Original Article

Orthodontic Treatment of Malocclusion Improves Impaired Skillfulness of Masticatory Jaw Movements

Wakako Tome[a]; Kohtaro Yashiro[b]; Kenji Takada[c]

ABSTRACT

Objective: To investigate whether individuals with malocclusion show less skillfulness, as represented by kinematic parameters that characterize masticatory jaw movement, compared with those having normal occlusion and, if so, to examine whether more skilled movements are achieved after completion of orthodontic treatment.

Materials and Methods: Lower incisor point movement in space during gum chewing was recorded, and the kinematic traits of such movement were compared among four subject groups: a Control Group (36 females with good occlusion), a Malocclusion Group (24 females with dental malocclusions), an Extraction Group (31 females who had received orthodontic treatment with premolar extraction) and a Nonextraction Group (27 females who had been treated orthodontically without tooth extraction). Before treatment, all subjects in the three experimental groups exhibited dental malocclusions and skeletal class I jaw-base relationship.

Results: Compared with the Malocclusion Group, the lower normalized jerk-cost, the shorter phase durations, the more symmetric property of the velocity profile, and the smaller variance of lateral jaw-closing trajectories near the tooth intercuspation position were determined in the Extraction Group and the Nonextraction Group as well as in the Control Group.

Conclusions: As measured by kinematic parameters such as normalized jerk-costs, velocity profile, and variance of movement trajectories near the endpoint of movement, dental malocclusions were associated with significantly lower skillfulness of masticatory jaw motion, whereas good occlusion and orthodontically improved occlusion (either with or without premolar extraction) were both associated with more skillful motion. (*Angle Orthod.* 2009;79:1078–1083.)

KEY WORDS: Kinematics; Mastication; Jerk-cost; Tooth extraction; Malocclusion; Jaw motion

INTRODUCTION

Improvement in occlusal function is an important goal in orthodontic practice. Functional problems associated with malocclusions are often difficult to measure. Although patients with malocclusions sometimes complain about the degree of effort required to chew foods effectively, tooth extraction may often be required to achieve a successful esthetic treatment outcome. To date, there have been controversies as to whether orthodontic tooth extraction impairs posttreatment occlusal function.[1,2] Although impairment of mechanical effect in food-breakage, termed "masticatory performance," has been reported extensively in patients with malocclusions,[3,4] changes in masticatory jaw function after orthodontic treatment have not been fully understood. Considering the fact that the masticatory jaw movements develop as a result of motor adaptation or learning with modification by the sensory feedback from the mouth, muscles, and joints,[5–8] it would be reasonable to postulate that patients with malocclusion show impaired skillfulness underlying the jaw movement kinematics, which may result in inefficient breakage of the food particle.

Concerning the control mechanisms of human motor

---

[a] Assistant Professor, Department of Orthodontics and Dentofacial Orthopedics, Graduate School of Dentistry, Osaka University, Osaka, Japan.

[b] Associate Professor, Department of Orthodontics and Dentofacial Orthopedics and Center for Advanced Medical Engineering and Informatics, Osaka University, Osaka, Japan.

[c] Professor and Department Chair, Department of Orthodontics and Dentofacial Orthopedics, Graduate School of Dentistry and Center for Advanced Medical Engineering and Informatics, Osaka University, Osaka, Japan.

Corresponding author: Kenji Takada, DDS, PhD, Graduate School of Dentistry, Osaka University, 1-8 Yamadaoka, Suita, Japan
(e-mail: opam@dent.osaka-u.ac.jp)

Accepted: October 2008. Submitted: May 2008.

DOI: 10.2319/052708-282.1

functions, it has been argued that body movement is organized to achieve optimized movement.[9,10] Generally, the smoothness of movement is quantified by means of a time integral of squared jerk (jerk-cost), where jerk is defined as a rate of change in acceleration.[11] Minimization of a jerk cost is defined as optimizing smoothness of movement. Indices such as movement time, peak velocity, symmetry of the velocity profile, and dispersion of the movement trajectory have been shown to be effective in explaining the degree of skillfulness of human saccadic eye and limb motions.[11,12] These studies documented that in skilled movements, the jerk-cost is reduced and the velocity profile is optimized to approximate a bell shape. In addition, it has been demonstrated that the greater the skillfulness of body movement, the smaller the variance of movement trajectories near the end-point of the movement.[11]

Masticatory jaw movement trajectories are known to be well-simulated by the minimum-jerk model. The factual masticatory jaw-movement trajectories were found to be highly correlated with the model-based trajectories,[13,14] which were computed on the basis of a modeling technique[10] reported previously. In addition, jerk-cost has been shown to be highly sensitive and proportional to the degree of occlusal interferences that have been experimentally induced by inserting acrylic fillings with varying vertical dimensions.[15] A previous report[14] has argued that skillfulness of the jaw motion can be diagnosed objectively and sensitively by such kinematic parameters as the normalized jerk-cost and the velocity profile.

