European Journal of Orthodontics 33 (2011) 628–635
doi:10.1093/ejo/cjq134
Advance Access Publication 24 January 2011

Variations in cyclic mandibular movements during treatment of Class II malocclusions with removable functional appliances

Kirsten M. Thieme, Hans Nägerl, Wolfram Hahn, Dankmar Ihlow and Dietmar Kubein-Meesenburg

Department of Orthodontics, Georg August University Göttingen, Göttingen, Germany

Correspondence to: Dr Kirsten M. Thieme, Department of Orthodontics, Georg August University Göttingen, Robert-Koch-Strasse 40, D-37099 Göttingen, Germany. E-mail: kmthieme@med.uni-goettingen.de

SUMMARY The aim of the study was to establish whether juveniles with a Class II malocclusion change the neuromuscular control of mandibular movements during the course of orthodontic treatment with removable functional appliances (RFAs).

Neuromuscular control can be indirectly evaluated by recording cyclic planar mandibular movements which were freely carried out by the patients (28 girls, 14 boys, aged 11.1 ± 1.1 years at the start of treatment) and measured with an ultrasonic device before, during, and after Class II functional appliance therapy, with either an activator or a bite jumping plate. The cyclic movements represented simultaneous rotations of the mandible around a maxillary and mandibular fixed axis (MFHA) and could be characterized by μ(α)-diagrams (μ = swing angle of MFHA, α = mouth opening angle) and path length (*L*) of the MFHA. The μ(α)-diagrams clearly divided into four parts: movement representing protrusion, mouth opening, and two parts of backward closing as known from Posselt diagrams. Parameters from the Posselt and μ(α)-diagrams were checked by one-factor analysis of variance on a 5 per cent significance level for group dependency.

For one-third of the patients investigated, no significant changes were seen in any parameter pre- or post-therapy. However, patients showing an initially large mouth opening capacity or a very short condylar path changed their neuromuscular control to that of Class I subjects.

Analysis of μ(α)-diagrams provides the possibility of assessing changes in the neuromuscular control of the mandible during Class II treatment.

Introduction

A number of studies have evaluated, using cephalometric data and/or magnetic resonance imaging, the skeletal and dental changes that arise from therapy of Class II malocclusions with removable functional appliances (RFAs; Ruf *et al.*, 2001; Watted *et al.*, 2001; Bendeus *et al.*, 2002; Lisson and Tränkmann, 2003; Shen and Darendeliler, 2006; Hönn *et al.*, 2006; Lohrmann *et al.*, 2006; Lee *et al.*, 2007). Only rarely has the influence of RFAs on jaw muscle activity been evaluated by means of electromyography (Miralles *et al.*, 1988; Ingervall and Thüer, 1991; Hiyama *et al.*, 2002; Tabe *et al.*, 2005). It remains unclear whether and how Class II treatment with RFAs influences the neuromuscular control of free mandibular movements.

The output of neuromuscular control can be evaluated by recording planar mandibular movements. It has previously been shown that subjects with sound temporomandibular joints (TMJs) only use 2 degrees of freedom for planar mandibular movements instead of three, which would be possible physically (Nägerl *et al.*, 1991, 1999; Kubein-Meesenburg *et al.*, 1999). These 2 degrees of freedom coincide with rotations around a maxillary and also a mandibular fixed hinge axis (MFHA) represented by the angles of rotation μ and δ, respectively, which are under neuromuscular control (Figure 1). The MFHA does not comply with the 'movable hinge axis' (Travers *et al.*, 2000; Nagy *et al.*, 2002; Matsumura *et al.*, 2006) and does not directly correspond to anatomical structures. For all subjects with sound TMJs, there exists a distinct point in the region around the condyle whose domain is degenerated to a pure line segment (Nägerl *et al.*, 1991, 1999; Thieme *et al.*, 2006). For any cyclic movement of the mandible, this point must move on this line segment back and forth. The line segment could closely be approximated by a circle with a radius, *R*, so that its centre, *C*, is the maxillary fixed axis (Figure 1). Around this fixed axis C, the MFHA swings with the positive angle μ counter-clockwise while opening the mouth with the negative angle α clockwise. Therefore, the position of the mandible could be specified by these two variables, μ and α. The opening angle, α, was identified instead of rotation angle, δ, due to improved graphical illustration since it holds true that $\Delta\alpha = \Delta\mu + \Delta\delta$. The motions of the mandible are then distinct lines in the orthogonal coordinate system of the μ(α)-diagram as shown in Figure 2 [also discussed by Nägerl *et al.* (1991) and Kubein-Meesenburg *et al.* (1999)]: subject BS started in

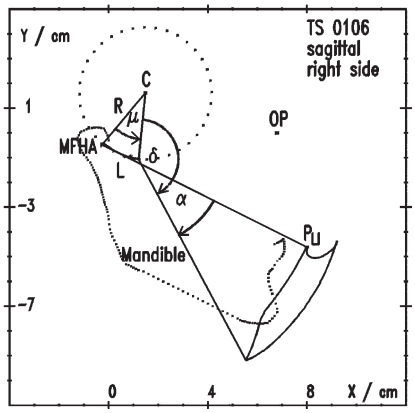

Figure 1 The path *L* of the mandibular fixed hinge axis (MFHA) can be approximated by a circle with centre *C* and radius *R*. MFHA rotates around C with an angle of rotation μ while the lower incisal edge P_{LI} moves during mouth opening with the opening angle α and rotates around MFHA with an angle of rotation δ (OP = infra-orbital point).

