THE INFLUENCE OF AN OCCLUSAL ALTERATION ON THE WORKING-SIDE CONDYLAR MOVEMENT AND THE ACTIVITY OF THE JAW MUSCLES DURING DEFINED LATERAL JAW MOVEMENTS

by

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DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

(Signed)

Bor-Yuan

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ABSTRACT

Natural tooth morphology is often changed during clinical dental practice but with little knowledge of the effects of these changes on jaw function, either in terms of effects on the movement of the temporomandibular joint (TMJ) condyle, or effects on jaw muscle activity. Our hypothesis was that a change in the occlusion alters jaw function in terms of condylar movement and jaw muscle activity. To determine this, a new indirect method was needed to register precisely the coordinates of multiple condylar points in a six-degrees-of-freedom jaw-tracking device. In addition, a detailed understanding of the electromyographic (EMG) activity of the jaw muscles during jaw movements was needed. Therefore, the aims of this study were: (a) to develop an indirect method to register the coordinates of anatomical condylar points in the coordinate system of JAWS-3D, a jaw-tracking device, and to test the accuracy of this method; (b) to investigate the influence of an occlusal alteration on the working-side condylar tracings during lateral jaw movements (laterotrusion); (c) to investigate EMG activity of related jaw muscles during laterotrusion; and (d) to investigate the influence of an occlusal alteration on the jaw muscle activity, especially the contralateral inferior head of the lateral pterygoid muscle (IHLP), during laterotrusion.

For aim (a), a new indirect method was developed to register the location of radiographically defined condylar points in the coordinate system of JAWS-3D, a six-degrees-of-freedom jaw-tracking device, and the accuracy of this method was determined by using a perspex model in one experiment and a dry skull in

another. A direct measurement ('the gold standard') of condylar point coordinates in the coordinate system of JASW-3D was made with the use of a three-dimensional (3D) digitizer (MicroScribe-3DX). The indirect measurement used a distributed fiducial marker as the interface between the coordinate system of MicroScribe-3DX (which was used to register the fiducial marker and the JAWS-3D coordinate system) and the coordinate system of the CT scans (used to define condyle anatomy and the relation with the fiducial marker). The coordinates of condylar points could then be calculated in the coordinate system of JAWS-3D. The results showed that the indirect method could register condylar point coordinates on either side of the face to an accuracy of ~ 0.5 mm.

For aim (b), CT scans from 13 healthy volunteers were used to determine five working-side anatomical condylar points: the most superior, the most anterior and the most posterior points, and the medial and lateral poles. Jaw movements were controlled by visual feedback and recorded by JAWS-3D. Ten trials of lateral jaw movement were repeated under three conditions: control 1 (before the occlusal alteration), occlusal alteration (immediately after the placement), and control 2 (immediately after the removal of the occlusal alteration). During the outgoing phase, the results showed that the paths of the multiple working-side condylar points under the occlusal alteration were significantly more inferior and anterior to those under the control conditions at the same amount of MIPT displacement from the intercuspal position. In addition, our results showed that the occlusal alteration could significantly reduce the rotation angles about the X-axis (i.e. antero-posterior) and Z-axis (i.e. supero-inferior) of the mandible and could significantly increase the rotational opening angle (about the Y-axis, i.e.

horizontal axis). The effect of the occlusal alteration at the return phase was qualitatively similar to that at the outgoing phase, although the working-side condylar paths at the return phase were different to those at the outgoing phase. During the return phase, the selection of the condylar points did change the overall statistical results of the comparison between the control 1 and occlusal alteration conditions. During the return phase, the results indicated a possible prolonged effect of the occlusal alteration and that other factors, such as possible alterations in jaw muscle activity, might be involved in influencing condylar movements.

For aims (c) and (d), recordings controlled by visual feedback from 16 healthy volunteers were made of the mid-incisor point (MIPT) movements, using JAWS-3D, as well as the EMG activity of the contralateral IHLP and bilateral anterior and posterior temporalis, masseter and submandibular muscles. Three lateral jaw movement tasks, at two speeds and two closing-force levels, and protrusion were recorded. Ten trials of each task were repeated under three conditions: control 1, occlusal alteration, and control 2. Each trial had five phases: intercuspal position (IP) 1, outgoing, holding, return and IP 2 phases.

For aim (c), under the low closing force with slow speed, of the nine muscles recorded, the contralateral IHLP was the only muscle that showed a clear increase in EMG activity throughout the outgoing, holding and return phases of laterotrusion in all subjects. The contralateral anterior and posterior temporalis muscles showed a decrease in activity from the original activity level at IP 1, reached a relatively stable level, and then returned to a level that was higher than that at IP 1. In the ipsilateral anterior and posterior temporalis and bilateral masseter muscles, more than one type of EMG activity pattern were shown across subjects and muscles. Under a high closing force with slow speed, the EMG activities of the contralateral IHLP and bilateral anterior temporalis and masseter were significantly higher than those under a low closing force. Under a fast speed at a low force, the EMG activity of the contralateral IHLP during the outgoing phase was significantly higher than that under a low closing force with slow speed, whereas the contralateral IHLP activity during the return phase and contralateral anterior temporalis activity during the outgoing phase was significantly lower.

For aim (d), under the occlusal alteration at the high-closing-force laterotrusion in 14 subjects, the bilateral anterior temporalis and masseter muscles showed a lower activity, especially on the ipsilateral (working) side, while the EMG activity in the contralateral IHLP was higher, especially at the return phase. There was no significant effect on the bilateral posterior temporalis and submandibular muscles in most subjects. Generally, the effects of the occlusal alteration on the jaw-closing muscles were very similar at the two closing force levels. However, the effects on the contralateral IHLP were more variable between subjects under the low closing force than those under a high closing force level. The results showed that the comparison within individual subjects among seven of nine muscles recorded under the fast-speed task was very similar to that under the slow-speed task with a low closing force.

The results support our hypothesis that a change in the occlusion has an immediate effect on jaw function, in terms of statistically significant effects on both the movement of the condylar head and on jaw muscle activity. The long-term effects of these neuromuscular changes are unclear and it would be expected that the jaw system would undergo further adaptations to the occlusal alteration.

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LIST OF ABBREVIATIONS

3D	Three-dimensional
A	The most anterior point at about the same horizontal level as the lateral pole
C1	Control 1
C2	Control 2
CED	Cambridge Electronic Design
CT	Computer tomography
EMG	Electromyographic
IHLP	Inferior head of the lateral pterygoid
IP	Intercuspal position
IP1	Intercuspal position 1
IP2	Intercuspal position 2
L	The lateral pole
LED	Light-emitting-diode
LP	Lateral protrusive
LR	Lateral retrusive
M	the medial pole
MIPT	Mid-incisor point
MVC	Maximum voluntary contraction
OA	Occlusal alteration
OA2	Occlusal alteration 2
P	The most posterior position at about the same horizontal level as the lateral pole
S	The most superior point
SD	Standard deviation
SHLP	Superior head of the lateral pterygoid
TMD	Temporomandibular disorder
TMJ	Temporomandibular joint

PUBLICATIONS

Papers Published

Part of this thesis has been published in the following papers.

