**ABSTRACT**

Occlusal splints are used for the management of temporomandibular disorders, although their mechanism of action remains controversial. This study investigated whether insertion of an occlusal splint leads to condyle-fossa distance changes, and to mandibular rotation and/or translation.

By combining magnetic resonance images with jaw tracking (dynamic stereometry), we analyzed the intra-articular distances of 20 human temporomandibular joints (TMJs) before and after insertion of occlusal splints of 3 mm thickness in the first molar region. For habitual closure, protrusion, and laterotrusion in the contralateral joint, occlusal splints led to minor—yet statistically significant—increases of global TMJ space and to larger increases at defined condylar areas. Condylar end rotation and translation in habitual closure were reduced. Hence, the insertion of a 3-mm-thick occlusal splint led to a change in the topographical condyle-fossa relationship, and therefore to a new distribution of contact areas between joint surfaces.

**KEY WORDS:** biomechanics, Magnetic Resonance Imaging, stress, mechanical, occlusal splints, temporomandibular joint disorders, temporomandibular joint.
on MR images, systemic diseases, or contraindications for MR recordings (implanted metal or medical devices, claustrophobia, tattoos). The local ethics committee approved the study protocol.

Occlusal Splint
The maxillary occlusal splint was constructed in a Gerber articulator (Condylator Service, Zürich, Switzerland) after the vertical dimension between the casts was increased until a clearance of slightly more than 3 mm between the mesial marginal ridge of the first molar and the opposing occlusal surfaces was reached. The splint, processed by means of cold-cure acrylic (Candulor Aesthetic, Candulor AG, Wangen b. Dübendorf, Switzerland), had all the features of a Michigan splint, i.e., coverage of all teeth, one occlusal contact point per antagonist, freedom in centric and canine guidance in protrusion and laterotrusion, to produce occlusal clearance in the molar area of approximately 1 mm. Only the slope of the anterior canine guidance was modified. Two grooves of approximately 1-mm depth were carved into the cuspid rise to guide the protrusive and laterotrusive movements reproducibly. After being processed, the splint was remounted and adjusted until one occlusal contact per antagonist and a thickness of approximated 3 mm in the first molar area were reached. For confirmation of splint thickness, a small hole was drilled in the splint at the mesial marginal ridge of the first molar, and verification measurements were performed by means of a calibrated rod inserted into the hole.

The same casts were also used to construct the metal frames used to attach the frames carrying the light-emitting diodes (LED) to the dental arches (Mang, 2006).

Data Acquisition
MR images were obtained from both temporomandibular joints and then software-reconstructed three-dimensionally (3D). The jaw was tracked opto-electronically. The tracking data were then combined with the anatomical data to display the position and the motion of the entire condyle within the fossa in 3D. This method, called “dynamic stereometry”, has been described in detail elsewhere (Palla et al., 2003; Gallo, 2005).

Experimental Procedure
At first, the occlusal splint was adjusted with the person sitting upright and performing rapid unguided opening and closing movements in the habitual closure path (habitual closure without splint = maximum intercuspation). The adjustment was terminated when even contacts between the splint occlusal surface and each antagonistic tooth were recorded by means of an articulating foil (Hanel 12 µ), and the person felt even occlusal contacts. Thereafter, the splint was removed, and the metal frames carrying the LEDs were attached to the upper and lower dental arches by means of light-cured glass-ionomer cement (Vitrebond, 3M ESPE, 3M AG, Rüschlikon, Switzerland). After the measurements required to combine the jaw-tracking coordinates with those of the MR images were taken (Fig. 1A), the person was asked to bite effortlessly in habitual closure (static measurement), and this position was recorded by means of the one-dimensional charge-coupled device (CCD) cameras of the opto-electronic system 3 times for approximately 1 sec each. Subsequently, 3 series of 4 protrusive and 4 laterotrusive movements to the right and left under tooth guidance were recorded (dynamic measurements). Finally, the splint was inserted, and corresponding recordings were performed, all with splint contact (Fig. 1B).

Data Analysis
Condyle-Fossa Distance
The effect of the occlusal splint on the condyle-fossa distance was assessed by two parameters: (1) the global minimum condyle fossa-distance \( h_{\text{min}} \), defined as the mean of the 30 minimal
distances between the polygon vertices of the condyle and fossa surfaces (Fig. 1C); and (2) the condyle-fossa distance \( h_{\theta} \) at the condylar point \( P_\theta \) defined as the point on the condylar surface closest to the fossa in maximum intercuspation, i.e., without the person wearing the splint (Fig. 2A). In this situation, \( h_{\text{min}} \) was identical to \( h_{\theta} \). The spatial coordinates of \( h_{\text{min}} \) in relation to the condylar surface were determined for the recordings without and with splint obtained in closed position. The parameters \( h_{\text{min}} \) and \( h_{\theta} \) were averaged over all time steps during each recording. The condyle-fossa distance during laterotrusion was calculated only for the balancing-side joint.