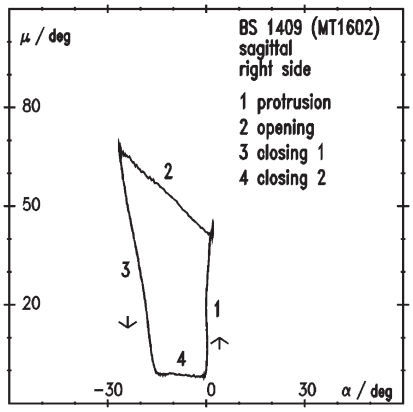

Figure 2 μ(α)-diagram of a subject with a Class I occlusion (measured with the MT1602 device). The individual components of movement labelled '2', '3', and '4' can each be approximated by a single straight line.

centric occlusion with μ = α = 0 degrees, moved the mandible forward under tooth contact to maximal protrusion while angle μ increased and α ≈ 0 degrees (1), opened the mouth as far as possible with increasing μ and α (2), and closed the mouth backwards in two parts—first μ decreased faster than α and almost reached 0 degrees (3) and then α decreased to 0 degrees during final rotation (4). Between the reversal points, maximal protrusion, maximal mouth opening, and backward closing between parts 1 and 2, the ratio Δμ/Δα remained constant and could be closely approximated by a straight line with a negative slope. The negative value and the constancy of the ratio Δμ/Δα have two meanings: firstly, rotations around the maxillary and mandibular axes were opposite and secondly, the mandible was guided during mouth opening and closing along the physically shortest distance, which is a straight line. This was interpreted as optimal neuromuscular control of the plane mandibular movement of the subject.

Schwestka-Polly *et al.* (1999, 2000) investigated, using the same method, adult patients with mandibular retrognathism combined with a Class II malocclusion, before and after orthodontic-surgical treatment. The patients showed differences in their μ(α)-diagrams before treatment, reflected in the ratio of Δμ/Δα that did not remain constant between the reversal points, and even switched to positive values. After therapy, they observed an increase of the constancy of the negative ratio Δμ/Δα in the μ(α)-diagrams and interpreted this as an improvement of neuromuscular control due to surgical treatment.

The aim of the present study was to determine, using the same method of evaluation of μ(α)-diagrams, whether changes in neuromuscular control appear as a consequence of RFA treatment in young patients with Class II malocclusions.

Subjects and methods

The long-term study was approved by the Ethics Committee of the University of Göttingen (8 October 2002).

Forty-two patients with a Class II malocclusion were followed throughout their RFA treatment. At the beginning of treatment, 28 girls and 14 boys (aged 9.3–14.3 years, mean 11.1 ± 1.1 years) had at least a half premolar width distal (Class II) relationship in the region of the first molars. Twenty-three (15 girls, eight boys) were treated with an activator (Andresen and Häupl, 1945; Klammt, 1969) and 19 (13 girls, six boys) with bite jumping plates (Sander and Wichelhaus, 1995). Four patients dropped out of study; one because of a relocation and three who no longer wished to participate. Measurements were undertaken on 18 girls and 12 boys before and during therapy at intervals of approximately 6 months and, if possible, at least 1 year after the end of therapy to assess stability. Ten girls and two boys were measured at irregular intervals during and after therapy. All patients were asked to wear the appliance 16 hours/day. The mean orthodontic treatment time with the RFAs was 2.2 ± 0.9 years.

The ultrasonic device CMS-JMA (Zebris Medizintechnik, Isny, Germany) was used to record the spatial movements of the mandible in relation to the maxilla, with 6 degrees of freedom, allowing the spatial path of any mandibular point to be calculated. The patients were asked to move their mandible preferably in the sagittal–vertical plane along the cranial border (Posselt diagram), in order to obtain the largest possible range of mandibular and, consequently, condylar motion.

For each patient and recording, the motion cycle was chosen which showed the largest possible range of mandibular motion in the path of the lower incisor, P_{LI} (Figure 1), including the greatest mouth opening and a clear

division in backward closing. As described by Thieme *et al.* (2006), the position of the MFHA for the right and left side of the head was located and its path approximated by a circle with radius, *R*, and centre, *C*. From this, it was possible to determine the angle μ while the MFHA swung around the (maxillary fixed) axis C when opening or closing the mouth with angle α (Figure 1), and the μ(α)-diagram was produced.

Different parameters of these selected motion cycles were evaluated: the radius, *R*, of the path of the MFHA approximating a circle, the inclination angle, γ, of the path of the MFHA (angle between the straight line MFHA-OP and a straight line formed by MFHA and that point on the path of MFHA 5 mm distant from MFHA), its path length *L* (back and forth), the swing angle μ_{max} for maximal mouth opening, the maximal mouth opening angle α_{max}, and the relationship of the swing angle μ_{protr}, needed for movement of maximal protrusion, to the swing angle μ_{max}.

Posselt and μ(α)-diagrams for the right and left side of the head were compared for all 188 measurements. Essentially, they differed in mouth opening movement, in the first part during backward closing and in the ratio μ_{protr}/μ_{max}. On this basis, the patients were divided into four groups. Therefore, the μ(α)-diagram (Figure 2) showing straight lines between the reversal points served as a standard for comparison.