1. Huang BY, Durrant CJ, Johnson CWL, Murray GM. (2002) A method of indirect registration of the coordinates of condylar points with a six-degrees-of-freedom jaw tracker. Journal of Neuroscience Methods 117: 183-191.

2. Huang BY, Johnson CWL, Murray GM. (1999) Indirect measurement of condylar landmarks using computer tomography scans. Visual Information Processing'99 108-111, non-refereed publication.

Papers to be Submitted

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Related Paper

The following paper has arisen from research projects undertaken during the author's period as a PhD candidate but is not included in this thesis.

9. Swintara W, Johnson CWL, Murray GM, Huang BY. (2001) The accuracy with which the human condyle can be expressed in the coordinate system of JAWS3D using a unilateral fiducial marker. Journal of Oral Rehabilitation. 2001; 28: 33-40.

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Part of this thesis has been published in the following abstracts.

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2. Huang BY, Murray GM, Whittle T, Wanigaratne K. (2001) Occlusal interferences influence jaw muscles in lateral movement at high closing force. Society for Neuroscience Abstracts 27 (Part 2): 2489 (938.2).

3. Huang BY, Johnson CWL, Durrant CJ, Murray GM. (2002) Occlusal alterations influence multiple ipsilateral condylar points' movements during laterotrusion. Journal of Dental Research 81 (Special Issue A; San Diego Abstracts): A-229 (1739).

PRESENTATIONS

Part of this thesis has been presented in the following conferences.

International conferences:

Oral presentations:

1. Huang BY, Johnson CWL, Whittle T, Wanigaratne K, Murray GM. Influence of occlusal alteration on jaw muscles during horizontal movements. International Association for Dental Research 79th General Session & Exhibition. 2001. Chiba, Japan.

2. Huang BY, Johnson CWL, Durrant CJ, Murray GM. Occlusal alterations influence multiple ipsilateral condylar points' movements during laterotrusion. International Association for Dental Research 80th General Session. 2002. San Diego, California, USA.

Poster presentations:

3. Huang BY, Murray GM, Johnson CWL, Whittle T, Wanigaratne K. The influence of occlusal alteration on jaw muscles during lateral movement. International College of Prosthodontists. 2001. Sydney, NSW, Australia.

4. Huang BY, Murray GM, Whittle T, Wanigaratne K. Occlusal interferences influence jaw muscles in lateral movement at high closing force. Society for Neuroscience 31st Annual Meeting. 2001. San Diego, California, USA.

Regional conferences: *Poster presentations*

5. Huang BY, Murray GM, Whittle T, Wanigaratne K. The influence of occlusal alteration on inferior lateral pterygoid activity. International Association for Dental Research (ANZ division). 40th Annual Scientific Meeting. 2000. Perth, WA, Australia.

6. Huang BY, Johnson CWL, Whittle T, Wanigaratne K, Murray GM. Influence of occlusal alteration on jaw muscles during horizontal movements. International Association for Dental Research (ANZ division). 41st Annual Scientific Meeting (Colgate Competition). 2001. Chiba, Japan.

7. Huang BY, Whittle T, Wanigaratne K, Murray GM. Occlusal alteration influences jaw muscles in lateral movement. International Association for Dental Research (ANZ division). 42nd Annual Scientific Meeting (Colgate Competition). 2002. Sydney, NSW, Australia.

Local conferences:

Oral presentations:

8. Huang BY, Whittle T, Wanigaratne K, Johnson CWL, Murray GM. The influence of dental occlusal alteration on the activity of the inferior head of human lateral pterygoid muscle. From Cell to Society 2. The University of Sydney. 2000. Leura, NSW, Australia.

9. Huang BY, Whittle T, Wanigaratne K, Murray GM. Occlusal alteration influences jaw muscles in lateral jaw movement at high closing force level. From Cell to Society 3. The University of Sydney. 2002. Leura, NSW, Australia.

Poster presentations:

10. Huang BY, Johnson CWL, Murray GM. Indirect measurement of condylar landmarks using computer tomography scans. Visual Information Processing. The University of Sydney. 1999. Sydney, NSW, Australia.

11. Huang BY, Murray GM, Whittle T, Wanigaratne K. The influence of occlusal alteration on inferior lateral pterygoid activity. Faculty Research Day. Faculty of Dentistry. The University of Sydney. 2000. Sydney, NSW, Australia.

12. Huang BY, Johnson CWL, Whittle T, Wanigaratne K, Murray GM. Influence of occlusal alteration on jaw muscles during horizontal movements. Faculty Research Day. Faculty of Dentistry. The University of Sydney. 2001. Sydney, NSW, Australia.

13. Huang BY, Whittle T, Wanigaratne K, Murray GM. Occlusal alteration influences jaw muscles in lateral movement. Faculty Research Day. Faculty of Dentistry. The University of Sydney. 2002. Sydney, NSW, Australia.

1 Literature review

1.1 Introduction

Natural tooth morphology is often changed during clinical dental practice but with little knowledge of the effects of these changes on jaw function. Thus, there is very little information about the influence of an alteration in tooth guidance on the movement of the condyle. Further, the influence of an occlusal alteration on the related jaw muscle activity during jaw movements is unclear.

It has, for many years, been assumed that condylar guidance was individual and immutable (e.g. Alsawaf and Garlapo, 1992). A few studies, that have used six-degrees-of-freedom tracking devices, have shown that a change to natural tooth guidance could alter both working-side (Coffey *et al.*, 1989; Hobo and Takayama, 1989; Ogawa *et al.*, 1998) and balancing-side (Sarinnaphakorn *et al.*, 1997; Ogawa *et al.*, 1998) condylar movement during lateral jaw movement (laterotrusion). These data suggest that condylar movement could be influenced by the teeth and therefore may not be immutable. However, there are a number of limitations with these studies that influence the applicability of these conclusions.

The major issue in these studies relates to the usage of a single condylar point. During a lateral jaw movement, for example, the working-side condyle is near the instantaneous centres of rotation. Therefore, no single point can adequately represent the movement of the working-side condyle, because the trajectory of the single point will be significantly influenced by the positional relationship of the point to these centres of rotation. Indeed, on the working side, in particular, *the trajectory of motion of one point has no more meaning than that of another* *unless it represents a point of specific anatomical significance (Hannam, 1992).* In addition, the methodology in most studies for the selection of condylar points is based on average values and individual differences are ignored. The points selected in relation to the anatomy are likely to be different between subjects. Further, studies have shown quantitatively and qualitatively that recordings of condylar point movement can be influenced by the location of the point selected (Hobo, 1984, Peck *et al.*, 1997, 1999a, b; Zwijnenburg *et al.*, 1996). The validity of the tracings in these studies as indicating what is happening at the condyle is thus questionable. Therefore, there is a need to develop a new method to register, with the use of three-dimensional radiographic images, multiple anatomically defined condylar points in a jaw-tracking system before further assessment can be made of the effects on the working-side condyle of changes to the occlusion.