The purposes of the present study were to investigate whether differences in skillfulness of masticatory jaw motion between subjects with dental malocclusion and a skeletal class I jaw-base relationship, subjects with good occlusion, and subjects who have been orthodontically treated with and without the extraction of the four premolar teeth, can be predicted effectively using the aforementioned kinematic parameters and, if so, to examine how those differences can be characterized.

MATERIALS AND METHODS

Subjects

The subjects were 118 females with full permanent dentition divided into four groups, three experimental and one control.

Experimental Groups

Malocclusion Group: 24 patients (mean age, 20 years 9 months; age range, 12 years 3 months to 28 years 3 months) who exhibited anterior occlusal guidance and had no previous history of orthodontic treatment.

Extraction Group: 31 patients (mean age, 23 years 4 months; age range, 14 years 3 months to 37 years 8 months) whose orthodontic treatment had been completed and had included the extraction of four premolar teeth.

Non-extraction Group: 27 patients (mean age, 20 years 7 months; age range, 14 years 1 months to 40 years 11 months) whose orthodontic treatment had been completed with no extraction of teeth.

The patients in the three experimental groups all exhibited dental malocclusions (greater than Grade 2 on the Index of Orthodontic Treatment Need) with skeletal Class I jaw-base relationship at the pretreatment stage.

Participants were selected consecutively from the patient database in order of their dates of registration at the university dental hospital during 1993 to 2002 for the Malocclusion Group and during 1993 to 2005 for the treated Groups. Decision for extraction or non-extraction for each patient was made according to the conventional Arch Length Discrepancy (ALD) standards. For the Extraction Group and the Non-extraction Group, wrap-around retainers had been used in the upper and lower dental arches after completion of active treatment with edgewise appliances.

Control group: 36 volunteer subjects (mean age, 24 years 11 months; age range, 19 years 10 months to 35 years 1 months) who exhibited good occlusion and no discernible clinical signs of jaw dysfunction.

Jaw movements in space during gum-chewing were measured for the four groups, with the records for the treated groups taken more than 12 months after the start of retention.

All subjects gave informed consent for participation after receiving a full explanation of the purpose and contents of the study. The experiment study was approved by the Ethics Committee of the Graduate School of Dentistry.

Data Recording and Analysis

Movement of the lower incisor point in space during gum chewing (Morimoto et al,[17] 15 mm width × 20 mm length × 1 mm depth, weight 2 g, 80 g in Bloom strength) was monitored by a stereotaxic device (Kinesiograph Model K-6, Myotronics, Seattle, Wash). Subjects were asked to perform unilateral gum chewing with the posterior teeth on the habitually preferred side. Data gathering continued for 30 consecutive cycles. A detailed description of the recording method has been reported elsewhere.[18]

Each set of chewing cycle data was divided into three subsets according to the jaw-opening phase, jaw-closing phase, and intercuspation phase.[19] The starting time of the jaw-closing phase was defined as the moment when vertical jaw displacement showed the minimum value, whereas the end of the jaw-closing phase was defined as the time when the jaw displacement changed from negative values to show zero. In addition, the jaw-closing phase was subdivided into the acceleration phase and the deceleration phase with the moment of maximum tangential jaw-closing movement velocity as the critical time point. Mathematical function of the 10th order Fourier series was fit to the time series data of lateral and vertical jaw displacements for each chewing cycle. The root-mean-square error of the fit was less than 0.002 mm. The functions x(t), y(t), and z(t), corresponding to the time series of lateral, anteroposterior, and vertical jaw displacement data, were thus obtained.

By differentiating the mathematical functions, tangential velocity TV(t) and tangential acceleration TA(t) could be evaluated. Smoothness of jaw movement was quantified using a time integral of squared jerk (jerk-cost). A decrease in the jerk-cost indicates an increase in the movement's smoothness. A detailed description of the mathematical data processing methods has been reported previously.[13,14] The minimum-jerk model[10,20,21] was applied to the factual jaw displacement trajectory data of the jaw-closing phase for each chewing cycle. The accuracy of the model prediction was measured by using Spearman's correlation coefficient (*r*) between the actual and predicted velocity profiles.