Group 1

The patients showed a normal Posselt movement of the lower incisor (Figure 3a) and straight lines in the μ(α)-diagrams (Figure 3b). The movement during mouth opening (2) could be approximated in the μ(α)-diagrams by two to three linear sections with negative slopes.

Group 2

In the Posselt movement of the lower incisor, the last part of the mouth opening (2) overlapped with the first part of mouth closing (3) in an angle range of Δα up to 8 degrees. Correspondingly, in the μ(α)-diagrams, these areas also showed no separation (Figure 3c). The slope for this part of the angle range had small negative values, changed to zero or became even positive. The first part of the mouth opening movement could be approximated in the μ(α)-diagrams by two to three linear sections with negative slopes, as in group 1.

Group 3

These patients showed the same characteristics as those in group 2, but the angle range at which there was overlapping of the opening and closing movement was greater: up to Δα = 16 degrees (Figure 4a). As in group 2, these areas also overlapped in the μ(α)-diagrams (Figure 4b). (The limit of the overlapping angle range of Δα = 8 degrees for group

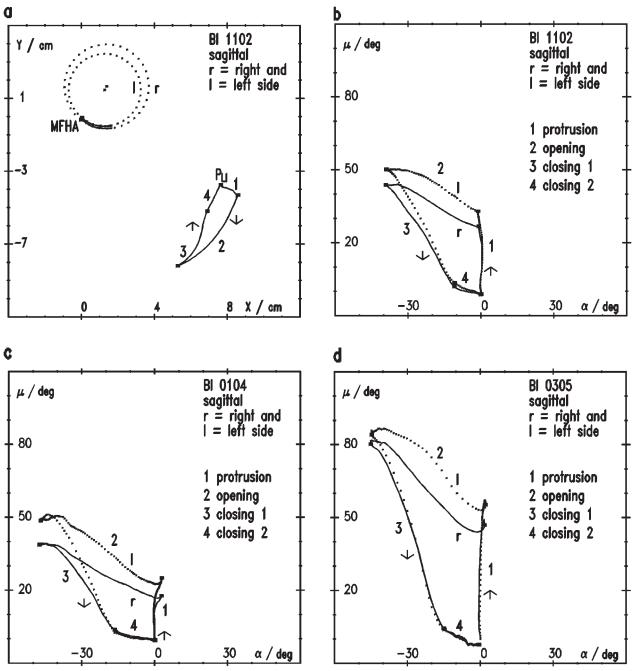

Figure 3 A subject in group 1. (a) Commencement of Class II treatment: right 1 and left 1.25 premolar width distal. Normal Posselt diagram and similar radii for mandibular fixed hinge axis for both sides of the head. (b) Corresponding μ(α)-diagrams. (c) 14 months later: right and left Class I. μ(α)-Diagrams belong to group 2 (Δα ≈ 5 degrees). (d) Fourteen months after completion of Class II treatment (month 28): right and left Class I. μ(α)-diagrams belong to group 1 again.

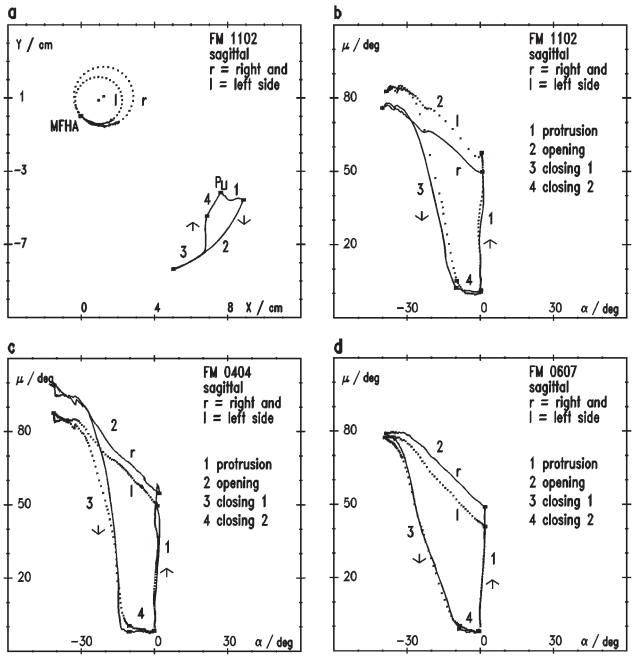

Figure 4 A subject in group 3. (a) Commencement of Class II treatment: right and left a half premolar width distal. Posselt diagram shows overlapping of movement parts 2 and 3 (Δα ≈ 15 degrees). (b) Corresponding μ(α)-diagrams. (c) Nineteen months later: right and left Class I. μ(α)-Diagrams: overlapping of parts 2 and 3 still present. (d) Thirteen months after completion of Class II treatment (month 57): right and left Class I. μ(α)-diagrams belong to group 1.

2 was chosen since it was half the maximal overlapping angle range found for the investigated patients. This was arbitrary, but reasonable for further consideration.)

Group 4

The Posselt diagrams for the lower incisor were normal as for those of the other groups (Figure 5a), but the μ(α)-diagrams appeared different (Figure 5b). The patients used more than 80 per cent of the maximal swing angle μ_{max} during protrusion, then the swing angle μ oscillated in a small angle range during mouth opening and increasing mouth opening angle α. The mean value of the slope for mouth opening was smaller than −0.2 or even positive.