In addition, while previous studies suggest that an occlusal alteration could influence condylar movements, there is a lack of information regarding the influence of an occlusal alteration on the electromyographic (EMG) activity of the jaw muscles. Although some early excellent studies (Belser and Hannam, 1985; Baba *et al.*, 1996, 2000) suggested that an occlusal interference could alter the EMG activity of the temporalis and masseter muscles, these studies were carried out at a static lateral jaw position. There is very limited information about the influence of an occlusal alteration on the jaw muscles during dynamic lateral jaw movements. Further, there is very little information of the effect of an occlusal alteration on the lateral pterygoid muscles which are thought to play an important role in the control of lateral jaw movements (Murray *et al.*, 2001; Phanachet *et al.*, 2001, 2002). In addition, although several studies have been done on jaw muscle activity during lateral jaw movements, most of them have focused on whether these muscles were active or not in the lateral jaw position, and the description of the activity pattern during lateral jaw movement was limited. In two recent studies (Murray *et al.*, 1999; Phanachet and Murray, 2000), the relationship of the muscle activity and contralateral (balancing) condylar movement was studied, however, only the balancing-side muscles were studied and the movements performed were unstandardized. Therefore, before studying the effect of an occlusal alteration on jaw muscle activity, a detailed study of jaw muscle activity during lateral jaw movement is needed.

The aims of this study were (a) to develop a new method to register the coordinates of the condylar referencing points in the coordinate system of a jaw-tracking device; (b) to investigate the effect of an occlusal alteration on the working-side condylar movement; (c) to describe the activity of jaw muscles during lateral jaw movements; and (d) to investigate the influence of an occlusal alteration on jaw muscle activity.

1.2 Mandibular and condylar movement during lateral jaw movement (i.e. laterotrusion) and the influence of an occlusal alteration

Before reviewing the effect of an occlusal alteration on the condylar movements during lateral jaw movement, a detailed review of the temporomandibular joints (TMJs), basic mandibular and condylar movements especially during laterotrusion, and the influence of an occlusal alteration on mandibular movements is required. Then, the selection of the condylar referencing points that have been used in the past will be reviewed.

1.2.1 Anatomy of the mandible and temporomandibular joint

The masticatory system involves a cranium carrying a fixed upper dental arch and a moveable mandible, which carries the lower dental arch. Articulation occurs in two (bilateral) joints between the condyles of the mandible and the glenoid fossae of the squamous part of the temporal bones. Other than the simple hinge movement, the human masticatory process includes protrusive, retrusive and lateral movements and a combination thereof. To achieve these, the condyle must undertake translatory as well as rotatary movement. Therefore, the human TMJ is described as a synovial sliding-ginglymus (i.e. hinge) joint (Ten Cate, 1994). To understand the movement of the mandible and the condyle, the functional anatomy of the TMJ will first be reviewed.

1.2.1.1 Mandible

The mandible consists of a horseshoe-shaped body that is continuous upward and backward on either side with the mandibular rami. Each ramus ends in two processes: the anterior coronoid process to which muscle is attached and the posterior articular condylar process. The body is thick, has a rounded lower border, and carries the alveolar process on its upper border, where the teeth are housed.

1.2.1.2 Temporomandibular components

The TMJ is the freely moveable (diarthrodial) articulation between the condyle of the mandible and squamous portion of the temporal bone. Although the articular surfaces are not composed of hyaline cartilage, it is a true synovial joint. Since the left and right condyles are part of the same mandible, one cannot function without the movement of the contralateral condyle. In fact, the term craniomandibular articulation is sometimes used to emphasise this bilateralness, instead of the term temporomandibular joint (DuBrul, 1988).

The TMJ is a complex articulation. Anatomically, the joint space between the condylar and temporal components is divided into separate superior (or upper) and inferior (or lower) compartments by the articular disc. Functionally, it can be classified as a hinge joint with a sliding socket. The hinge (ginglymus) movement takes place in the inferior compartment, between the condyle and the disc. While the sliding (arthrodial, gliding, translatory) movement predominates in the superior compartment, between the disc and the articular eminence of the temporal bone. The TMJ is the only joint of the human body that can be dislocated without extrinsic forces acting upon it (Gardner *et al.*, 1963).

Mandibular condyle

The articular surface of the mandible is represented by the upper and anterior surface of the mandibular condyle. Its adult antero-posterior dimension averages 8 to 10 mm; medio-laterally, it is about twice this dimension. Its articulating surface is strongly convex in an anterio-posterior direction and slightly convex medio-laterally. When the mandible is in the maximally intercuspidated position (centric occlusion), the articular surface of the condyle typically faces the posterior slope of the articular eminence rather than the deepest portion of the mandibular (glenoid) fossae (Mohl, 1988).

Medially and laterally, the condyle terminates at the medial and lateral poles, respectively. The medial pole, in particular, extends beyond the neck of the condyle and is positioned more posteriorly. Thus, the long axis of the condyle deviates from the coronal plane such that, when extended, it runs medially and backward to meet a similar axis drawn from the other condyle at the anterior border of the foramen magnum. The axes of both sides are not parallel and form an obtuse angle of between 145° and 160° (Fig. 1.2-1; Hylander, 1992; DuBrul, 1988).

