Influence of bolus size and chewing side on temporomandibular joint intra-articular space during mastication

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Abstract: Previous studies suggested that, during mastication, magnitude and location of mechanical load in the temporomandibular joint (TMJ) might depend on chewing side and bolus size. Aim of this study was to dynamically measure the TMJ space while chewing on standardized boluses to assess the relationship among minimum intra-articular distances (MID), their location on the condylar surface, bolus size, and chewing side. Mandibular movements of 12 participants (6f, 24±1y.o.; 6 m, 28±6y.o.) were tracked optoelectronically while chewing unilaterally on rubber boluses of 15 × 15 × 5, 15 × 15 × 10, and 15 × 15 × 15 mm3 size. MID and their location along the main condylar axis were determined with dynamic stereometry. MID were normalized on the intra-articular distance in centric occlusion. Repeated measures ANOVA (= 0.05) showed that MID were smaller on the balancing (0.74±0.19) than on the working condyle (0.89±0.16) independently of bolus size ($p < 0.0001$). MIDs did not differ between 5 and 10 mm bolus thicknesses (0.80±0.17) but increased for 15 mm (0.85±0.22, $p = 0.024$) and were located mostly laterally, close to the condylar center. This study confirmed higher reduction of TMJ space on the balancing than on the working condyle during mastication. Intra-articular distances increased significantly for the greatest bolus thickness. Loaded areas were located laterally, for both working and balancing joint.

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Influence of bolus size and chewing side on temporomandibular joint intra-articular space during mastication

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ABSTRACT

Previous studies suggested that, during mastication, magnitude and location of mechanical load in the temporomandibular joint (TMJ) might depend on chewing side and bolus size. Aim of this study was to dynamically measure the TMJ space while chewing on standardized boluses to assess the relationship among minimum intra-articular distances (MID), their location on the condylar surface, bolus size, and chewing side. Mandibular movements of 12 participants (6f, 24±1y.o.; 6 m, 28±6y.o.) were tracked optoelectronically while chewing unilaterally on rubber boluses of 15 × 15 × 5, 15 × 15 × 10, and 15 × 15 × 15 mm^3 size. MID and their location along the main condylar axis were determined with dynamic stereometry. MID were normalized on the intra-articular distance in centric occlusion. Repeated measures ANOVA ($\alpha = 0.05$) showed that MID were smaller on the balancing (0.74±0.19) than on the working condyle (0.89±0.16) independently of bolus size ($p < 0.0001$). MIDs did not differ between 5 and 10 mm bolus thicknesses (0.80±0.17) but increased for 15 mm (0.85±0.22, $p = 0.024$) and were located mostly laterally, close to the condylar center. This study confirmed higher reduction of TMJ space on the balancing than on the working condyle during mastication. Intra-articular distances increased significantly for the greatest bolus thickness. Loaded areas were located laterally, for both working and balancing joint.

1. Introduction

Osteoarthritis (OA) or degenerative joint disease (DJD) of the temporomandibular joint (TMJ) is a severe form of temporomandibular disorder (TMD), which results from the failure of balance between degenerative and regenerative tissue responses under sustained mechanical load exceeding the adaptive capacity of the joint tissues [1,2]. Functional overload, due to various factors, such as excessive use, parafunction, anatomical incongruity, and emotional stress, is considered a possible cause of DJD [3].

Mastication is a complex physiological function of the stomatognathic system. During the masticatory process, the first stage of digestion is initiated through the crushing and grounding of food by the teeth [4]. While performing chewing movements, the masticatory system undergoes the highest functional load in terms of muscle activation and joint reaction forces. Previous studies investigated muscle activation patterns during masticatory movements by means of surface electromyography (EMG) [5–9]. Farella et al. [6] showed that the mean EMG amplitude of masseter and temporalis muscles activity measured by chewing of hard food was highest than other functional and parafunctional movements such as static and dynamic incisal biting, jaw protrusion, laterotrusion, light clenching. Furthermore, masticatory muscle activity was higher on the working than on the balancing side.