The above-mentioned parameters—radius *R*, inclination angle γ, path length *L*, swing angle μ_{max}, and maximal mouth opening angle α_{max}—were statistically analysed. They depended on the calculation of the position of the MFHA. The ultrasonic device could determine the position of mandibular points with an accuracy of about 0.03 mm (Hugger *et al.*, 2001). The mean spacing between the path of the MFHA forward and back during mouth opening and closing was about 0.12 mm (Thieme *et al.*, 2006). The comparison between the circle-like paths of the MFHA and the approximated circles yielded a mean correlation coefficient of 0.99 ± 0.01. This is equivalent to an average deviation of the parameters of 1 per cent. Since for all measurements the mean radius *R* was 13.9 ± 3.1 mm, the mean path length *L* 34.9 ± 5.9 mm, and the mean swing angle μ_{max} 74.8 ± 17.9 degrees, the value for the possible error of the lengths and angles was below 0.5 mm and 1 degree, respectively.

Although this study was not a randomized controlled trial, the data were normally distributed. Therefore a one-factor analysis of variance at a 5 per cent significance level was justified. The parameters were checked for dependency of the four groups and comparison of pre- and post-treatment.

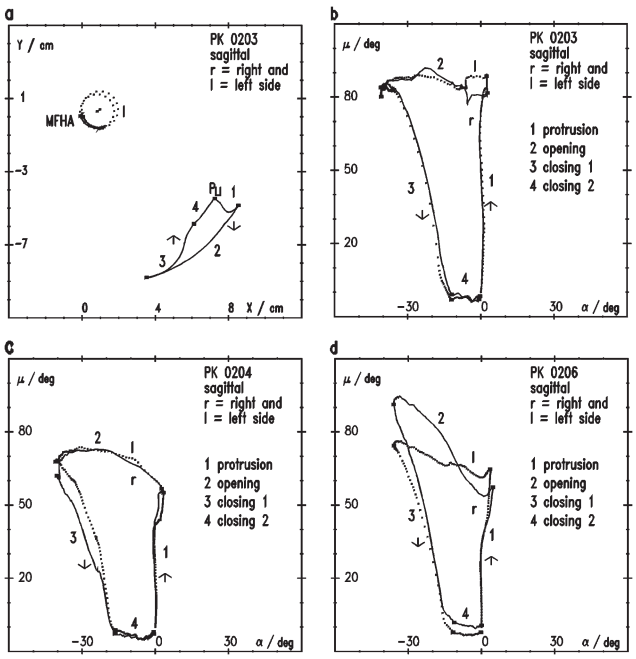

Figure 5 A subject in group 4. (a) Commencement of Class II treatment: right 0.75 and left 1 premolar width distal (PW). Posselt diagram shows overlapping of movement parts 2 and 3 ($\Delta\alpha \approx 7$ degrees). (b) Corresponding μ(α)-diagrams: $\mu_{protr} \approx \mu_{max}$. (c) Twelve months later: right Class I, left 0.25 PW. μ(α)-diagrams: $\mu_{protr} \approx 70$ per cent μ_{max}. (d) Completion of Class II treatment after 35 months: right Class I, left 0.75 PW. μ(α)-diagrams belong to group 1.

Results

Table 1 shows the means of five parameters for all 188 measurements from the 42 subjects for the right and left side of the head in relation to the four groups. The means of the radius, *R*, and the inclination angle γ of the path of the MFHA showed no significant group dependence ($P > 0.05$). However, the means of the path length, *L*, of the MFHA, the maximal swing angle μ_{max}, and the maximal mouth opening angle α_{max} showed highly significant group dependency ($P < 0.001$). For groups 1, 2, and 3, all three mean values increased highly significantly, while the means for group 4 were highly significantly lower than for group 1.

The correlation between the path length, *L*, of the MFHA and the maximal mouth opening angle α_{max} was $c = 0.59$ for

Table 1 Mean and standard deviation (SD) of the parameters: radius *R* of the path of the mandibular fixed hinge axis, inclination angle γ of its path, path length *L* (back and forth), maximal swing angle μ_{max}, and maximal mouth opening angle α_{max} as a function of the four groups (*P* value obtained with analysis of variance; ***$P < 0.001$).

Parameters	Group (*n*)	Mean	SD	*P* value
R/mm	1 (176)	14.3	3.2	0.07
	2 (139)	13.7	3.2	
	3 (34)	13.1	2.2	
	4 (27)	13.1	3.3	
γ/degree	1 (176)	43.9	7.1	0.12
	2 (139)	44.6	8.8	
	3 (34)	42.1	8.7	
	4 (27)	46.8	7.0	
L/mm	1 (176)	33.9	5.1	***
	2 (139)	35.9	5.3	
	3 (34)	40.8	5.0	
	4 (27)	28.1	5.9	
μ_{max}/degree	1 (176)	70.6	15.8	***
	2 (139)	78.0	17.4	
	3 (34)	91.0	14.6	
	4 (27)	65.4	21.2	
α_{max}/degree	1 (176)	35.2	4.4	***
	2 (139)	36.6	4.5	
	3 (34)	40.8	4.5	
	4 (27)	34.7	6.7	

n = number of evaluated measurements.

all measurements, $c = 0.45$ for group 1, $c = 0.55$ for group 2, $c = 0.68$ for group 3, and $c = 0.87$ for group 4.