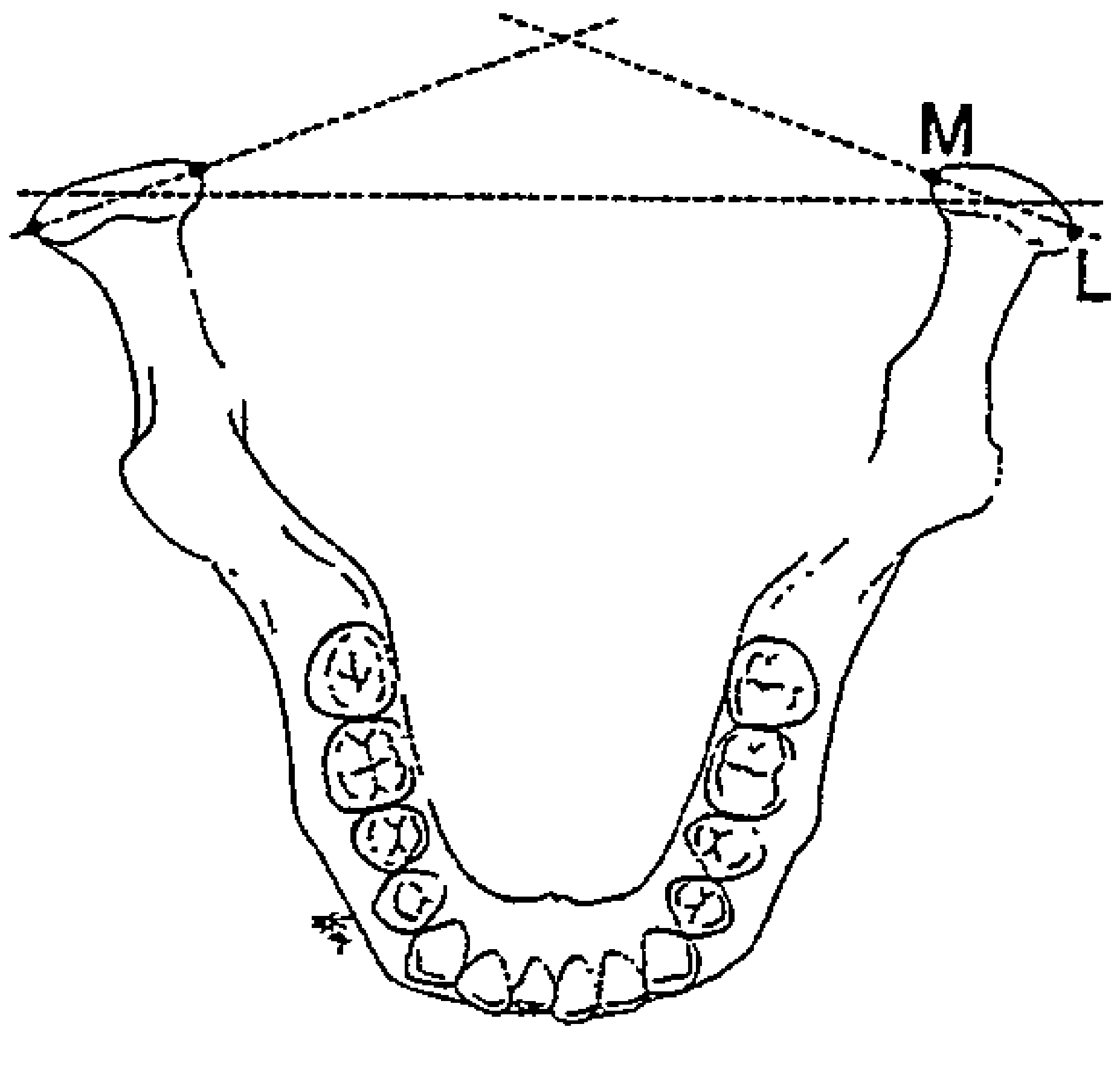


Fig. 1.2-1 Horizontal condylar inclination. Note that lines projected through the lateral (L) and medial (M) poles of the condyle meet medially and posteriorly at an obtuse angle of 145° to 160°. The lateral pole lies anterior to the intercondylar transverse axis while the medial pole lies posterior to this axis (adapted from: Mohl, 1988).

There is a large degree of variation among human condyles, both in shape and in the angle at which the condyle is related to the ramus of the mandible (Yale *et al.*, 1966). In any individual, the left condyle may not have the same form as the right condyle. Thus, this might increase further the error of the condylar points in the studies that used average values to determine the reference condylar points.

Cranial component

The cranial component mainly consist of two parts: the glenoid fossa and the articular eminence. The glenoid fossa, also known as the mandibular fossa or articular fossa, is the concavity within the temporal bone that houses the mandibular condyle. The anterior wall of the fossa is formed by the articular eminence of the squamous temporal. The articular fossa is that portion of the glenoid fossa that is lined by articular tissues, and is formed entirely by the squamous temporal.

Articular disc

The articular disc is a firm but flexible structure, located between the mandibular condyle and the articular eminence. It consists of dense fibrous tissue and its shape conforms to the articular surfaces to which it is opposed. During the mandibular movement, the disc changes its shape and position related to these structures. It provides a largely passive movable articular surface accommodating the translatory movement made by the condyle.

1.2.1.3 Muscles of the mandible

Five powerful muscles, the masseter, the temporalis, the medial pterygoid, the lateral pterygoid and the digastric muscles, are often referred to as the muscles of mastication. These muscles, in conjunction with groups of muscles of the face, tongue, palate, and hyoid bone, function in a co-ordinated manner during mastication. Their roles are in moving, balancing, and stabilizing during chewing cycles.

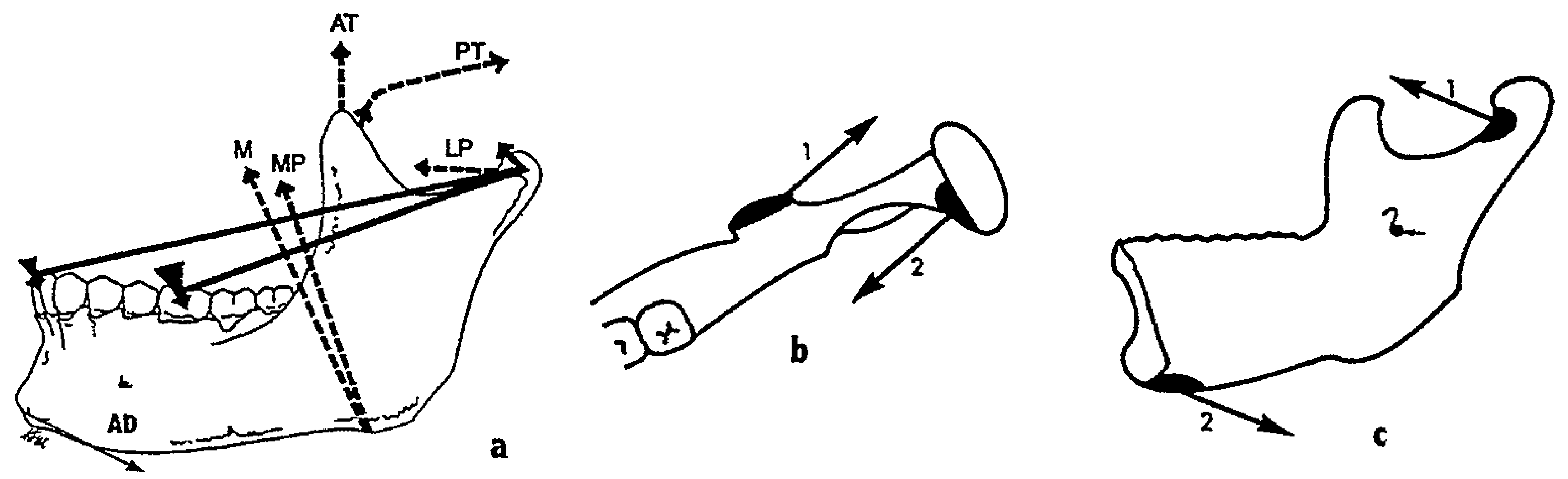


Fig. 1.2-2 (a) Relative position of the vectors produced on the mandible by the muscles of mastication: lateral pterygoid (LP); anterior border of masseter (M); anterior border of medial pterygoid (MP); anterior border of temporalis (AT); and posterior fibres of temporalis (PT) with its effective pull in a posterior and superior direction. In addition, the position of the vector of the anterior belly of digastric muscle (AD) is also shown (modified from: Mohl, 1988). (b) Force-couples: Superior view of mandible showing force-couple rotating jaw laterally. (1) Vector of posterior fibers of temporalis muscle. (2) Vector of lateral pterygoid muscle (modified from: DuBrul, 1988). (c) Force-couples: Internal view of mandible showing force-couple rotating jaw in opening. (1) Vector of lateral pterygoid muscle. (2) Vector of digastric muscle (modified from: DuBrul, 1988).