**Condylar Translation and Rotation**

To analyze the effect of occlusal splint insertion on condylar position, we computed the spatial translation (mm) and rotation (°) around the condylar main axis (Fig. 2B). The reference point for the rotation was the mid-point of the condylar main axis connecting the 2 condylar poles. A detailed description of the materials and methods has been published elsewhere (Mang, 2006).

**Statistical Analysis**

Data from the left joints were mirrored so that all asymmetric parameters had the medial part on the left and the lateral part on the right. After Kolmogorov-Smirnov tests, data were analyzed by analysis of variance for repeated measurements at a significance level of \( p < 0.05 \), with the following intra-individual factors: side, presence/absence of splint, and mandibular position/movement (habitual closure, protrusion, laterotrusion).

**RESULTS**

**Condyle-Fossa Distance**

**Global Minimum Condyle-Fossa Distance \( (h_{\text{min}}) \)**

The insertion of the occlusal splint led to a slight, yet statistically significant, increase of \( h_{\text{min}} \) for all positions: habitual closure (median/mean of 0.3/0.3 mm; interquartile range, 0.2 to 0.6 mm), protrusion (median/mean of 0.4/0.3 mm; interquartile range, 0.0 to 0.5 mm), and laterotrusion (median/mean of 0.3/0.2 mm; interquartile range, 0.0 to 0.6 mm) (Table). The increase in \( h_{\text{min}} \) was found in 16 TMJs in closed position and in 15 TMJs during protrusion and laterotrusion. Splint insertion led to a change in the position of the global minimum joint space in relation to the condylar surface dorsoventrally (median of 1.7 mm, range -7.5 to 5.4 mm), latero-medially (median of 1.8 mm, range -2.1 to 7.7 mm), and craniocaudally (median of 2 mm, range -1.2 to 4.6 mm) (example of one joint in Fig. 3A). The displacement vectors for all left and right joints are represented in Fig. 3B.

**Condyle-Fossa Distance \( (h_\theta) \) at Point \( P_\theta \)**

The insertion of the occlusal splint produced a statistically significant increase of \( h_\theta \) for all positions: habitual closure (median/mean of 1.5/1.6 mm; interquartile range, 0.9 to 2.1 mm), protrusion (median/mean of 1.7/1.8 mm; interquartile range, 1.3 to 1.9 mm), and laterotrusion (median/mean of 1.6/1.6 mm; interquartile range, 1.1 to 2.1 mm) (Table). The increase was observed in all joints.

**DISCUSSION**

The objective of this study was to analyze, by means of dynamic stereometry, the effect of the insertion of a 3-mm-thick occlusal splint on the condyle-fossa distance in asymptomatic persons while mandibular teeth were kept occluding in various positions, such as habitual closure, during protrusion, and during laterotrusion. This study is therefore the first to provide an analysis of changes in the condyle-fossa distance, not only three-dimensionally and dynamically, but also over the entire joint surface, in contrast to other studies, where the condyle-fossa distances were measured statically and only on one joint section (Kuboki et al., 1997, 1999).

The results revealed that the global minimum condyle-fossa distance \( h_{\text{min}} \) increased significantly after the insertion of a 3-mm-thick occlusal splint for effortless habitual closure, as well as
vectors (in red) of condylar position. It is worth noting that the most posterior condylar region. As for the measurement of than the variation of different disc thickness that would coincide with the rotation/translation of the condyle-disc complex and/or by a simultaneous jaw opening in persons wearing the occlusal splint. further revealed a slight ventral and caudal shift of the condyle and a shock absorption. When its properties are altered, the functional disc to serve as the primary element for stress distribution and poroviscoelastic properties (Beek et al., 2003). These allow the minimum joint space \( h_{min} \) in habitual closure without and with the occlusal splint. The shaded portion of the Fig. shows the average main condylar axes (in orange) and hemi-ellipses bordering the cranio-ventral quadrants of the condyles (in brown). The intracondylar distance is not to scale. All displacement vectors are located cranio-ventrally to the main condylar axes. Cc, caudocranial; dv, dorsoventral; rl, right-left.

