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S P T S

Technical Note

Measurement of anterior translation of the mandibular condyle using sonography

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Abstract. [Purpose] To establish a standardized sonographic approach to quantify anterior translation of the mandibular condyle during mouth opening by examining the reliability of image acquisition and processing, and to understand how anterior condylar translation contributes to mouth opening. [Participants and Methods] Twenty-eight participants without temporomandibular disorder (TMD) participated. During day 1 of data collection, all participants performed maximal mouth opening while an examiner recorded anterior condylar translation using sonography. The mouth opening range of motion was also obtained. On day 2 of data collection, the same procedure was performed on 6 participants that participated in day 1 of data collection. To establish reliability of image processing, 3 examiners measured condylar translations on 2 separate days. To determine reliability of image acquisition, images obtained from 2 days of data collection were analyzed. [Results] Excellent intra-class correlation coefficients (ICCs) and small standard errors of measurement (SEMs) for image acquisition and processing were shown. A significant, linear model was found to describe the relationship between condylar anterior translations and mouth opening. [Conclusion] Anterior condylar translation during mouth opening can be reliably measured using sonography. The linear relation between condylar motion and mouth opening can be used to guide clinical practices.
Key words: Temporomandibular joint, Anterior translation, Mouth opening

INTRODUCTION

Restricted mandibular depression (mouth opening) is a common limitation in individuals with temporomandibular dysfunction (TMD)[1)], however the arthrokinematics of the temporomandibular joint (TMJ) *in vivo* have been sparsely studied. A common clinical approach to quantify temporomandibular joint (TMJ) kinematics of mouth opening is to measure the distance between the tips of upper and lower incisors using a millimeter ruler[2)]. Although this method is able to determine if there is an osteokinematic limitation[2)], it fails to give information for determining arthrokinematic abnormalities. Specifically, it has been suggested that anterior translation of the mandibular condyle on the temporal bone is a required arthrokinematic component to achieve mouth opening[3)]. To date, current literature reveals conflicting evidence on whether there is an association between mouth opening (osteokinematics) and anterior translation of the mandibular condyle (arthrokinematics)[4, 5)].

With a 3-dimensional (3D) motion capture system, quantification of the movement of mandibular condyle during mouth opening can be made[4–6)]. However, the major challenge of quantifying TMJ kinematics during mouth opening is that the condylar points of interests (located 2 cm subcutaneously) cannot be identified accurately by using skin markers[6)]. Baltali and colleagues[6)] have reported that computerized tomography is needed in conjunction with a 3D motion capture system to improve the accuracy of reference point locations.

It has been shown that ultrasound imaging allows cost effectiveness, convenience in the clinical setting and no exposure to ionizing radiation[7]. Previous researchers have made attempts to use ultrasound imaging to measure condylar mobility during mouth opening[8–11]. It remains challenging to standardize a reference marker on the mandibular condyle for tracking condylar movements at different frames during mouth opening given that ultrasound imaging reveals only a partial view of the mandibular condyle (a curvilinear, hyperechoic line). The current approach relies on the subjective identification of the most prominent/ highest point on the curvilinear line for the definition of the center of the mandibular condyle[9, 11], which can be a source of errors in the measurements of condylar movements. Additionally, the association between sonography-measured anterior translation of the mandibular condyle and mouth opening range of motion (ROM) has not yet been studied.

Fig. 1. Ultrasound transducer placement at (A) mouth closed and (B) mouth opened positions.

As such, this study aimed to develop a standardized sonographic protocol to measure anterior translation of the mandibular condyle during mouth opening. As measurement errors may result from image acquisition (i.e., transducer placement) and data processing (i.e., image interpretations) between days, this study was designed to establish reliability for both image processing and image acquisition. The other purpose of this study was to determine the relationship between mouth opening ROM and anterior translation of mandibular condyle.