We compared the four groups according to the kinematic features for the jaw-closing movements. Normalized jerk-costs (NJCs),[20] phase durations, and the peak tangential velocity in the jaw-closing and deceleration phases in the jaw-closing phase were calculated. In addition, we examined the symmetric property of the velocity profile in the jaw-closing phase using an index which calculated the deceleration phase duration relative to the closing phase duration and the absolute value of the difference between the proportion and 0.5. Finally, the variances in the jaw-closing movement trajectories in the lateral (x) and anteroposterior (y) directions close to the vertical jaw position of 2 mm below the intercuspal position were calculated and compared between the four groups.

Statistical Analyses

Spearman's correlation coefficient (r) between the actual and predicted velocity profiles was computed for each subject to evaluate the accuracy of the model simulation. We employed the Kruskal-Wallis test and the nonparametric multiple comparisons of the Tamhane (T2) test. The significance of coefficients and mean difference were tested at the $\alpha = 0.05$ level, using statistical analysis software (SPSS v10.0, SPSS, Inc, Chicago, IL, USA).

RESULTS

Mean correlation coefficients (r) between the actual and predicted velocity profiles of the jaw-closing movement that were calculated for each of the Control Group, the Malocclusion Group, the Extraction Group and the Nonextraction Group, were 0.972 ($P < .0001$), 0.952 ($P < .0001$), 0.961 ($P < .0001$) and 0.961 ($P <$ .0001), respectively.

Table 1 shows results of the inter-group comparisons between medians and 25-75 percentiles of the normalized jerk-costs (NJCs) in the jaw-closing phase and the deceleration phase. The NJCs calculated for the Malocclusion Group were significantly ($P < .001$) greater than those for the Control Group. The differences between the NJCs of the Extraction Group and the Nonextraction Group were not statistically significant. The NJCs computed for both the Extraction

Table 1. Medians and 25th to 75th Percentiles of Normalized Jerk-costs in the Jaw-closing Phase and the Deceleration Phase

Subject Group (sample size)	**Normalized jerk-cost ($\times 10^3$) (median and 25-75 percentile)**			
	Closing phase		**Deceleration phase**	
Untreated samples				
Control Group	4.60		0.85	
(n=36)	(3.77-5.66)	*	(0.64-1.12)	*
Malocclusion Group	4.74	*	0.89	*
(n=24)	(3.12-7.37)	* * *	(0.47-1.60)	* * *
Treated samples		*		*
Extraction Group	2.72		0.31	
(n=31)	(1.64-4.54)	NS	(0.12-0.77)	NS
Nonextraction Group	2.96		0.35	
(n=27)	(1.70-4.50)		(0.15-0.83)	

(* P < 0.001 , N.S. : P>0.05)

Table 2. Medians and 25th to 75th Percentiles of Phase Durations and Peak Tangential Velocities of the Lower Incisor Point Movement for the Jaw-closing Phase and the Deceleration Phase, and the Symmetric Property Indices of Velocity Profiles During Chewing for the Four Subject Groups

Subject Group (sample size)	Phase duration(s) (median and 25-75 percentile) Closing phase	Deceleration phase	Peak tangential velocity (m / s)	Symmetric property of the velocity profile
Untreated samples				
Control Group (n=36)	0.332 (0.280-0.390)	0.209 (0.171-0.245)	0.122 (0.093-0.150)	0.182 (0.120-0.248)
Malocclusion Group (n=24)	0.364 (0.309-0.426)	0.247 (0.189-0.298)	0.108 (0.072-0.153)	0.203 (0.128-0.267)
Treated samples				
Extraction Group (n=31)	0.312 (0.270-0.362)	0.192 (0.147-0.240)	0.100 (0.075-0.127)	0.154 (0.073-0.225)
Nonextraction Group (n=27)	0.303 (0.258-0.357)	0.188 (0.144-0.240)	0.106 (0.081-0.138)	0.151 (0.079-0.227)
Control Group – Malocclusion Group	**	**	NS	*
Malocclusion Group – Extraction Group	**	**	**	**
Extraction Group – Nonextraction Group	NS	NS	**	NS
Malocclusion Group – Nonextraction Group	**	*	NS	**
Control Group – Extraction Group	**	*	**	**
Control Group – Nonextraction Group	**	*	**	**

(* :P < 0.05, **:P < 0.0001 ,N.S.:P>0.05)

Group and the Nonextraction Group were found to be significantly lower ($P < .001$) than those determined for the Malocclusion Group and the Control Group. These findings were consistent for both phase durations.