Biomechanics researchers have also investigated TMJ reaction forces during masticatory movements. In the past, attempts of direct measurement of these forces was performed in primates by inserting strain gauges into the joint space. Results suggested that reaction forces during chewing were higher than during clenching and incisal biting [10,11]. However, due to anatomical features, a direct approach for the measurement of human TMJ loading is not ethically feasible. Mathematical modeling based on non-invasive methods remains the best way to investigate TMJ function. Finite element method (FEM) and musculoskeletal modeling are widely used to estimate forces acting on masticatory system

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[12–19]. While those results suggest a higher loading of the lateral part of the TMJ disc, FEM requires several mathematical assumptions and musculoskeletal modeling often rely on a simplified representation of TMJ and mandibular anatomy, which calls into question the results.

Another indirect approach to assess TMJ loading is offered by the "dynamic stereometry" method that combines 3D software models of mandibular anatomy with jaw tracking information. With this method it has been observed that TMJ space reduction can indicate the areas of higher joint loading [20–24]. Studies based on dynamic stereometry presented a non-invasive and more precise determination of subject-specific intra-articular space during function, providing information about mechanical loading of TMJ articular surfaces. However, most of these studies described mechanical stress relative to the articular surface of the fossa and to the fossa eminence, and the results focused on the most compressed part of the articular disc or on the translation path of the most stressed points during joint motion [13,24,25]. To date, little has been investigated with regard to the condylar articular surface, even though, according to imaging observations, the most severe tissue deterioration involves mostly the bone structures of the joint, especially the condylar head [26,27].

The aim of this study, therefore, was to investigate the stress distribution on the articular surface of the TMJ condylar head during chewing of a standard bolus and to evaluate the influence of chewing side and bolus size on the part of the condyle undergoing the highest load. For this purpose, the joint space between articular surfaces was traced by means of dynamic stereometry and the location with the minimum joint space value was marked on the articular surface of the TMJ condylar head.

The following null hypotheses were tested: (a) TMJ space changes are independent of chewing side and food bolus size; (b) TMJ stress-field location is independent of condylar topography, chewing side and food bolus size.

2. Materials and methods

2.1. Subjects

Twelve subjects (6 females, aged 24 ± 1 year; 6 males, aged 28 ± 6 years) were enrolled in this study as paid volunteers among students and staff members of the University of Zurich. The sample size was chosen based on previously reported data [20]. At the time of the study all subjects were older than 18 years and had no history, signs, or symptoms of TMD, based on magnetic resonance imaging (MRI) and assessments performed by calibrated examiners according to the guidelines of the diagnostic criteria for temporomandibular disorders (DC/TMD) [28,29] (http://www.iadr.org/INfORM/DC-TMD). Subjects with confirmed pregnancy, severe skeletal class II or class III occlusion, wearing orthodontic brackets or wires, were excluded from the study. Participants were informed about the experimental procedure and assured that they could leave the study at any time. The Ethics Committee of the State of Zurich approved the study protocol and written informed consent was obtained from all participants (KEK-ZH Nr. 2014-0123).

2.2. Data acquisition

TMJ intra-articular distances were measured by means of dynamic stereometry. This non-invasive, *in vivoin vivo*, three-dimensional, and subject-specific analysis of the TMJ, yields information on the geometric relationship between condyle and fossa, and indirectly on contact stresses arising during movement in the joint capsule space. Dynamic stereometry combines three-dimensional digital reconstructions of the TMJ anatomy obtained with 3D imaging techniques with kinematic recordings, and animates them with six degrees of freedom [21].