Fig. 1.2-2 (a) shows the relative position of the vectors produced on the mandible by the muscles of mastication. No jaw muscle contracts in isolation, nor do jaw muscles contract unilaterally (Hannam, 1994). These muscles often work as "force-couples" during function. Thus, two muscles, or two groups of muscles, pull in opposite directions but not in the same line to turn the mandible around a common axis of rotation (fulcrum; as shown in Fig. 1.2-2 (b) and (c)). Further details about the muscles and the influence of an occlusal alteration on these muscles are reviewed in the Section 1.3.

1.2.2 Mandibular movements

Mandibular movements include the hinge movement (opening and closing) as well as protrusive, retrusive, lateral movement, and a combination thereof. To achieve these movements, the mandible must undertake a complex series of six-degrees-of-freedom motions, which can be described by three-dimensional translational displacements along three orthogonal axes and three rotational movements about the three orthogonal axes.

These movements are produced by the activation of the different jaw muscles. The masticatory muscles are the main muscle groups. In addition, other muscles groups, such as sternocleidomastoid, suprahyoid and infrahyoid, cervical, and posterior neck muscles, also play a role in assisting these movements (Eriksson *et al.*, 1998). The activation and interaction of all these muscles are required for precise movement of the mandible, and a finely tuned dynamic balance of head and neck muscles facilitates normal jaw function. The combined and simultaneous movements of both TMJs are also an important component of mandibular movement.

1.2.2.1 Mechanics of mandibular movements

The mechanics of the temporomandibular articulation are difficult to understand. Unlike many other joints, most movements of the mandible are not only directed by the shape of the articulating surfaces and by the configuration of the articular ligaments, but are also influenced either by interplay of the mandibular muscles and the morphology of teeth or by the muscles alone. In fact, the TMJ is unique because it is the only joint system with a rigid end point of closure -- specifically, the calcified occlusal surfaces of the teeth that are fixed to bone via periodontal ligaments. Thus, during mandibular movements, the shapes, alignments and shifting occlusal engagements of these rigid units introduce an extraordinary influence on the positions and movements of the components within the joint capsule, the condyle and the disc. Any alteration of these rigid components is therefore likely to influence mandibular movements. Therefore, in order to study these movements, the fundamental movements of the mandible must be discussed.

Mandibular movement is a complex series of interrelated three-dimensional rotational and translational activities. It is determined by the combined and simultaneous activities of both TMJs. For better understanding of the complexities of mandibular movement, it is beneficial first to isolate the movements that occur within a single TMJ. Therefore, the fundamental movements of jaw motions can be discussed and then the three-dimensional movements of the joint will be divided into movements within a single plane.

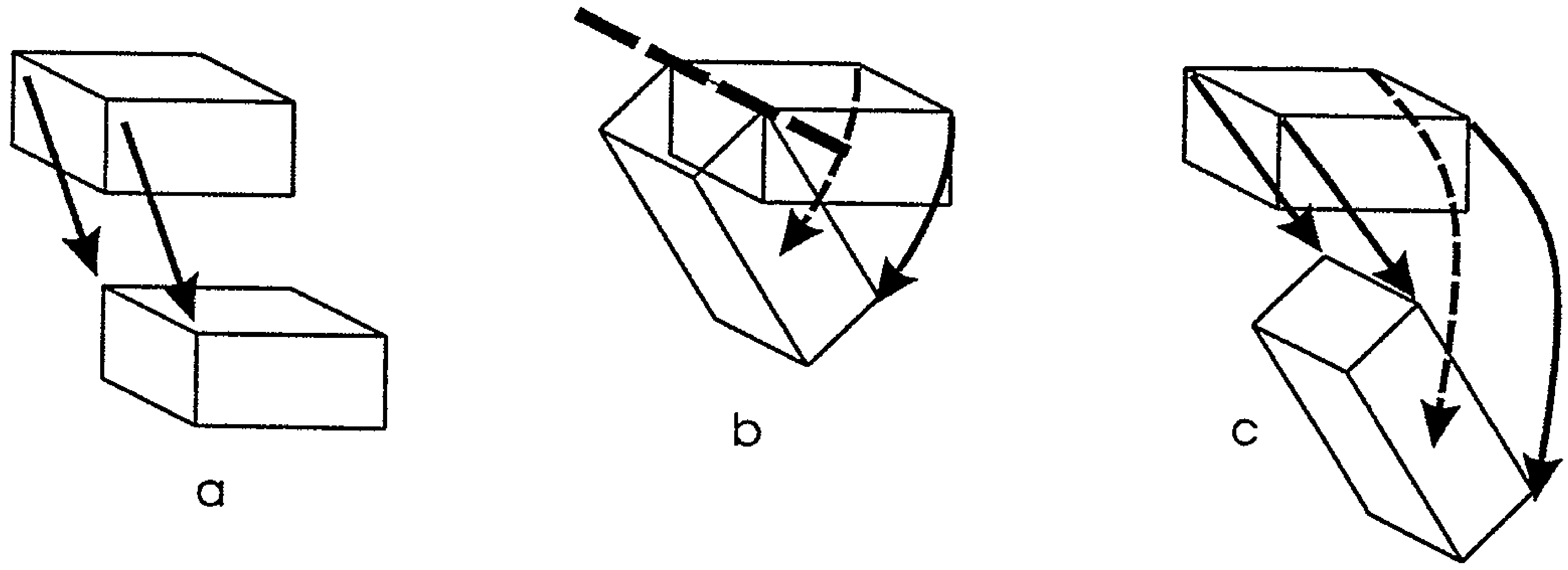


Fig. 1.2-3 Movements. (a) Translation. (b) Rotation. (c) Combined translation and rotation in a single movement.

Two types of fundamental movement occur in the TMJ: rotation (Fig. 1.2-3 (a)) and translation (Fig. 1.2-3 (b)). For most mandibular movements, both movements occur simultaneously (Rocabado, 1983; Merilini and Palla, 1988; Salaorni and Palla, 1994). That is, while the mandible is rotating around one or more of the axes, each of the axes is translating (changing its orientation in space; Fig. 1.2-3 (c)).

Salaorni and Palla (1994) state that the representation of jaw movements by both rotation and translation allows a better understanding of jaw movement as well as a better description of the actual joint movement than the commonly used registration of the translatory path alone. However, in the description of the basic background knowledge of jaw motions, the two fundamental movements will be discussed individually in the following section.