Table 2 shows results for the inter-group comparisons of medians and 25th to 75th percentiles calculated for the phase durations as well as the peak tangential velocities and the symmetric property of the velocity profile in the jaw-closing phase. The jaw-closing phase durations for the Malocclusion Group were significantly longer ($P < .001$) than for the Control Group, whereas significant differences were not found between the Extraction Group and the Nonextraction Group. Both the jaw-closing phase durations determined for the Extraction Group and the Nonextraction Group were significantly shorter ($P < .001$) than those found for the Malocclusion Group and Control Group. These findings were consistent with the deceleration phase, but were weaker statistically.

Significant differences between the Control Group and the Malocclusion Group were not found for peak tangential velocity ($P > .05$). The peak tangential velocity for the Extraction Group was found to be significantly slower ($P < .001$) than for the other three Groups. The peak tangential velocity of the Nonextraction Group was found to be significantly slower than for the Control Group ($P < .001$), whereas a significant difference was not found between the Nonextraction Group and the Malocclusion Group ($P > .05$).

The Extraction Group and the Nonextraction Group both showed significantly more symmetric velocity pro-

Table 3. Variances of Jaw-closing Trajectories in the Lateral and Anteroposterior Directions at the Vertical Jaw Position of −2 mm Below the CO Position

Subject Group (sample size)	The dispersion of the jaw displacements(z=-2mm) Lateral (x) directions	Antero-posterior (y) directions
Untreated samples		
Control Group (n=36)	2.597	0.276
Malocclusion Group (n=24)	2.774	0.359
Treated samples		
Extraction Group (n=31)	2.527	0.293
Nonextraction Group (n=27)	2.517	0.287
Control Group – Malocclusion Group	*	**
Malocclusion Group – Extraction Group	**	NS
Extraction Group – Nonextraction Group	NS	NS
Malocclusion Group – Nonextraction Group	**	NS
Control Group – Extraction Group	NS	**
Control Group – Nonextraction Group	NS	**

(* : P < 0.05, ** : P < 0.001 ,N.S.:P>0.05)

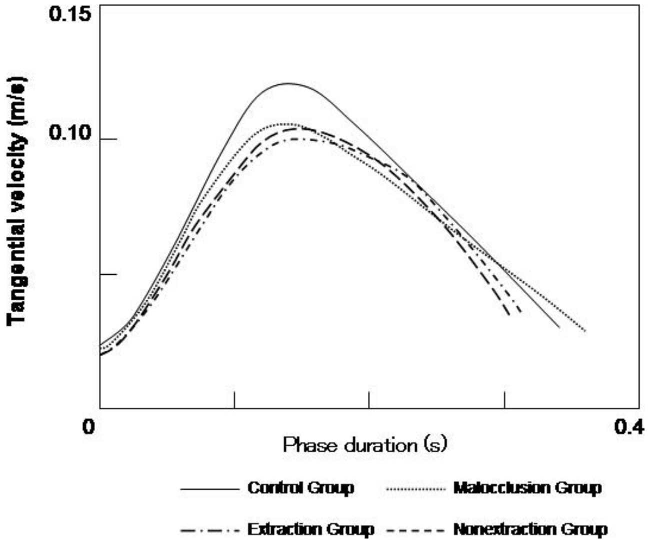

Figure 1. Comparison of mean tangential velocity profiles of the lower incisor point movement in the jaw-closing phase during chewing in the four subject groups. Longitudinal axis, tangential velocity (m/s); Abscissa axis, normalized jaw-closing phase duration(s).

files ($P < .0001$) than the Malocclusion Group and the Control Group. The Control Group showed significantly more symmetric profiles ($P < .0001$) than the Malocclusion Group. There was no significant difference between the Extraction Group and the Nonextraction Group in the symmetric property of the velocity profiles (Table 2 and Figure 1).

Variances in jaw-closing movement trajectories in the lateral direction estimated for the Malocclusion Group were significantly greater than for the Control Group ($P < .05$), the Extraction Group, and the Nonextraction Group (both $P < .001$, (Table 3). Significant differences were not found between the Control Group, the Extraction Group, or the Nonextraction Group. Concerning the anteroposterior direction, variances estimated for the Control Group were significantly smaller ($P < .001$) than for the Malocclusion Group, the Extraction Group, or the Nonextraction Group. Significant differences were not found between the Malocclusion Group, the Extraction Group, or the Nonextraction Group ($P > .05$).