For the purpose of this study, MR scans of both TMJ anatomies were obtained for each subject by means of a 1.5 Tesla system (Gyroscan ACS-II R, Philips Medical Systems, Netherlands) with image stack dimensions 160 × 160 × 75 mm and voxel size 0.9 × 0.9 × 0.9 mm^3. During the scan, the subjects were biting on a customized occlusal appliance rigidly connected to a face-bow carrying a reference system, used to associate the MR coordinates with those of the motion tracking system [30]. Successively, the contours of condyle and fossa images were manually segmented and the anatomical surfaces by means of a 3D visualization software (Amira™ v. 6, FEI, Hillsboro OR, USA) [21,24,31]. Mandibular movements were recorded by means of a custom-built optoelectronic system (OPTIS, Laboratory of physiology and biomechanics of the masticatory system, University of Zurich), consisting of three custom-made cameras with cylindrical lenses (dimensions: 25 × 50 mm, Focal Length: 75 mm, Edmund Optics Ltd, York, UK) and linear CCD arrays (2048 elements, array length 26.624 mm) mounted on a metal arm with fixed geometry. The cameras record the location of a maximum of three triplets of light-emitting diodes (LEDs) arranged triangularly on printed circuit boards (triangular target frames, TTFs), thus acquiring maxillary and mandibular position with six degrees-of-freedom at 200 Hz frequency and a resolution ≤ 5 μm. The collected analog signals of the TTFs are sent to a digital signal processor (DSP) and the digitized signal are saved in a Windows® based computer connected to the DSP via TCP/IP [32,33].

2.3. Experimental procedure

In a first session, alginate impressions of the upper and lower dentition of the subjects were taken (Palgat TM plus, 3M ESPE, 3M Deutschland, GmbH, Neuss, Germany) and two custom acrylic partial splints matching the front teeth of the superior and inferior arch were formed (DuraLay dema dent AG, Grindelstrasse 6, CH-8303 Basserdorf).

On the day of the recording, the splints were rigidly connected to the teeth using a dental compomer (Filtek Supreme XTE Flowable Nanocomposite, 3M ESPE, 3M Deutschland, GmbH, Neuss, Germany) without etching or bonding the tooth surface. The splints were positioned so that they interfered neither with each other nor with the patient's occlusion. Before the jaw tracking session, one TTF was connected to the superior splint (maxillary TTF), and the second to the inferior splint (mandibular TTF), always on the right-hand side of the head (Fig. 1). At the beginning of the session, two static recordings were taken, the first one (*registration*) with the subject biting into the same occlusal appliance connected to the face-bow used as a reference in the MR scan, and the second one in *centric occlusion*. Afterwards, subjects were instructed to chew unilaterally for three times on standardized rubber boluses of unalterable consistency (Permadyne Penta H impression material, 3M ESPE, 3M Deutschland GmbH, Neuss, Germany). For the experiments, three types of boluses with prismatic geometry, differing only in thickness, were formed (15 × 15 × 5 mm^3, 15 × 15 × 10 mm^3, 15 × 15 × 15 mm^3) (Fig. 1a). Each movement recording was repeated three times. For each subject, a set of recordings was made, first while chewing the rubber bolus ipsilaterally (working side), and then contralaterally (balancing side) to the TTFs (Fig. 1b).

2.4. Data processing

After the jaw tracking session, the digital models of the TMJ anatomies were animated with the motion information using a custom-made software developed at the Laboratory of Physiology