PARTICIPANTS AND METHODS

Twenty-eight participants (14 males and 14 females) between 18 and 45 years of age (average age=25.9 ± 4.1 years) without a clinical diagnosis of TMD were recruited. The sample size was determined based on existing literature with a similar research design for correlating imaging-based measurements with the those quantified by an existing method[12]. Participants were excluded if they had any of the following: 1) a diagnosis of TMD, 2) pain, swelling, or clicking sound of TMJ, and 3) mouth opening ROM less than 35 mm. Individuals with TMD were excluded to minimize potential bias from existing osteokinematic abnormalities. We excluded participants who had mouth opening less than 35 mm as 35 mm is considered a functional range for daily TMJ activities[13]. Prior to participation, all participants were informed of the nature of the study and signed a consent form approved by the Institutional Review Board of the University of Nevada, Las Vegas.

The study procedure was designed to obtain ultrasound 1) image processing reliability and 2) image acquisition reliability. Data acquisition was performed on 2 separate days, at least 7 days apart. During day 1 of data collection, imaging was acquired for all 28 participants for the purposes of obtaining image processing reliability among and within examiners. Prior to image acquisition, maximum mouth opening ROM was measured using a millimeter ruler on all participants. On day 2 of data collection, the same ultrasound image acquisition procedure was performed on 6 of the participants that participated in day 1 of data collection in order to assess the transducer placement reliability (i.e. reliability of image acquisition) between days. The 6 participants (3 males and 3 females) were chosen due to their availability of participating in both days of data collection. It has been suggested that 5 or more participants is deemed acceptable for establishing the test-retest imaging reliability[14, 15].

A trained investigator (physical therapist) obtained ultrasound imaging of bilateral TMJ from all participants. High-resolution dynamic ultrasound images were acquired at a rate of 25 frames per second using a General Electric NextGen LOGIQe scanner (GE Healthcare, Milwaukee, WI, USA). Brightness-mode sonographic images were captured using a linear transducer at a central frequency of 10 MHz and depth of 3 cm. Participants were asked to repeatedly open the mouth as wide and as gently as possible while seated. The transducer was placed transversely overlying the TMJ and the zygomatic arch to ensure that the lateral edge of the mandibular condyle remained visible (Fig. 1)[16]. When the mandibular condyle was consistently visible at both mouth closed and opened positions, a 10-second video was recorded. A total of three 10-second videos were collected on each side of the participants.

To obtain mouth opening ROM, participants were asked to perform maximal mouth opening in a seated position 3 separate times. A single investigator (physical therapist) recorded the distance between the tips of upper and lower incisors (Fig. 2)[2]. The greatest range achieved out of 3 attempts was recorded to represent the participant's mouth opening ROM. To determine test-retest reliability, one investigator performed repeated measurement of 10 participants on each day with 7 days apart. Intra-class correlation coefficient ($ICC_{(2,1)}$)[17], standard error of measurement (SEM), and minimal detectable change (MDC_{95}) were used to assess the reliability of the investigator between day 1 and 2. The detailed definitions of SEM and MDC_{95} are described later. The investigator demonstrated excellent measurement reliability (ICC=0.958) with a low SEM (0.764 mm) and a low MDC_{95} (2.106 mm).