In addition to the classification of all measurements in the four groups, the treatment progress of the 30 patients for whom measurements were obtained before, during, and after Class II therapy was determined (Table 2).

Before commencement of orthodontic treatment, nine patients were allocated to group 1 and during therapy remained more or less in that group. Seven patients were allocated to group 2 for a short period of time. An example can be seen in Figure 3c and 3d. After 14 months of orthodontic treatment, the patient showed a small overlapping during maximal mouth opening ($\Delta\alpha \approx 5$ degrees), which was not observed at the end of therapy.

For most of the 12 patients in group 2, the range of angles of overlapping in the area of maximal mouth opening decreased during therapy so that they could be finally allocated to group 1. Five remained in group 2. Two of them switched to group 3 during therapy, enlarging the range of angles of overlapping to more than 8 degrees. At the end of therapy, the range in the angle of overlap decreased to $\Delta\alpha \approx$ 2 degrees.

For the six patients in group 3, the range in the angle of overlap in the area of maximal mouth opening also decreased during therapy and the patients could be allocated to group 2 and finally group 1. An example is shown in Figure 4c and 4d. Only one patient was allocated again to group 3 at the end of treatment.

One year after the start of therapy, mouth opening movement of the three patients in group 4 was still not linear in the $\mu(\alpha)$-diagrams, but the magnitude of the swing angle μ_{protr} during protrusion decreased to about 70 per cent of the total amount of swing angle μ_{max}. At the end of therapy, the patients showed linear $\mu(\alpha)$-diagrams for both sides of the head and could therefore be allocated to group 1 (Figure 5c and 5d).

Table 3 shows the dependence of the means of different parameters before and after Class II therapy for the same 26 patients. While the parameters in group 1 showed no significant change after RFA treatment, the means of groups 2 and 3 changed. The mean of the radius R became significantly greater ($P = 0.002$) as the maximal swing angle μ_{max} and maximal mouth opening angle α_{max} became significantly smaller ($P < 0.001$). In group 4, the mean of the path length, L, increased significantly ($P < 0.05$) and the mean of the maximal mouth opening angle α_{max} decreased significantly.

Almost all patients who started with a Class II malocclusion achieved a Class I occlusion at the end of therapy. This was consistent with the corresponding $\mu(\alpha)$-diagrams: the linearity of the lines, the constancy of the ratio $\Delta\mu/\Delta\alpha$, increased. This was more obvious for the patients in groups 2, 3, and 4. However, these patients reached a stable Class I occlusion after 1.6 ± 0.8 years while they were constant in group 1 after 2.5 ± 1.4 years.

Table 2 Number of patients in the four groups before and after Class II therapy.

Groups	Pre-therapy			Post-therapy		
	Female	Male	Total	Female	Male	Total
1	4	5	9	10	9	19
2	8	4	12	4	2	6
3	5	1	6	1	0	1
4	1	2	3	0	0	0
All	18	12	30	15	11	26

Four patients dropped out of the study during therapy.

Table 3 Comparison of the means of radius R of the path of the mandibular fixed hinge axis, path length L (back and forth), maximal swing angle μ_{max}, and maximal mouth opening angle α_{max} before and after Class II therapy in each group (P value obtained with analysis of variance; ***$P < 0.001$).

Group (n) pre-therapy	Parameters	Mean pre-therapy	Mean post-therapy	P value
1 (16)	R/mm	14.8	13.4	0.24
	L/mm	31.1	30.8	0.80
	μ_{max}/degree	63.7	67.8	0.62
	α_{max}/degree	33.9	33.0	0.58
2 + 3 (30)	R/mm	12.3	14.2	0.002
	L/mm	35.2	34.0	0.39
	μ_{max}/degree	84.5	69.7	***
	α_{max}/degree	37.5	33.0	***
4 (6)	R/mm	11.0	11.5	0.45
	L/mm	34.3	37.7	0.02
	μ_{max}/degree	90.1	94.4	0.40
	α_{max}/degree	41.1	37.1	0.03

n = number of evaluated measurements.

Discussion

Nägerl *et al.* (1991) measured the mandibular movements of adult individuals with a Class I occlusion with an ultrasonic device and investigated their $\mu(\alpha)$-diagrams. They were able to show that, for most subjects, the lines in the $\mu(\alpha)$-diagrams could be approximated by several straight lines with a negative slope: $\Delta\mu/\Delta\alpha < 0$. That means that the two rotations around the maxillary axis C and the mandibular axis MFHA (Figure 1) were opposite. In case BS1409 from the study of Nägerl *et al.* (1991) (Figure 2), it can be seen how the individual only changed the ratio of $\Delta\mu/\Delta\alpha$ at the reversal points of the movement parts 2, 3, and 4. The three movement parts could each be fitted by only one straight line in the $\mu(\alpha)$-diagram. This control pattern was interpreted as being optimal since it allows the physically shortest way to move from one reversal point to the next with a constant angular velocity. The $\mu(\alpha)$-diagram with these characteristics served as a standard for comparison of the $\mu(\alpha)$-diagrams of the juveniles investigated in the present study.