DISCUSSION

We examined whether the original masticatory jaw-closing trajectories (raw data) could be well-explained by the minimum-jerk modeling technique.[10] The factual jaw-closing trajectory data were found to be highly correlated with the corresponding model-based data that were generated using the technique. The results thus confirmed the robustness of the current modeling method when applied to those with normal occlusion as well as malocclusions and were basically consistent with previous reports.[13,21]

The results of this study suggest that dental malocclusions are likely to impair skillfulness of the masticatory jaw movements. In agreement with a previous study,[22] subjects with malocclusions exhibited a prolonged deceleration phase rather than acceleration and deceleration phases of equal durations in the jaw-closing motion, in contrast with the bell-shaped velocity profiles of visually guided arm movements.

According to the minimum variance theory,[11] the neural strategy of body movement is to displace the end effecter to the goal of the movement with minimum energy consumption and without damaging the end effecter. In the jaw motion paradigm, the highest-priority neural strategy is to minimize the variance of the jaw position in the jaw-closing phase near the centric occlusal position so as to optimize skillfulness of jaw movements, that is, minimize the normalized jerk-cost in each individual. This supports optimization of masticatory jaw motion in management of the food bolus. Thus, it is essential for the lower jaw (and the teeth) to be able to approach the goal accurately from a limited angle so that the teeth can be tightly interdigitated with the food bolus. If there is an obstacle in the movement trajectory, a possible neural strategy of the body motion would be to alter the orbit to avoid a traumatic collision with the obstacle or, if collision is inevitable, the motion will be naturally decelerated to reduce the magnitude of the impact. Jerk-cost will be sacrificed as a result, however. In mastication, occlusal interference presents an obstacle, and reduction of impact is achieved reflexively by a transient stop of jaw-closing muscle contraction called the silent period[23] and/or feed-forwardly.[7]

Orthodontic treatment serves to minimize the variance of movement trajectories so that obstacles on the movement orbit are reduced and the end effecter can take a straightforward approach with a narrower angle to the end point of movement. The results of the present study suggest that in functional adaptation, shortening the jaw-closing motion is given priority over increasing peak tangential velocity in response to the altered occlusal condition. This contributes to reducing the risk of a large diversity of variances in movement trajectories near the movement's goal. Based on these facts and the slowed-down peak velocity found in the Extraction Group, it seems reasonable to conclude that an adaptive response of the body, that is, an increase in jaw-closing speed to deliver strong impact to foods, comes after the minimization of variance is well learned.

A recent case report[24], using the current kinematic parameters, has documented improved masticatory jaw function as a result of progress in orthodontic treatment. In agreement with this, the morphologically improved occlusal state achieved as a result of orthodontic treatment was found to provide kinematically optimized masticatory jaw motion that was more skillful than that seen in individuals with untreated malocclusions. It should be emphasized that in the study described in this article, improved skillfulness of masticatory jaw motion, which was considered a possible consequence of the observed kinematic parameter changes, was found consistently in the treated subjects, regardless of whether or not the four premolar teeth had been extracted. Previous studies[1,2] have found no significant differences between orthodontic patients whose treatment involved extraction of premolar teeth and those who did not, in terms of post-treatment overbite, vertical dimension, jaw movement pathways, and displacement of condylar positions. From our results, it can be speculated that orthodontic improvement of occlusal morphology helps patients unconsciously improve skillfulness of masticatory jaw motion and that extraction of premolar teeth is not a cause of masticatory jaw hypofunction but rather, if the treatment is designed optimally, contributes to improving skillfulness of masticatory jaw motion.

CONCLUSIONS

- Dental malocclusions were associated with lower skillfulness of masticatory jaw motion, whereas good occlusion and orthodontically improved occlusion resulted in more efficient motion skillfulness.
- Skillfulness of masticatory jaw motion in subjects with dental malocclusion whose orthodontic treatment included the extraction of four premolar teeth did not differ from subjects treated without tooth extraction.

ACKNOWLEDGMENTS

This research was supported by the Grants (B-14370695 and B-14370696) sponsored by the Japanese Ministry of Education, Science and Culture. We also thank Dr N. Kremenak for grammatical correction.