ImageJ software (National Institutes of Health, Bethesda, MD, USA) was used to quantify anterior translation of mandibular condyle during mouth opening. Anterior translational distance was defined as the traveling distance by the mandibular condyle from the mouth closed position to the mouth opened position. Specifically, using the still image frames of both closed
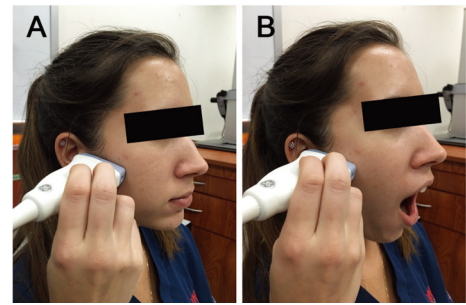
Fig. 2. Measurement of mouth opening range of motion using a millimeter ruler.
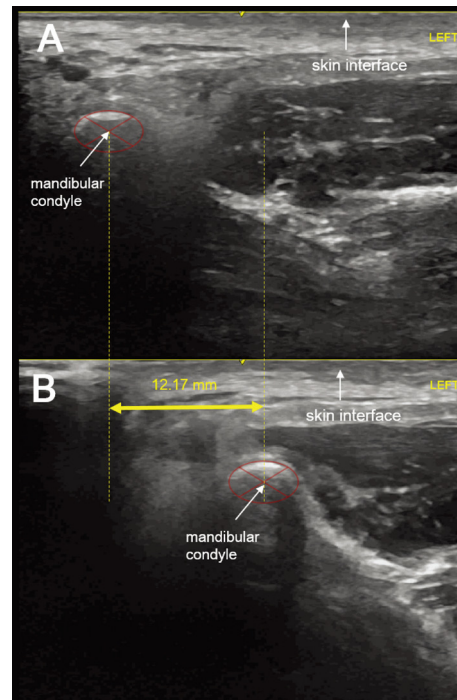
Fig. 3. The transverse section of ultrasound imaging of left TMJ at (A) mouth closed and (B) mouth opened positions. Each oval represents the lateral aspect of the mandibular condyle. The anterior displacement distance was defined as the distance between the centers of the ovals at the 2 positions.

and opened, an oval with the same size and radius was drawn around the lateral aspect of mandibular condyle to represent the mandibular condyle in each position (Fig. 3). An oval was chosen because of the ovoid nature of the mandibular condyle[18]. A line was then measured from the center of each oval to represent the distance that the condyle translated from closed to opened positions (Fig. 3). The greatest range achieved out of the 10-second video was recorded to represent the participant's anterior translation of mandibular condyle.

To establish inter-and intra-rater reliability of image processing, 3 investigators measured condylar translational distance during mouth opening of 28 participants on 2 separate days with 7 days apart. A single investigator performed the measurement on the images of the 6 participants who underwent both days 1 and 2 of data collection for the purposes of obtaining image acquisition reliability. Each set of images (right and left) of the participants was measured 3 times and the average values of each side were used for statistical analyses.

$ICC_{(2,3)}$ and $ICC_{(2,1)}$ were used to determine reliability of image processing and image acquisition, respectively[17]. The SEM and MDC_{95} were also calculated. The SEM was estimated by multiplying the standard deviation by $\sqrt{1}$ minus the reliability coefficient and MDC_{95} was calculated as $1.96 \times \sqrt{2} \times SEM$[19]. The proposed ultrasound imaging method was deemed acceptable if the ICCs were greater than 0.9 (excellent)[19]. A linear regression analysis was used to determine the relationship between anterior condylar translation and maximum mouth opening ROM. Averages of right and left anterior translation distances measured by all 3 investigators were used to obtain the anterior translation values used in the regression analysis. All statistical analyses were performed on SPSS® 22.0 (International Business Machines Corp., NY, USA). A statistical significance was defined as p<0.05.

RESULTS

Analysis of the data revealed excellent inter-rater reliability with low SEMs and MDCs among the 3 examiners for measurement of the right and left TMJs (ICC=0.989–0.999; SEM=0.136–0.471 mm; MDC_{95}=0.375–1.30 mm) (Table 1). Excellent intra-rater reliability for measurement of both TMJs was also achieved (ICC=0.960–0.977; SEM=0.704–0.871 mm; MDC_{95}=1.94–2.40 mm) (Table 2). Our data also revealed excellent intra-rater reliability for ultrasound image acquisition of the right and left TMJs (ICC=0.929–0.939; SEM=0.901–1.20 mm; MDC_{95}=2.49–3.31 mm) (Table 2).