Rotational movements

As defined in the Dorland's Electronic Medical Dictionary (Dorland, 2000), rotation is "*the process of turning around an axis: movement of a body about its axis.*" In the masticatory system, rotation occurs when the mandible performs an open-close as well as a lateral jaw movement around an axis near the condyle. Rotation of the TMJ occurs as movement between the superior surface of the condyle and inferior surface of the articular disc within the inferior cavity of the joint. Rotational movement of the mandible can be divided into three reference planes: horizontal, frontal (vertical), and sagittal. In each plane it occurs around a point, called the "axis". The axis of rotation for each plane will be described and illustrated.

(a) Y-axis of rotation (perpendicular to the sagittal plane)

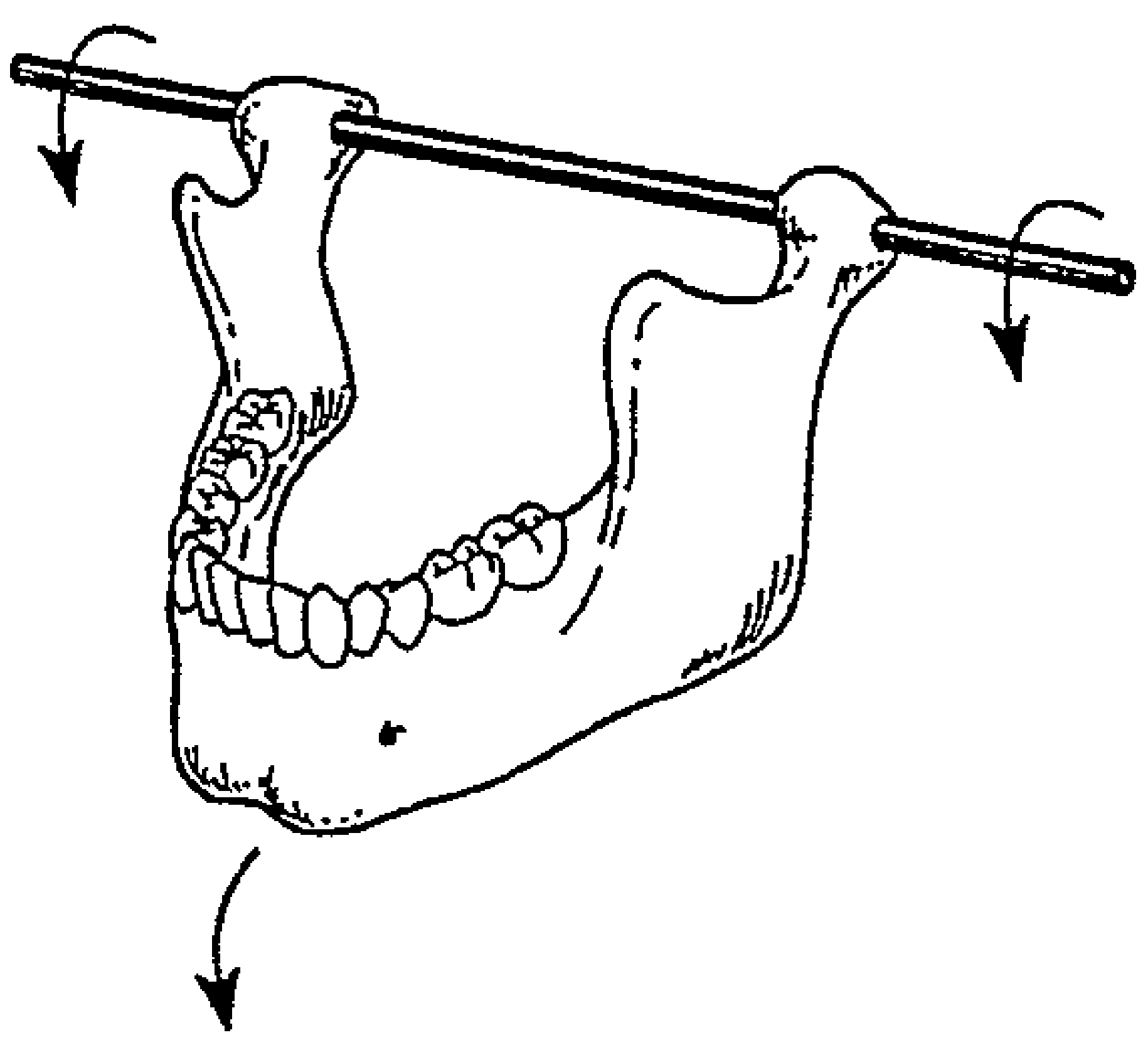


Fig. 1.2-4 Rotational movement around the Y-axis (from: Okeson, 1998).

Mandibular movement around the horizontal axis (i.e. Y-axis) is an opening and closing motion. It is referred to as a hinge movement, and the horizontal axis around which it occurs is therefore referred to as the hinge axis (Fig.1.2-4).

It was believed that the hinge axis movement is probably the only example of mandibular activity in which a "pure" rotational movement occurs. While the condyles are in their most superior position in the glenoid fossae and the mouth is purely rotated open, the axis of the rotation is called the "terminal hinge axis". In other words, the teeth can be separated until the anterior teeth are 20 to 25 mm apart and then occluded with no positional change of the condyles. In all other movements, rotation around the axis is accompanied by translation of the axis (Dawson, 1989; Hylander, 1992; Okeson, 1998). However, other studies (Rocabado, 1983; Merlini and Palla, 1988; Peck *et al.*, 1992; Salaorni and Palla, 1994) questioned whether a pure hinge movement exists in all subjects. These studies showed that the anterior translation and the rotation of the mandible occur simultaneously in some subjects, although there are some conflicts about the quantitative relationship between the amount of translation and opening angle.

(b) Z-axis of rotation (perpendicular to the horizontal plane)