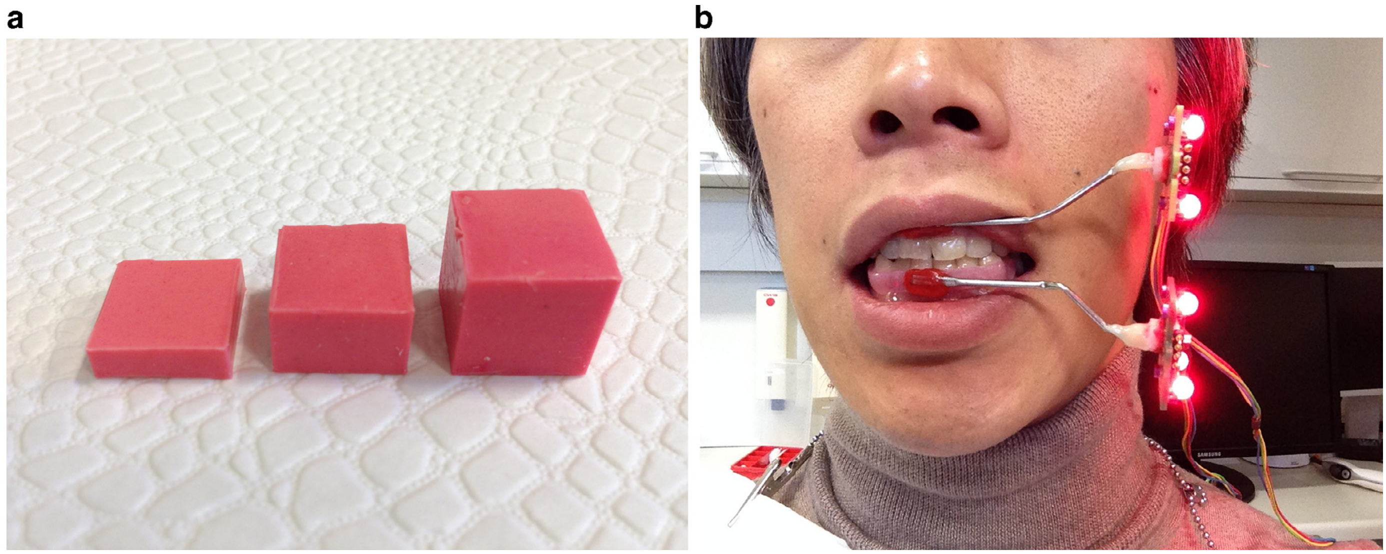

Fig. 1. (a) The synthetic boluses manufactured for the mastication experiment. The dimensions only differ in the thickness (5 mm, 10 mm, 15 mm), whereas the base remains the same (15 × 15 mm^2). (b) Positioning of the custom-made splints on the subject's dental arches. The splints carry the TTFs with the triplets of LEDs to be recorded by the CCD-cameras.

and Biomechanics of the University of Zurich. The software application was written in the programming language C++, using the Fast Light Toolkit (FLTK) libraries for the generation of the Graphical User Interfaces (GUI) and Open Inventor libraries, based on OpenGL® API, for the visualization and handling of 3D Objects. More detailed information on the software features and its applications can be found elsewhere [32]. At each time step of mandibular motion, the magnitude and spatial location of the minimum intra-articular distance (MID, X_{mid}, Y_{mid}, Z_{mid}) between the condyle and fossa surfaces were determined for all joints and all recorded movements. MIDs for chewing movements were determined for each chewing cycle and normalized as the ratio between the minimum value of the intra-articular distance determined in the chewing movement and the average value of the intra-articular distance measured with the teeth in gentle contact (*centric occlusion*). Furthermore, the mediolateral position of the MID along the main condylar axis was assessed as a measure of the stress-field location in the joint [31,34,35]. For this purpose, lateral and medial condylar poles (LP and MP) were marked on the surface of the 3D model of the condyle, and the center point of the condyle (CP) was calculated as the mid-point of the LP-MP segment (*intracondylar axis*). Finally, the normalized location of the minimum intra-articular distance Z_{mid} along the intracondylar axis was determined for each joint. Zero value was located at CP, negative values were located laterally (lateral pole = −0.5) and positive values were located medially (medial pole = 0.5).

2.5. Statistical analysis

In a preliminary analysis, descriptive statistics and normality tests were implemented. According to Kolmogorov-Smirnov and Shapiro-Wilk tests the data was normally distributed. The effect of bolus size and chewing side were then tested by analysis of variance (ANOVA) for repeated measures. The level of significance was set at $\alpha = 0.05$. When a significant difference was found, post hoc tests with Bonferroni correction were performed. Statistical analyses were performed using IBM SPSS 22.0 (IBM Corp, Armonk, NY, USA). All values given in the results section are represented as mean ± standard deviation unless differently specified.

Table 1
Minimum intra-articular distances during mastication of rubber boluses. Mean±standard deviation of minimum intra-articular distances normalized by minimum distances at resting position.