The regression analysis revealed a linear model to describe the relationship between condylar anterior translation and

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Table 1. Summary of the inter-rater reliability of image processing

| | Image processing: inter-rater | | | | | | | | | | | |
| | Examiner 1 vs. 2 | | | Examiner 1 vs. 3 | | | Examiner 2 vs. 3 | | | Mean ± Standard Deviation | | |
	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)
Right	0.994	0.371	1.022	0.999	0.144	0.398	0.994	0.370	1.021	0.996 ± 0.003	0.295 ± 0.131	0.814 ± 0.360
Left	0.989	0.471	1.299	0.999	0.136	0.375	0.990	0.451	1.245	0.993 ± 0.006	0.353 ± 0.188	0.973 ± 0.519

ICC: intra-class correlation coefficient; SEM: standard error of measurement; MDC$_{95}$: minimal detectable change of 95% subjects in this population.

Table 2. Summary of the intra-rater reliability of image processing and image acquisition

| | Image processing: intra-rater | | | | | | | | | | | | Image acquisition: intra-rater | | |
| | Examiner 1 | | | Examiner 2 | | | Examiner 3 | | | Mean ± Standard Deviation | | | Examiner 1 | | |
	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)	ICC	SEM (mm)	MDC$_{95}$ (mm)
Right	0.975	0.731	2.015	0.970	0.793	2.187	0.977	0.704	1.942	0.974 ± 0.004	0.743 ± 0.046	2.048 ± 0.126	0.939	1.199	2.486
Left	0.968	0.737	2.032	0.960	0.871	2.402	0.971	0.717	1.977	0.986 ± 0.016	0.441 ± 0.301	1.217 ± 0.829	0.929	0.901	3.308

ICC: intra-class correlation coefficient; SEM: standard error of measurement; MDC$_{95}$: minimal detectable change of 95% subjects in this population.

mouth opening ROM with a significant correlation coefficient of 0.673 (slope=0.924; intercept=41.1; p<0.0001) (Fig. 4).

DISCUSSION

The primary purpose of the current study was to develop a standardized sonographic protocol for measuring anterior translation of the mandibular condyle during mouth opening. Our findings demonstrated excellent reliability in image acquisition and processing, suggesting that anterior condylar translation during mouth opening can be measured reliably using our ultrasound imaging approach. With respect to the relationship between mouth opening and sonography-measured anterior condylar translation, our findings revealed a linear regression model describing the association between mouth opening ROM and anterior translation of mandibular condyle during mouth opening.

Our data showed that ROM during mouth opening ranged from 40 to 62 mm (mean=52.75 ± 1.09 mm) and condylar translation from 4.03 to 20.51 mm (mean=12.55 ± 2.4 mm) (Fig. 4). The kinematics of mouth opening measured in the current study are comparable with those reported in existing literature[4, 5, 9, 11]. Through use of a 3D tracking system, Travers et al.[5] showed that the average maximal mouth opening was 46.6 mm and the average

Fig. 4. The linear regression model for describing the association between anterior translation of the mandibular condyle and mouth opening range of motion. The solid outer lines highlight the 95% confidence interval of the model.

anterior condylar translation was 11.9 mm in individuals without TMD. Similarly, Salaorni and Palla[4] reported ROM during mouth opening ranging from 43 to 72 mm (mean=55 ± 6 mm) and condylar translation ranging from 5 to 25 mm (mean=14 ± 4.2 mm) in individuals without TMD. Using sonography, Landes and Sader[10], Chen et al.[9], and Yao et al.[11] reported an average translational distance of 10.9 ± 3.6 to 12.9 ± 3.3 mm, 10.3 ± 3.7 mm, and 13.7 ± 2.5 mm during mouth opening in participants with no TMD, respectively. Additionally, compared to similar studies using sonography to quantify condylar translational movements, our study revealed better inter-rater reliability (higher overall ICCs) for both image processing[9, 11] and image acquisition[9]. We speculate that this was due to the improved approach that we developed in this study for identifying the center of the mandibular condylar (Fig. 3).