Figure 3. Changes in TMJ space due to splint insertion. (A) Example of the position of the global minimum joint space \( h_{min} \) in habitual closure without and with the occlusal splint. (B) Displacement vectors (in red) of \( h_0 \) for all left and right joints studied. The shaded portion of the Fig. shows the average main condylar axes (in orange) and hemi-ellipses bordering the cranio-ventral quadrants of the condyles (in brown). The intracondylar distance is not to scale. All displacement vectors are located cranio-ventrally to the main condylar axes. Cc, caudocranial; dv, dorsoventral; rl, right-left.

as during sliding movements. The increase was small, however, and it is arguable whether this difference translates into joint load reduction. Due to the incongruent shapes of both the condyle and the fossa, the location of \( h_{min} \) shifted in all joints. Analysis of our data further revealed a slight ventral and caudal shift of the condyle and a simultaneous jaw opening in persons wearing the occlusal splint.

Also, the minimum condyle-fossa distance \( h_0 \) at point \( P_0 \) (i.e., the point on the condylar surface closest to the fossa in maximum intercuspation with the person not wearing the splint) increased significantly with splint insertion, both in habitual closure as well as during sliding movements. The variation of \( h_0 \) was much larger than the variation of \( h_{min} \). This change might be caused either by the rotation/translation of the condyle-disc complex and/or by a different disc thickness that would coincide with \( P_0 \) at the new condylar position. It is worth noting that \( P_0 \) was never located in the most posterior condylar region. As for the measurement of \( h_{min} \), notable inter-individual differences have also been observed for \( h_{0} \), possibly due to differences in joint anatomy.

It has been postulated that during clenching as well as jaw movements, forces between the condyle and the articular eminence are compressive and tangential in nature and undergo different magnitude levels (Kuboki et al., 1997, 1999). It can be assumed that the intra-articular distance is mainly influenced by the disc’s poroviscoelastic properties (Beek et al., 2003). These allow the disc to serve as the primary element for stress distribution and shock absorption. When its properties are altered, the functional effectiveness of the disc is reduced, presumably resulting in increased joint failure (Chen et al., 1999). Hence, degenerative joint disorders may be the result of mechanical joint overload, and there seems to be an association between the intensity and frequency of mechanical stress and the reaction of the cartilage matrix (Milam and Schmitz, 1995). Investigating joint load in vivo, however, requires invasive direct monitoring of joint forces, which has never been successfully performed due to technical challenges. Therefore, rather than investigating intra-articular distances of the TMJ under load, this study focused on joint space changes when joint forces were minimized by keeping the mandibular teeth occluding with only minimal pressure in effortless habitual closure.

We also observed that the path of the minimum condyle-fossa distance during movements varied, likely due to person-specific TMJ morphologies (data not reported). This effect, as well as the shift of the area of minimum condyle-fossa distance in habitual closure after occlusal splint insertion, is an indirect indicator of changes in contact areas, and therefore contact stresses, between and among the different joint components. This contact area shift may contribute to an altered TMJ mechanical environment, a concept well-established for other load-bearing joints, such as the knee, where wedge osteotomies are performed to redistribute contact stresses for the management of osteoarthritis (Dahl et al., 2005; Brouwer et al., 2006; Ramsey et al., 2007).

However, the findings of this study must be interpreted with caution regarding pain relief following splint therapy in the case, for instance, of osteoarthritis. First, our data were collected on a sample of asymptomatic persons, and therefore cannot be extrapolated to pain patients. Second, dynamic stereometry is based on the reconstruction and animation of the TMJ by means of anatomical and kinematic data. Although the technique is currently the most suitable method to study variations of the intra-articular space under static and dynamic conditions, it is still unknown whether mandibular deformation affects condyle-fossa measurements under larger bite forces, as might occur during parafunction. Nevertheless, it has been reported that bilateral biting in the canine area, even with a force up to 150 N, does not produce a mandibular deformation in the premolar area (Jiang and Ai, 2002). Since the participants in this study held the mandible effortlessly in contact with the opposing arch (without and with splint), it can be reasonably assumed that negligible deformation occurred in the TMJ area.

With the same method, results of experiments in which the person was asked to clench on a force transducer placed in different areas of the dental arch showed that the minimum intra-articular distance decreased with increasing bite forces (unpublished...
observations). It is therefore likely that the augmented global minimum intra-articular distance found in this study could be neutralized if the person were to clench or brux with high force. Splint insertion, however, is likely to cause a shift in the position of the minimum intra-articular distance (and therefore of the contact stress areas), when habitual closure as well as sliding movements occur with high force. This will be the focus of future studies.

In conclusion, dynamic stereometry showed that the insertion of a 3-mm-thick occlusal splint led to a redistribution of the condyle-fossa distances in the TMJ, both during habitual closure as well as during sliding movements, thus redistributing contact areas between joint surfaces.

ACKNOWLEDGMENTS

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REFERENCES


Table. Condyle-Fossa Distance Parameters without and with Occlusal Splint and Differences (1st q = first quartile; 3rd q = third quartile; * = p < 0.05; ** = 0.01; *** = 0.001)

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