REFERENCES

1. McLaughlin RP, Bennett JC. The extraction-nonextraction dilemma as it relates to TMD. *Angle Orthod.* 1995;65:175–186.
2. Beattie JR, Paquette DE, Johnston LE Jr. The functional impact of extraction and nonextraction treatments: a long-term comparison in patients with ''borderline'' equally susceptible Class II malocclusions. *Am J Orthod Dentofacial Orthop.* 1994;105:444–449.
3. English JD, Buschang PH, Throckmorton GS, Austin D, Wintergerst AM. Does malocclusion affect masticatory performance? *Angle Orthod.* 2002;72:21–27.
4. Toro A, Buschang PH, Throckmorton G, Roldán S. Masticatory performance in children and adolescents with class I and II malocclusions. *Eur J Orthod.* 2006;28:112–119.
5. Belser UC, Hannam AG. The influence of altered working-side occlusal guidance on masticatory muscles and related jaw movement. *J Prosthet Dent.* 1985;53:406–413.
6. Dellow PG, Lund JP. Evidence for central timing of rhythmical mastication. *J Physiol.* 1971;215:1–13.
7. Komuro A, Morimoto T, Iwata K, Inoue T, Masuda T, Hidaka O. Putative feed-forward control of jaw-closing muscle activity during rhythmic jaw movements in the anesthetized rabbit. *J Neurophysiol,* 2001;86:2834–2844.
8. Morimoto T, Takada K. The sense of touch in the control of ingestion. In Neurophysiology of Ingestion, ed Booth DA. Pergamon Studies in Neuroscience, No. 6, Oxford, Tokyo, Pergamon Press. 1993:79–97.
9. Nelson WL. Physical principles for economies of skilled movements. *Biol Cybern.* 1983;46:135–147.
10. Hogan N. An organizing principle for a class of voluntary movements. *J Neurosci.* 1984;4:2745–2754.
11. Harris CM, Wolpert DM. Signal-dependent noise determines motor planning. *Nature.* 1998;394:780–784.
12. Hreljac A. The relationship between smoothness and performance during the practice of a lower limb obstacle avoidance task. *Biol Cybernetics.* 1993;4:375–379.
13. Yashiro K, Yamauchi T, Fujii M, Takada K. Smoothness of human jaw movement during chewing. *J Dent Res.* 1999;78:1662–1668.
14. Yashiro K, Fujii M, Hidaka O, Takada K. Kinematic modeling of jaw-closing movement during food breakage. *J Dent Res.* 2001;80:2030–2034.
15. Takada K, Yashiro K, Takagi M. Reliability and sensitivity of jerk-cost measurement for evaluating irregularity of chewing jaw movements. *Physiol Meas.* 2006;27:609–622.
16. Brook P, Shaw WC. The development of an index of orthodontic treatment priority. *Eur J Orthod.* 1989;11:309–320.
17. Morimoto T, Takada K, Hijiya H, Yasuda Y, Sakuda M. Changes in facial skin temperature associated with chewing efforts in man: a thermographic evaluation. *Arch Oral Biol.* 1991;36:665–670.
18. Takada K, Yashiro K, Sorihashi Y, Sakuda M. Tongue, jaw, and lip muscle activity and jaw movement during experimental chewing efforts in man. *J Dent Res.* 1996;75:1598–1606.
19. Hannam AG, Wood WW, De Cou RE, Scott JD. The effects of working-side occlusal interferences on muscle activity and associated jaw movements in man. *Arch Oral Biol.* 1981;26:387–392.
20. Wiegner AW, Wierzbicka MM. Kinematic models and human elbow flexion movements: quantitative analysis. *Exp Brain Res.* 1992;88:665–673.
21. Yashiro K, Takada K. Model-based analysis of jaw-movement kinematics by using jerk-optimal criterion: simulations of human chewing cycles. *J Electromyograph Kinesiol.* 2005;15:516–526.
22. Ostry DJ, Flanagan JR. Human jaw movement in mastication and speech. *Arch Oral Biol.* 1989;34:685–693.
23. Takada K, Nagata M, Miyawaki S, Kuriyama R, Yasuda Y, Sakuda M. Automatic detection and measurement of EMG silent periods in masticatory muscles during chewing in man. *Electromyogr Clin Neurophysiol.* 1992;32:499–505.
24. Yashiro K, Miyawaki S, Tome W, Yasuda Y, Takada K. Improvement in smoothness of the chewing cycle following treatment of anterior cross bite malocclusion: a case report. *J Craniomand Practice.* 2004;22:151–159.