Condition\bolus	5 mm	10 mm	15 mm	All boluses
working	0.87 ± 0.13	0.86 ± 0.08	0.95 ± 0.21	0.89 ± 0.16
balancing	0.73 ± 0.18	0.73 ± 0.21	0.76 ± 0.18	0.74 ± 0.19
All conditions	0.80 ± 0.17	0.80 ± 0.17	0.85 ± 0.22	

3. Results

The values of the normalized MID during three unilaterally chewing cycles for the working side and the balancing side with 5 mm, 10 mm, and 15 mm bolus thickness respectively are described in Table 1.

MIDs were smaller on the balancing side than on the working side independently of the bolus size ($p < 0.0001$). Distances did not differ between 5 mm bolus and 10 mm bolus but increased for the 15 mm bolus for both balancing and working side ($p = 0.03$) (Fig. 2).

The MID spatial position, indirectly representing the stress-field location, was mostly located centrally and slightly laterally on both of the working and balancing side (Fig. 3). The average distance of the MID to the condylar center CP for the working side and the balancing side with 5 mm, 10 mm, and 15 mm bolus thickness are reported in Table 2. No statistically significant differences were found among bolus sizes nor chewing side (Fig. 4).

4. Discussion

This study investigated the relationship between the area of the TMJ condylar surface mostly loaded during chewing, bolus size and chewing side by analyzing the magnitude and location of the minimum TMJ intra-articular distances during unilateral chewing of a standardized bolus with constant consistency.

As results show, during unilateral chewing the articular space decreased more on the balancing side than on the working side, which implies that compressive stresses on the condylar surface were greater in the non-bolus TMJ than in the bolus TMJ. This result is in accordance with previous studies. These studies analyzed the location of the minimum intra-articular distance during

Table 2
Medio-lateral location of the minimum intra-articular distance on the articular surface of the condyle. Mean±standard deviation of the location of the minimum intra-articular distances along the medio-lateral direction of the condylar head. Condylar head center line = 0; lateral pole = −0.5; medial pole = 0.5.

Condition\bolus	5 mm	10 mm	15 mm	All boluses
Working	−0.03 ± 0.17	−0.01 ± 0.15	−0.01 ± 0.13	−0.02 ± 0.15
Balancing	−0.01 ± 0.16	0.00 ± 0.14	−0.02 ± 0.15	−0.01 ± 0.15
All conditions	−0.02 ± 0.16	−0.01 ± 0.14	−0.02 ± 0.14	

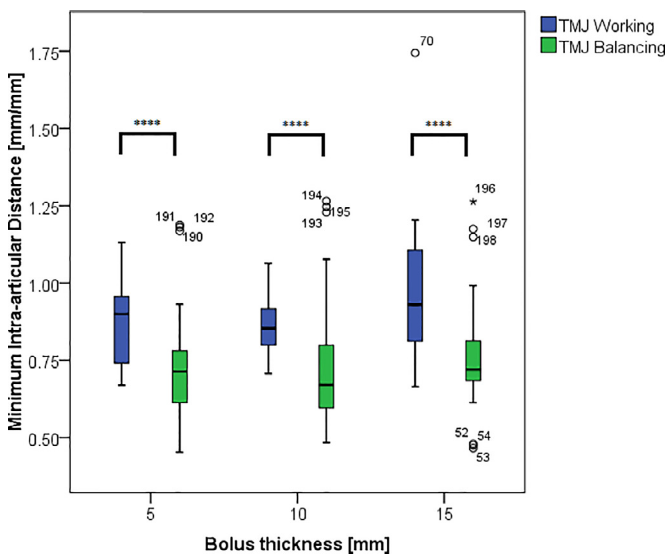

Fig. 2. Boxplots of the normalized values of MID (mm/mm) according to bolus thickness (5 mm, 10 mm, 15 mm), with TMJ acting as working side (blue) or balancing side (green). Black circles and their corresponding numbers represent the cases with values between 1.5 and 3 times the inter-quartile (IQ) range (outliers). MID was significantly smaller for the joint acting as balancing than for the joint acting as working, for all bolus thicknesses (****=$p < 0.0001$).