Differences in neuromuscular control in relation to the groups

Group 1. The patients who were allocated to this group had lines in the μ(α)-diagrams, which could be approximated by straight lines with a negative slope (Figure 3b and 3d). However, the juvenile patients altered the slope Δμ/Δα several times while opening the mouth. No μ(α)-diagram for which the mouth opening could be approximated by only one straight line was found. Optimal neuromuscular control with a constant Δμ/Δα from one reversal point to the next such as that shown for BS1409 (Nägerl *et al.*, 1991; Figure 2) seems to be exceptional.

Groups 2 and 3. These patients showed overlapping in the range of maximal mouth opening up to Δα = 8 degrees (Figure 3c) and Δα = 16 degrees (Figure 4b and 4c). The overlapping resulted from a peculiarity in backward closing (3): during mouth closure while the mouth opening angle α became smaller, the MFHA still remained anterior; i.e. the swing angle μ remained maximal. Within this angle range, these patients were not able to move their MFHA in a posterior direction during mouth closure. As can be seen from Table 1, the probability of overlapping in the range of maximal mouth opening increased with increasing length *L* of the MFHA, increasing swing angle μ_{max}, and increasing mouth opening angle α_{max}. This means that the wider a subject can open their mouth and the more anterior they can move their condyles, the higher the probability that the muscles that close the jaw cannot pull the condyles posteriorly at the start of mouth closure.

Harper *et al.* (1997) investigated jaw muscle activity of subjects with a Class I occlusion and of patients with a Class II malocclusion before and after surgical treatment during sagittal border movement (Posselt envelope). Their findings showed that during mouth opening and the first part of mouth closing, the lateral pterygoid and suprahyoid group of muscles were active. The activity levels of the lateral pterygoid muscles were also clearly lower for the Class II patients than for the control group.

Obwegeser *et al.* (1987) were able to show on lateral tomograms of 51 volunteers with sound TMJs that their condyles moved increasingly in an anterior direction along the articular eminence with greater mouth opening. For 41 subjects, the condyle moved beyond the eminence. This positive correlation between maximal mouth opening and the length of the path of the condyle was confirmed by Muto *et al.* (1994) and Muto and Kanazawa (1996). Their values for the correlation of $c = 0.56$ and $c = 0.62$, respectively, are similar to those in the present study ($c = 0.59$ for all groups). For those patients in this study who showed a large overlapping range in the Posselt and μ(α)-diagram, together with wide mouth opening, their condyles were probably far beyond the eminence so that the direction of muscle force was inappropriate and the condyles could first not be moved in a posterior direction while the mouth was already closing. This possible interpretation could only have been confirmed by simultaneous cephalometric or tomographic investigations, as well as electromyography such as that undertaken by Harper *et al.* (1997).

Travers *et al.* (2000) and Fukui *et al.* (2002) were unable to find any correlation between maximal mouth opening and condyle path length. They recorded the mandibular movements of young females with opto-electric devices and evaluated the paths of the condyles and the lower incisor edge, determining the distances between the start and end point of the paths. In this connection, the choice of the location of the condyle must be considered with care. In the region of the condyles, the mandibular points have loops of different lengths (Thieme *et al.*, 2006) which have no specific kinematic characteristics compared with other points. In fact, there is only one point whose path is circular with an enclosed area almost equal to zero. This point is the MFHA which is not located in the centre of the condyle, but most frequently anteriocranial to it (Kubein-Meesenburg *et al.*, 2008).

Group 4. These patients used more than 80 per cent of the maximal swing angle μ_{max} for protrusion (Figure 5b) so that only a small amount of the path length of the MFHA remained for the motion of mouth opening. Their path lengths for protrusion were the same as for the other subjects, but the total path lengths were too short for subsequent mouth opening. These patients used only one axis of rotation for one movement part: the maxillary fixed axis for protrusion or the mandibular fixed axis for mouth opening.

Schwestka-Polly *et al.* (1999, 2000) obtained comparable μ(α)-diagrams. In five of the 20 adult patients in their studies with mandibular retrognathism combined with a Class II malocclusion, the path length of MFHA was also too short.

Neuromuscular control in the course of Class II therapy

The patients allocated to group 1 (Table 2) showed linear μ(α)-diagrams at the beginning of Class II treatment. They had optimal anticipation of their neuromuscular control in relation to movement efficiency, which changed only minimally during therapy. The means for the four parameters for pre- and post-therapy showed no significant changes ($P > 0.05$) (Table 3).

The patients in groups 2 and 3 with an overlapping for a greater angle range of maximal mouth opening showed a coincidental increase in radius *R* and decrease in maximal swing angle μ_{max} which was accompanied by a length *L* which did not change significantly (Table 3). This could be primarily a geometric effect. It could mean that the distance from the mandibular axis to the maxillary axis increased by approximately 1.9 mm during therapy.

Numerous authors (Ingervall, 1972; Agerberg, 1974a,b; Landtwing, 1978; Rothenberg, 1991; Hirsch *et al.*, 2006) investigated subjects in different age groups (5–19 years) and found a positive correlation between maximal mouth opening and age or body height. They evaluated maximal mouth opening by the distance between the incisal edges. This value was not investigated in the present study, but the distance between the incisal edges of the patients increased since they experienced a growth spurt due to puberty during Class II therapy. A constant maximal mouth opening angle α_{max} pre- and post-Class II therapy, as observed for group 1, could be interpreted as a proportional growth of the skull in both the horizontal and vertical directions, as well as corresponding growth of the controlling muscles. In contrast, a decrease in maximal mouth opening angle α_{max} during therapy, as observed in groups 2 and 3, could reflect increased growth in the horizontal direction. Since there was no control group, it is not possible to substantiate the hypothesis that subjects who showed a large mouth opening demonstrated decelerated growth with RFAs.

