthodontists.

Left–right asymmetry in interdental forces arises because the human face is asymmetric. Lateral asymmetry in humans is a widespread phenomenon: shoe size, extremity length,

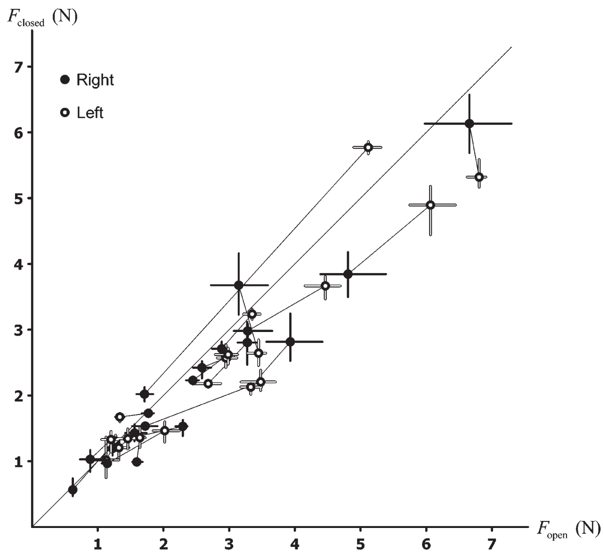

Figure 3 Graph of the pull on the stainless steel strip when the mouth is closed versus that when the mouth is open. The thin line is the (first) median ($F_{open} = F_{closed}$). Any point below this line is a case in which the interdental force is greater when the mandible is open. The horizontal and vertical bars at each point are the 95 per cent confidence intervals (CIs; vertical: closed mouth and horizontal: open mouth); the bars are not always symmetric about the resampled mean because of BC_a. Some CIs are so small that they cannot be displayed at the resolution of this graph. When the CIs do not cross the first median, the difference between the interdental forces is significant. Open circles represent left canine cases. The lines connecting the points indicate which left/right cases are from the same individual. Only one individual has both the left and the right canine exerting a significantly greater interdental force when the mandible is closed. If the horizontal and vertical CIs of a left case of one mandible do not overlap with those of the right case for the same mandible, then the lateral left ↔ right asymmetry is considered significant. The range of friction (1–6 N) implies that the interdental forces range from 4 to 21 N because the coefficient of friction has been estimated to be 0.145.

skull morphology, etc. (Schaefer *et al.*, 2006). Facial skull asymmetry implies asymmetric musculature and, consequently, asymmetry of forces on the mandibular body leading to its asymmetric deformation. Measuring interdental forces on the left separately from on the right estimates their respective contributions to mandibular deformations and consequently cancels out the contributions of local tooth movements, as clarified below. In this study, bite forces were excluded, so as not to add other force components that would mask the effects quantified.

Anthropologists have observed fluctuating asymmetry—an inter-individual variation in lateral asymmetry of the mandible in a population (Schaefer *et al.*, 2006). The variation of interdental force in the canine region could be due to a variation in dental crowding (Miethke, 2000; Acar *et al.*, 2002). All changes indicate that mandibular deformations contribute to the instability observed in clinical practice. Head posture influences the relationship between mandibular position and the upper jaw (Proffit, 1992; Fuhrmann *et al.*, 1998). A tendency to crowding has been attributed to late mandibular growth (Proffit, 1992). The present findings indicate that mandibular deformation due to opening and closing is also a contributing factor.

The implications for the practicing orthodontist are shown in Figure 3. Most obvious is the observation that the left and right sides of the mandible behave differently in many cases: a large percentage of the individuals have non-overlapping left and right CIs—many scores were not even close together. The lines connecting the right and left scores were often roughly parallel to the median; therefore, the change in interdental force, while different in the right and left canine region of the mandible, remained proportional. This proportionality is due to the overall geometry of the mandible, in particular its directional asymmetry (van Steenbergen and Nanda, 1995; Schaefer *et al.*, 2006) as well as confirmation that the mandible deforms in its entirety.