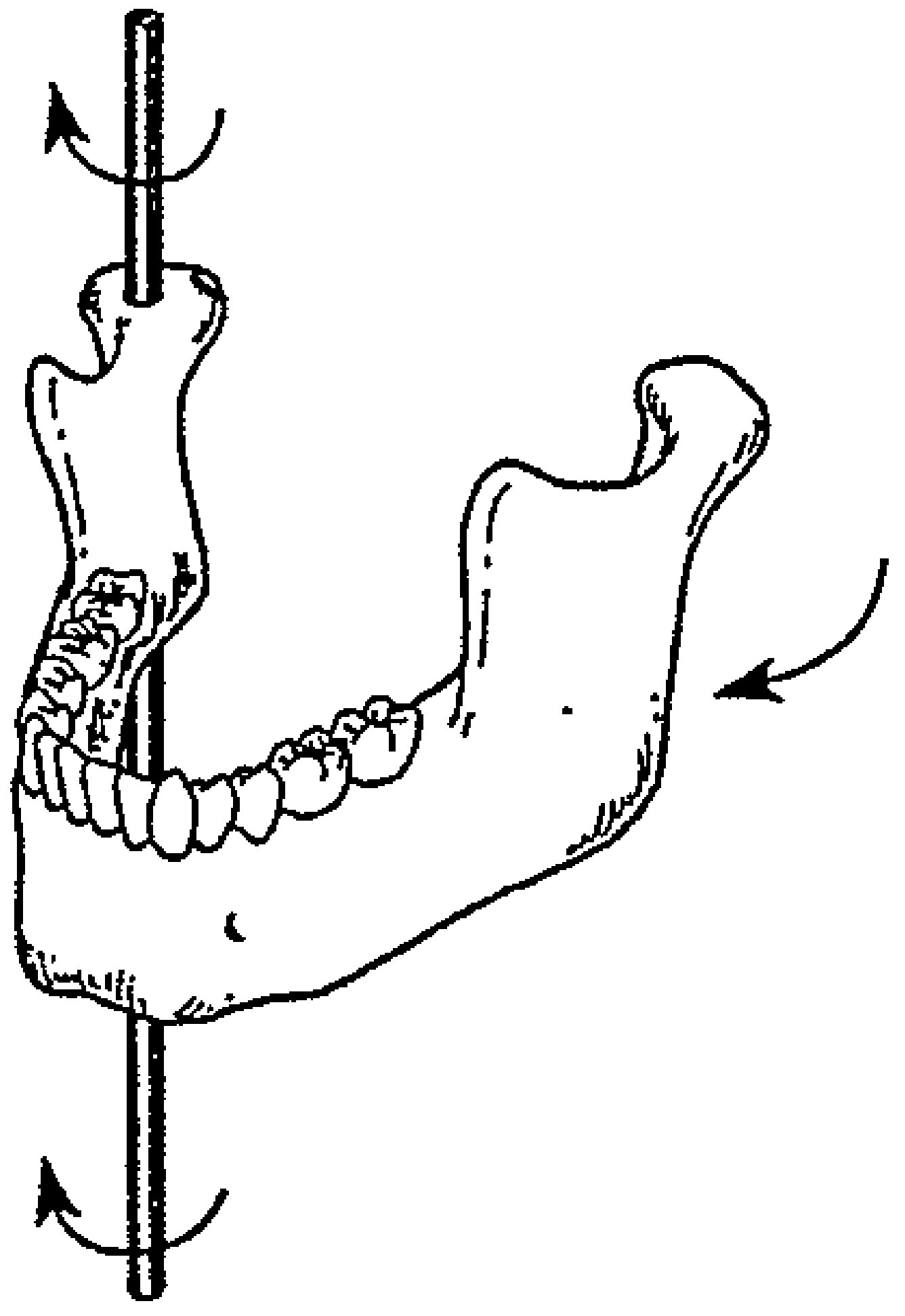


Fig. 1.2-5 Rotational movement around the vertical axis (i.e. Z-axis; from: Okeson, 1998).

Mandibular movement around the vertical axis (i.e. Z-axis; infero-superior) occurs when one condyle moves anteriorly out of the terminal hinge position with the vertical axis of the opposite condyle remaining in the glenoid fossae (Fig.1.2-5). Because of the inclination of the articular eminence, which dictates that the vertical axis tilts as the moving or orbiting condyle travels anteriorly, this type of isolated movement does not occur naturally.

(c) X-axis of rotation (perpendicular to the frontal plane)

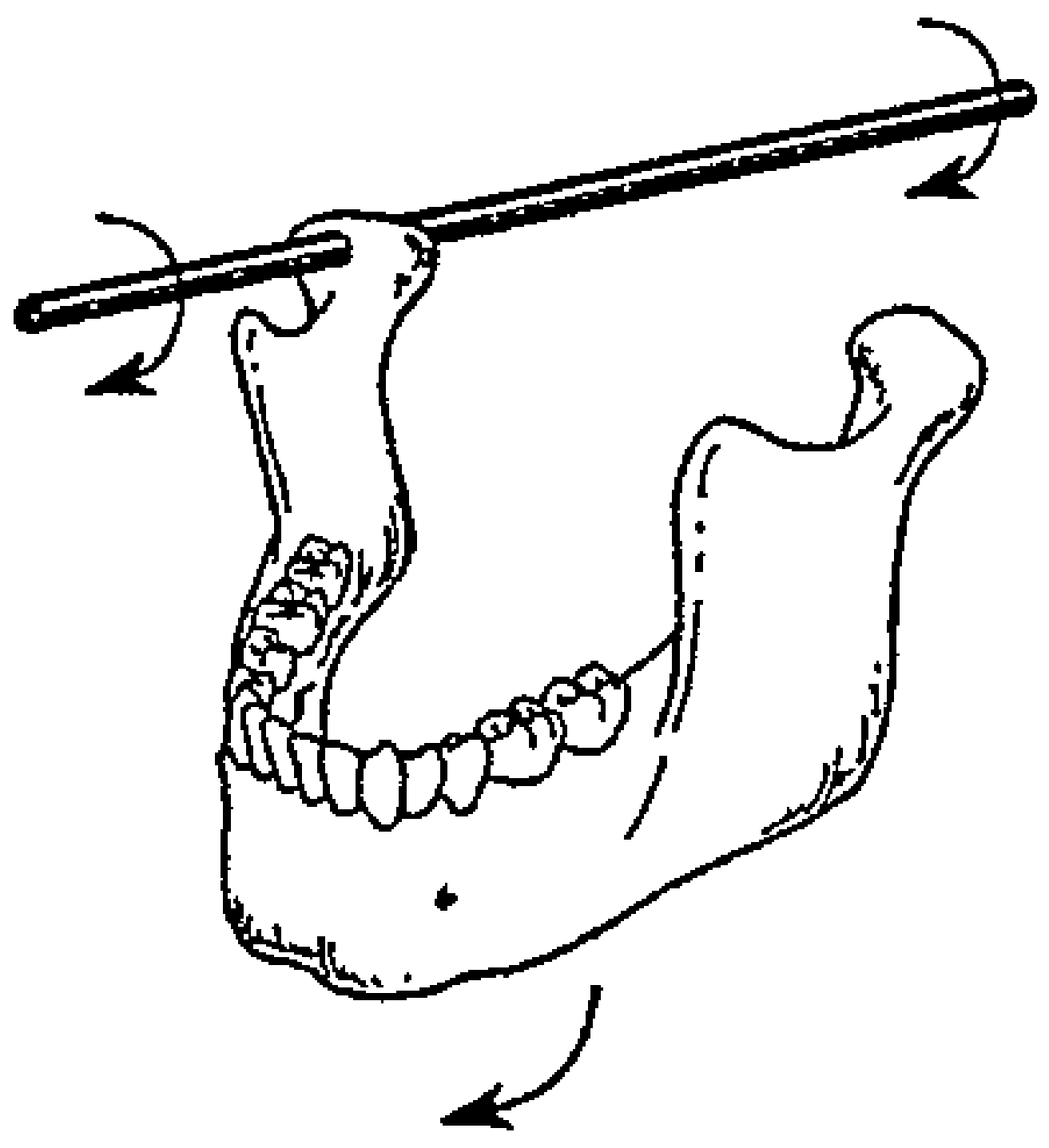


Fig. 1.2-6 Rotational movement around the X-axis (from: Okeson, 1998).