The effectiveness of RFAs is conjectural. Some authors have interpreted their results with bite jumping plates and activator-headgear combinations as inhibition of growth of the maxilla in the horizontal direction rather than a stimulation of growth in the length of the mandible (Bendeus *et al.*, 2002; Lisson and Tränkmann, 2003). Other authors have assumed skeletal growth in the vertical direction with activators (Ruf *et al.*, 2001; Hönn *et al.*, 2006; Lohrmann *et al.*, 2006). A decrease in temporal and masseter muscle activity and an increase in digastric muscle activity caused by RFAs (activator and bite jumping plates) was shown by Tabe *et al.* (2005) who investigated male adults with and without the appliances *in situ* both during the night and day. The influence of the appliances on jaw muscle activity was clearly higher in the day than during the night. There were also small differences between activator and bite jumping plates in relation to the different muscle groups.

For the three patients who were allocated to group 4 at the beginning of Class II treatment because of $\mu_{protr}/\mu_{max} > 80$ per cent, the comparative statistical evaluation (Table 3) produced an increase in path length L of the MFHA, as well as a decrease in the maximal mouth opening angle α_{max} during therapy ($P < 0.05$). This finding should be interpreted with caution due to the small number of patients. It can only be suggested that wearing of the RFA led to a change in the muscles responsible for mouth opening (e.g. the lateral pterygoid and the suprahyoid group of muscles; Harper *et al.*, 1997) so that these patients could move their condyles more in an anterior direction during mouth opening after Class II therapy.

The fact that the patients in groups 2, 3, and 4 achieved a stable Class I occlusion (after 1.6 ± 0.8 years) faster than group 1 (after 2.5 ± 1.4 years) can be interpreted that the neuromuscular system needs more time to adapt compared with dental adjustment.

Conclusions

Analysis and comparison of the $\mu(\alpha)$-diagrams of juvenile patients with a Class II malocclusion demonstrated that neuromuscular changes in free mandibular movements during treatment depend on different parameters. Whereas for one-third of the patients investigated no significant change in neuromuscular control was seen, there were clear differences in the development of those patients with a large mouth opening capacity and those with very short condylar paths. The latter seems to occur comparatively rarely. The disorder of neuromuscular control could not be detected by dental or cephalometric parameters before therapy. Further studies are required to investigate whether these disorders will result in future problems with TMJs.

Routine measurements and analyses of free mandibular movements of patients during Class II treatment should provide information concerning the type of neuromuscular control of mandibular movements and whether additional investigations, such as lateral radiographs during maximal mouth opening or measurements of jaw muscle activity (e.g. lateral pterygoid muscles), are necessary. This method could also be helpful in establishing the progress and success of Class II therapy.

Funding

Deutsche Forschungsgemeinschaft (SCHW 427/2-1, 2-2, KU 535/6-3).

References

Andresen V, Häupl K 1945 Funktionskieferorthopädie. Die Grundlagen des norwegischen Systems. Johann Ambrosius Barth, Leipzig

Agerberg G 1974a Maximal mandibular movements in children. Acta Odontologica Scandinavica 32: 147–159

Agerberg G 1974b Maximal mandibular movements in teenagers. Acta Morphologica Neerlando-Scandinavica 12: 79–102

Bendeus M, Hägg U, Rabie B 2002 Growth and treatment changes in patients treated with a headgear-activator appliance. American Journal of Orthodontics and Dentofacial Orthopedics 121: 376–384

Fukui T, Tsuruta M, Murata K, Wakimoto Y, Tokiwa H, Kuwahara Y 2002 Correlation between facial morphology, mouth opening ability, and condylar movement during opening-closing jaw movements in female adults with normal occlusion. European Journal of Orthodontics 24: 327–336

Harper R P, de Bruin H, Burcea I 1997 Muscle activity during mandibular movements in normal and mandibular retrognathic subjects. Journal of Oral and Maxillofacial Surgery 55: 225–233

Hirsch C, John M T, Lautenschläger C, List T 2006 Mandibular jaw movement capacity in 10-17-yr-old children and adolescents: normative values and the influence of gender, age, and temporomandibular disorders. European Journal of Oral Sciences 114: 465–470

Hiyama S, Kuribayashi G, Ono T, Ishiwata Y, Kuroda T 2002 Nocturnal masseter and suprahyoid muscle activity induced by wearing a bionator. Angle Orthodontist 72: 48–54

Hönn M, Schneider C, Dietz K, Godt A, Göz G 2006 Treating Class II patients with removable plates and functional orthopedic appliances. Journal of Orofacial Orthopedics 67: 272–288

Hugger A, Bölöni E, Berntien U, Stüttgen U 2001 Accuracy of an ultrasonic measurement system for a jaw movement recording. Journal of Dental Research 80: 1226 (Abstract)

Ingervall B 1972 Range of sagittal movement of the mandibular condyles and inclination of the condyle path in children and adults. Acta Odontologica Scandinavica 30: 67–87