The eliminated outliers are cases where the measurement was unsuccessful, such as a volunteer involuntarily moving while the strip was being pulled, etc. Because the measurements in the present investigation were made *in vivo*, not on plaster casts, as in the study of Acar *et al.* (2002), considerable fluctuations of friction between the enamel and the stainless steel were observed (Figure 2a). It is not clear why stainless steel is not smooth enough to ensure a less noisy registration curve, perhaps due to measuring the dynamic friction at a resolution of 1 ms. A device with a lower time resolution may not record the maximum pull without a significant noise estimate, as would be the case for spring dynamometers (Southard *et al.*, 1989, Fuhrmann *et al.*, 1998, Acar *et al.*, 2002). It is therefore more expedient to use repeated median smoothing until convergence of the high-resolution transducer output. Repeated median smoothing until convergence is not based on any assumptions concerning the distribution of the fluctuations in the transducer signal and it is robust against outliers during the data run. Furthermore, sections from the same strip were used to eliminate possible variation in the coefficient of friction between strips.

This method and the statistical analysis showed remarkably consistent results (Figures 3 and 4): in 91 per cent of the cases the interdental force was significantly greater when the mandible was open. In particular, if the change in interdental forces showed the same sign on the left as on the right, then the deformation of the mandible must be a larger effect than any individual-specific root movement that may modulate the signal. A shortening of the dental arch when the mandible is closed occurs more frequently (Figure 4).

The interdental forces were large: 4–21 N. The numerical value of the coefficient of friction found by Southard *et al.* (1989), namely 0.145, implies that the measured friction is roughly 29 per cent of the interdental force.

Interdental force asymmetries allow an estimation of mandibular deformations during mandibular movement. Indeed, the mandible deformations while the jaw opens/closes may contribute to changes in dental crowding in

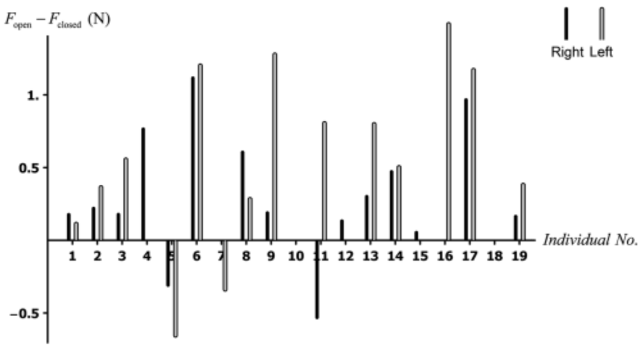

Figure 4 The pattern of interdental force differences and their asymmetries in the canine region of the mandibles of the 19 volunteers. Only statistically significant differences are shown. These occur more often when the mandible is open (86 per cent of 29 cases), and in only four (16 per cent) was the interdental force greater for the closed mandible. There are 10 mandibles (91 per cent) in which the interdental force is greater both on the left and on the right confirming the hypothesized model of anterior foreshortening when the mouth is closed. For one mandible (of volunteer 11), the asymmetry is so large that the mandible foreshortening is different between the left and right sides. In the 10 mandibles that conform to the hypothesized model, 80 per cent have a difference greater in the left part of the mandible.

regions not investigated in this study. Overall, the underlying causes for force asymmetries require more detailed explanations that can be found with further investigations. The putative causes not only deal with how the contact forces vary but also why. Because the mandible is not infinitely rigid, biomechanical explanations, such as outcomes of finite element analysis, would address the observed variations.

Tooth movement ascribable to mandibular deformation may imply the need for a lifelong retainer (Southard, 1992; Southard *et al.*, 1992; Little, 2009). The present findings are insufficient to specify how to customize individual canine-to-canine retainers. As these forces are larger than the forces exerted by the appliances, then the interdental forces between all teeth of the dentition need to be measured when designing customized retainers. Further investigations should aim at translating the implications of these findings into applications in a dental clinic.