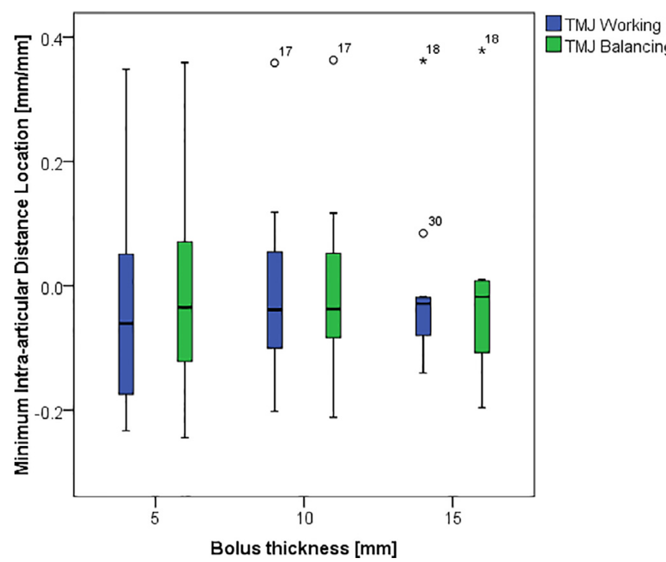

Fig. 4. Boxplots of the normalized location of MID (mm/mm) on the mediolateral direction of the intra-condylar axis, according to bolus thickness 5 mm, 10 mm, 15 mm, with the TMJ acting as working side (blue) or balancing side (green). Black circles and their corresponding numbers represent the cases with values between 1.5 and 3 times the inter-quartile (IQ) range (outliers).

opening-closing, protrusion, laterotrusion, and mastication, by tracing however the minimum distance location relative to the fossa and eminence instead of the condyle as done here. Foundation data were laid by a number of studies on stress-field translation and energy density in asymptomatic as well as in clicking joints for border movements [24,25,31,36–38]. Subsequent work for masticatory

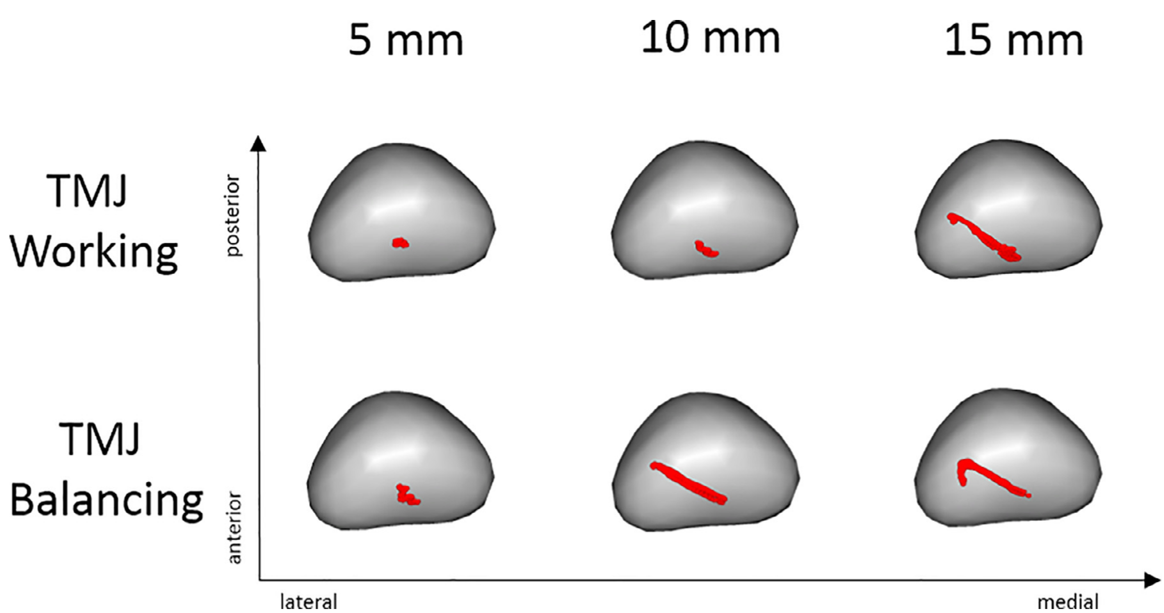

Fig. 3. Top view of the right condyle of one subject (#11) visualizing the location of the MID-path on the TMJ condyle surface for chewing a bolus of thickness 5 mm, 10 mm, 15 mm when the joint is acting as working or balancing. The location of MID is predominantly anterior and centro-laterally located.