Ingervall B, Thüer U 1991 Temporal muscle activity during the first year of Class II, division 1 malocclusion treatment with an activator. American Journal of Orthodontics and Dentofacial Orthopedics 99: 361–368

Klammt G 1969 Die Arbeit mit dem Elastischen Offenen Aktivator. Fortschritte der Kieferorthopädie 30: 305–310

Kubein-Meesenburg D, Nägerl H, Schwestka-Polly R, Thieme K M, Fanghänel J, Miehe B 1999 Functional conditions of the mandible: theory and physiology. Annals of Anatomy 181: 27–32

Kubein-Meesenburg D *et al.* 2008 Mandible, maxilla and cervical spine—a functional unit? Journal of Physiology and Pharmacology 59: 75–80

Landtwing K 1978 Evaluation of the normal range of vertical mandibular opening in children and adolescents with special reference to age and stature. Journal of Maxillofacial Surgery 6: 157–162

Lee R T, Kyi C S, Mack G J 2007 A controlled clinical trial of the effects of the Twin Block and Dynamax appliances on the hard and soft tissues. European Journal of Orthodontics 29: 272–282

Lisson J A, Tränkmann J 2003 Treatment begin and treatment effect in functional orthopedics with jumping-the-bite appliances. Journal of Orofacial Orthopedics 64: 341–351

Lohrmann B, Schwestka-Polly R, Nägerl H, Ihlow D, Kubein-Meesenburg D 2006 The influence of functional orthodontics and mandibular sagittal split advancement osteotomy on dental and skeletal variables—a comparative cephalometric study. European Journal of Orthodontics 28: 553–560

Matsumura H, Tsukiyama Y, Koyano K 2006 Analysis of sagittal condylar path inclination in consideration of Fischer's angle. Journal of Oral Rehabilitation 33: 514–519

Miralles R, Berger B, Bull R, Manns A, Carvajal R 1988 Influence of the activator on electromyographic activity of mandibular elevator muscles. American Journal of Orthodontics and Dentofacial Orthopedics 94: 97–103

Muto T, Kanazawa M 1996 The relationship between maximal jaw opening and size of skeleton: a cephalometric study. Journal of Oral Rehabilitation 23: 22–24

Muto T, Kohara M, Kanazawa M, Kawakami J 1994 The position of the mandibular condyle at maximal mouth opening in normal subjects. Journal of Oral and Maxillofacial Surgery 52: 1269–1272

Nägerl H, Kubein-Meesenburg D, Fanghänel J, Thieme K M, Klamt B, Schwestka-Polly R 1991 Elements of a general theory of joints. 6. General kinematical structure of mandibular movements. Anatomischer Anzeiger 173: 249–264

Nägerl H, Kubein-Meesenburg D, Schwestka-Polly R, Thieme K M, Fanghänel J, Miehe B 1999 Functional condition of the mandible: physical structures of free mandibular movement. Annals of Anatomy 181: 41–44

Nagy W W, Smithy T J, Wirth C G 2002 Accuracy of a predetermined transverse horizontal mandibular axis point. The Journal of Prosthetic Dentistry 87: 387–394

Obwegeser H L, Farmand M, Al-Majali F, Engelke W 1987 Findings of mandibular movement and the position of the mandibular condyles during maximal mouth opening. Oral Surgery 63: 517–525

Rothenberg L H 1991 An analysis of maximum mandibular movements, craniofacial relationships and temporomandibular joint awareness in children. Angle Orthodontist 61: 103–112

Ruf S, Baltromejus S, Pancherz H 2001 Effective condylar growth and chin position changes in activator treatment: a cephalometric roentgenographic study. Angle Orthodontist 71: 4–11

Sander F G, Wichelhaus A 1995 Skelettale und dentale Veränderungen bei der Anwendung der Vorschubdoppelplatte. Ein kephalometrischer Vergleich zu einer unbehandelten Klasse-II-Gruppe. Fortschritte der Kieferorthopädie 56: 127–139

Schwestka-Polly R, Kubein-Meesenburg D, Nägerl H 2000 Harmonization of free mandibular movements by orthodontic-surgical treatment of patients with mandibular retrognathism. International Journal of Adult Orthodontics and Orthognathic Surgery 15: 205–231

Schwestka-Polly R, Kubein-Meesenburg D, Nägerl H, Fanghänel J, Miehe B 1999 Alteration of the functional condition of the mandible during clinical treatment. Annals of Anatomy 181: 45–50

Shen C, Darendeliler M A 2006 Cephalometric evaluation of condylar and mandibular growth modification: a review. Orthodontics and Craniofacial Research 9: 2–9

Tabe H *et al.* 2005 Influence of functional appliances on masticatory muscle activity. Angle Orthodontist 75: 616–624

Thieme K M, Kubein-Meesenburg D, Ihlow D, Nägerl H 2006 Is a 'movable hinge axis' used by the human stomatognathic system? Acta of Bioengineering and Biomechanics 8: 13–25

Travers K H, Buschang P H, Hayasaki H, Throckmorton G S 2000 Associations between incisor and mandibular condylar movements during maximum mouth opening in humans. Archives of Oral Biology 45: 267–275

Watted N, Witt E, Kenn W 2001 The temporomandibular joint and the disc-condyle relationship after functional orthopaedic treatment: a magnetic resonance imaging study. European Journal of Orthodontics 23: 683–693