Conclusions

The following conclusions can be drawn from the results of this study:

1. Interdental forces vary when the mandible opens and closes. This force variation is ascribable to mandibular deformations.
2. Interdental forces were asymmetrically distributed: most were found to be larger on the left side.
3. Interdental force changed from the open to the closed mandibule were rarely the same on the left and right sides.
4. The interdental forces almost always increased from the closed to the open position.
5. The interdental forces fluctuated asymmetrically within this study population.

Acknowledgements

We wish to thank A. Kühnelt-Leddihn and C. Vlaschitz, Technische Versuchs-und Forschungsanstalt, Vienna Technical University, for assistance with the experiment and electronic storage of the transducer output. We also thank the 19 volunteers who participated in this experiment.

References

Acar A, Alcan T, Erverdi N 2002 Evaluation of the relationship between the anterior component of occlusal force and postretention crowding. American Journal of Orthodontics and Dentofacial Orthopedics 122: 366–370

Baydas B, Yavuz I, Atasari N, Ceylan I, Dagsuyu I M 2004 Investigations of the changes in the positions of upper and lower incisors, overjet, overbite, and irregularity index in subjects with different depths of curve of Spee. Angle Orthodontist 74: 349–355

Bernabé E, Villanueva K M, Flores-Mir C 2004 Tooth width ratios in crowded and noncrowded dentitions. Angle Orthodontist 74: 765–768

Crawley M J 2007 The R book. Wiley and Sons, Chichester

Efron B 1981 Nonparametric estimates of standard error: the jackknife, the bootstrap and other methods. Biometrika 68: 589–599

Efron B 1987 Better bootstrap confidence intervals. Journal of the American Statatistical Association 81: 171–200

Efron B, Tibshirami R J 1998 An introduction to the bootstrap. Monographs on Statistics and Applied Probability 57. Chapman & Hall/CRC Press, Boca Raton

Fuhrmann R, Grave C, Diedrich P 1998 Perioperative progress check of interdental forces following extraction of third molars. Journal of Orofacial Orthopedics 59: 155–167

Little R M 2009 Clinical implications of the University of Washington post-retention studies. Journal of Clinical Orthodontics 43: 645–651

Miethke R R 2000 No correlation between primary mandibular anterior crowding and vertical craniofacial configuration or lower incisor inclination. Journal of Orofacial Orthopedics 61: 297–304

Mochers O, Aubry M, Mafart B 2004 Dental crowding in a prehistoric population. European Journal of Orthodontics 26: 151–156

Proffit W R 1992 Contemporary orthodontics. Mosby Yearbook, St Louis

Schaefer K, Lauc T, Mitteroecker P, Gunz P, Bookstein F L 2006 Dental arch asymmetry in an isolated community. American Journal of Physical Anthropology 129: 132–142

Shigenobu N, Hisano M, Shima S, Matsubara N, Soma K 2007 Patterns of dental crowding in the lower arch and contributing factors: a statistical study. Angle Orthodontist 77: 303–310

Simon J L 1998 Resampling: the new statistics. Resampling Inc., Arlington

Solar P, Pleschberger M, Wiesinger S, Matejka M, Watzek G 1994 Auslenkung von implantatgetragenem Zahnersatz durch funktionelle Verformung der Mandibula. Zeitschrift für Zahnärztliche Implantologie 10: 106–112

Southard T E 1992 Third molars and incisor crowding: when removal is unwarranted. Journal of the American Dental Association 123: 75–79

Southard T E, Behrendts R G, Tolley E A 1989 The anterior component of occlusal force. Part I: measurement and distribution. American Journal of Orthodontics and Dentofacial Orthopedics 96: 493–500

Southard T E, Southard K A, Tolley E A 1992 Periodontal force: a potential cause of relapse. American Journal of Orthodontics and Dentofacial Orthopedics 101: 221–227

Southard T E, Southard K A, Weeds L W 1991 Mesial force from unerupted third molars. American Journal of Orthodontics and Dentofacial Orthopedics 99: 220–225

van Steenbergen E, Nanda R 1995 Biomechanics of orthodontic correction of dental asymmetries. American Journal of Orthodontics and Dentofacial Orthopedics 107: 618–624