The current literature reveals conflicting evidence regarding the association between anterior condylar translation and mouth opening ROM. Travers and the colleagues[5] reported that no significant correlation existed between mouth opening ROM and condylar translation. Our data agreed with the findings reported by Salaorni and Palla[4] that showed a linear relationship between condylar translation and opening angle (R=0.993) using an optoelectric tracking system. These inconsistent findings between our study and their reports may be due to different methodology being used between studies. For instance, the non-significant findings reported by Travers et al. may have been caused by the inaccurate placements and/or movements of skin markers during mouth opening. As the mandibular condyle cannot be visualized directly, Salaorni and Palla[4] utilized a mathematical model to estimate the movement of a preselected condylar point and determine the distance of condylar movement during mouth opening, thereby yielding a higher coefficient. Our ultrasound imaging protocol employed a more direct approach through visual identification of the true anatomical condylar head. We believe that such direct identifications are more representative of actual condylar location than mathematical estimation, since osseous morphology of the TMJ varies significantly between individuals[18]. The ultrasound imaging protocol herein accounts for this variation and decreases confounding effects of osseous condylar variation between participants.

The linear regression model presented in this study suggested that 45.3% of mouth opening ROM can be explained by anterior translation of the mandibular condyle. It is speculated that the rest of variance can be explained by other arthrokinematic components associated with mouth opening, primarily anterior rotation of the mandibular condyle[3]. However, due to the limited penetration depth of ultrasound imaging, quantification of rotational movements of the mandibular condyle in the sagittal plane is nearly impracticable. Furthermore, translational movements in superior-inferior and medial-lateral directions during mouth opening may explain some additional variance even though these movements are small[3, 6]. Nevertheless, we believe that the linear correlation equation established in this study can be applied for use in clinical settings to estimate anterior condylar translation using measurements obtained during maximal mouth opening with a millimeter ruler. For instance, clinicians can use this equation to estimate the anterior translation distance of the mandibular condyle that a person should have based on the normal mouth opening value, and vice versa. This method also provides clinical rationale for applying a manual mobilization maneuver (e.g., direction and grades) in clinical practices.

With respect to the findings of the current study, 2 major limitations should be recognized. First, only the reliability of
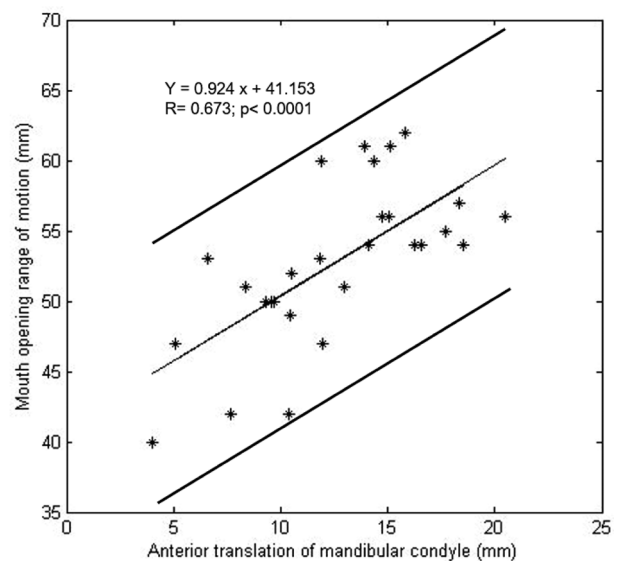
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ultrasound image acquisition and processing of anterior condylar translation was assessed. Future studies should assess the validity of the ultrasound imaging protocol established here through comparison with advanced imaging methods to measure anterior condylar translation, such as magnetic resonance imaging or cone beam computerized tomography. Furthermore, future studies should examine the reliability of the ultrasound imaging protocol established here amongst persons with TMD since TMJ kinematics of healthy participants may differ from those with TMD.

In conclusion, the current study demonstrated that anterior condylar translation during mouth opening can be measured reliably using the ultrasound imaging approach established in this study. A linear regression model was also established to describe the relationship between anterior condylar translation and mouth opening. These findings may impact the evaluation and treatment for individuals with TMD.

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