movements showed that the minimum condyle-fossa-distance was smaller during the closing phase than during the opening phase and reduced bilaterally during the closing phase, but significantly more in the balancing than in the working joint, which is in line with our results [20].

In this study, minimum intra-articular distances increased significantly bilaterally with bolus thickness raised from 10 to 15 mm. A possible explanation could be that the balancing condyle translates more out of the fossa with increasing bolus thickness and the compressive force of the masticatory muscles decreases with the degree of mouth opening, i.e. when the condyle exits the fossa and reaches the posterior slope of the articular eminence [39]. On the other hand, the relationship between compressive force and food consistency shows that the minimum TMJ space increases as the food becomes softer [20], which is however not conceivable in this study, given the unalterable consistency of the test food chosen.

The areas mostly stressed during chewing were located close to the middle line of the condyle only slightly towards LP, regardless of whether the TMJ was functioning as working or balancing joint. The results seem to indicate that the mostly stressed part of the TMJ condylar head is not located laterally as it appeared to be the case for the disc and the articular surface of the fossa and eminence in previous studies on stress-fields of the TMJ [24,31,40]. Also during jaw opening/closing, minimum distances were traced mainly on the midline of the condylar surfaces and deviated slightly during movement in different directions. Although the sample size was enough to demonstrate differences of minimum distances during chewing, it appeared too small for a *classification* of the pattern of minimum distance paths on the articular surface of the condylar head.

In an observational study, osteoarthritic patterns of 684 joints were categorized by means of cluster analysis into three types (*antero-medial, lateral* and *entirely-involved*) [26]. The antero-medial type was the most prevalent, followed by the lateral and the entirely-involved type, whereas clinical symptoms (pain, noise, etc.) were more prevalent in opposite order. Based on those observations, it was suggested that OA on the lateral part of the TMJ condyle could result in more severe degeneration than on the antero-medial part. The findings of this study seem therefore to indicate a more common loading of the condylar surface in its central area during jaw opening/losing as well as mastication, with the stress area translating mainly in *antero-posterior* direction, which is consistent with the more common less severe *antero-medial* osteoarthritic degeneration. Conversely, it can be hypothesized that damage to disc cartilage in the lateral area due to higher tissue loading as found in former studies could be associated with the more severe degeneration in the *lateral* area of the condylar surface [31].

The strength of the present study was the novel, dynamic recording of the mechanical environments of the TMJs simultaneously on both sides and their comparison during chewing and other functional jaw movements. However, this method required an effort in accurately fabricating the splints and exactly repositioning them during MRI and jaw tracking. In analyzing the data one must consider that the acquisition of the kinematic data of the joint ipsilateral to the target frames is much more precise than for the joint contralateral to the target frames [41]. A further limitation of the study is that the sample size did not allow for gender differentiation. Nonetheless, in order to be as representative as possible, we balanced the subjects' genders [42].

In conclusion, this study confirmed that the condyle with normal disc position is loaded more when acting as balancing side and the most loaded part in the medio-lateral dimension appears to be the center of the condyle. This supports the recommendation by many clinicians to patients with TMD to chew on the painful side in order to unload the ipsilateral TMJ. The significant increase of the intra-articular distances at 15 mm bolus thickness should be carefully be interpreted by further research on the modulation of joint reaction forces according to the degree of jaw opening.

Declaration of Competing Interest

None.

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Ethical approval

The study was approved by the Ethics Committee of the State of Zurich (KEK-ZH Nr. 2014-0123) and written informed consent was obtained from the participants.

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