Mandibular movement around the sagittal axis (i.e. X-axis; antero-posterior) occurs when one condyle moves inferiorly while the opposite condyle remains in the glenoid fossae (Fig. 1.2-6). Because the ligaments and musculature of the TMJ prevent a large inferior displacement of the condyle (dislocation), this type of isolated movement is unlikely to occur naturally. It does occur in conjunction with other movements, however, when the orbiting condyle moves downward and forward across the articular eminence.

Translational movements

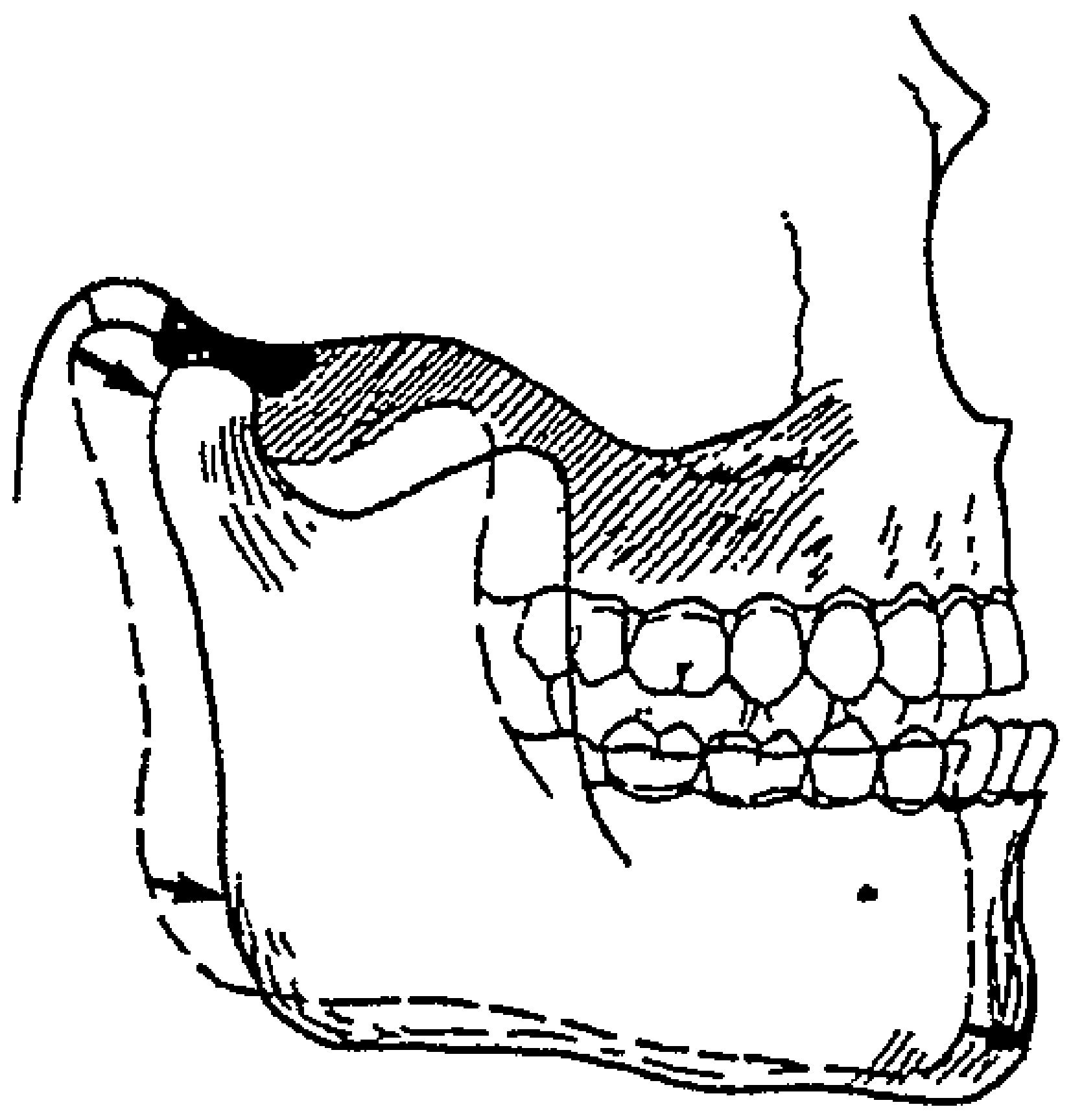


Fig. 1.2-7 Translational movement of the mandible (from: Okeson, 1998).

Translation is defined as a movement in which every point of the moving object has simultaneously the same velocity and direction. Translation of the TMJ occurs within the superior cavity of the joint between the superior surface of the articular disc and the inferior surface of the mandibular fossa (i.e., between the condyle-disc complex and the mandibular fossa). In the masticatory system, it was believed that "pure" translation occurs when the mandible moves forwards, as in protrusion (Fig. 1.2-7; Okeson, 1998). However, a recent study (Peck *et al.*, 1999b) has shown that incisal movements of the lower jaw during protrusion could be different to the condylar movements within the same subject. In other words, some rotation may also occur during protrusion.

1.2.2.2 Border movements of the mandible

Mandibular movement can be divided into two categories: the functional mandibular movements and border movements. Functional movements are the movements made during speech, mastication, yawning, swallowing, and other associated movements {The Glossary of Prosthodontics Terms - Seven Edition, 1999}. Border movements are the movements of the mandible made at the limits dictated by anatomical structures {The Glossary of Prosthodontics Terms - Seven Edition, 1999}. As this study mainly focuses on the influence of an occlusal alteration on the working-side condylar head movement and related jaw muscle activity during laterotrusion or lateral jaw movements with the teeth together, only the border movements are reviewed.

Mandibular movements take place within certain three-dimensional limits. These movements are those limited by ligaments and teeth against the maximal effort of the muscles. The mandible can move about 10 mm laterally, open about 50 to 60 mm, protrude approximately 9 mm, and retrude about 1 mm. These limited movements, known as border movements of the mandible, were first described by Posselt (1952) in his classic diagram, termed Posselt's diagram (Fig. 1.2-8). Border movements can be simply defined as the most extreme movements that the mandible is able to make. These movement pathways are generally considered to be relatively stable and reproducible, except under certain pathological states.

The border movements can be described in sagittal, frontal and horizontal planes. In examining the Posselt's diagram in the following planes, it is important to remember that the limits of mandibular movements, in Posselt's diagram, are derived from movement of the mandibular central incisors only. In addition, it should be remembered that different phases of mandibular movements are limited by different structures. For example, in the sagittal plane as well as the frontal plane, the most superior aspects are limited by tooth contact, while the remaining movements are limited by joint structures and ligaments.

Sagittal plane border movements

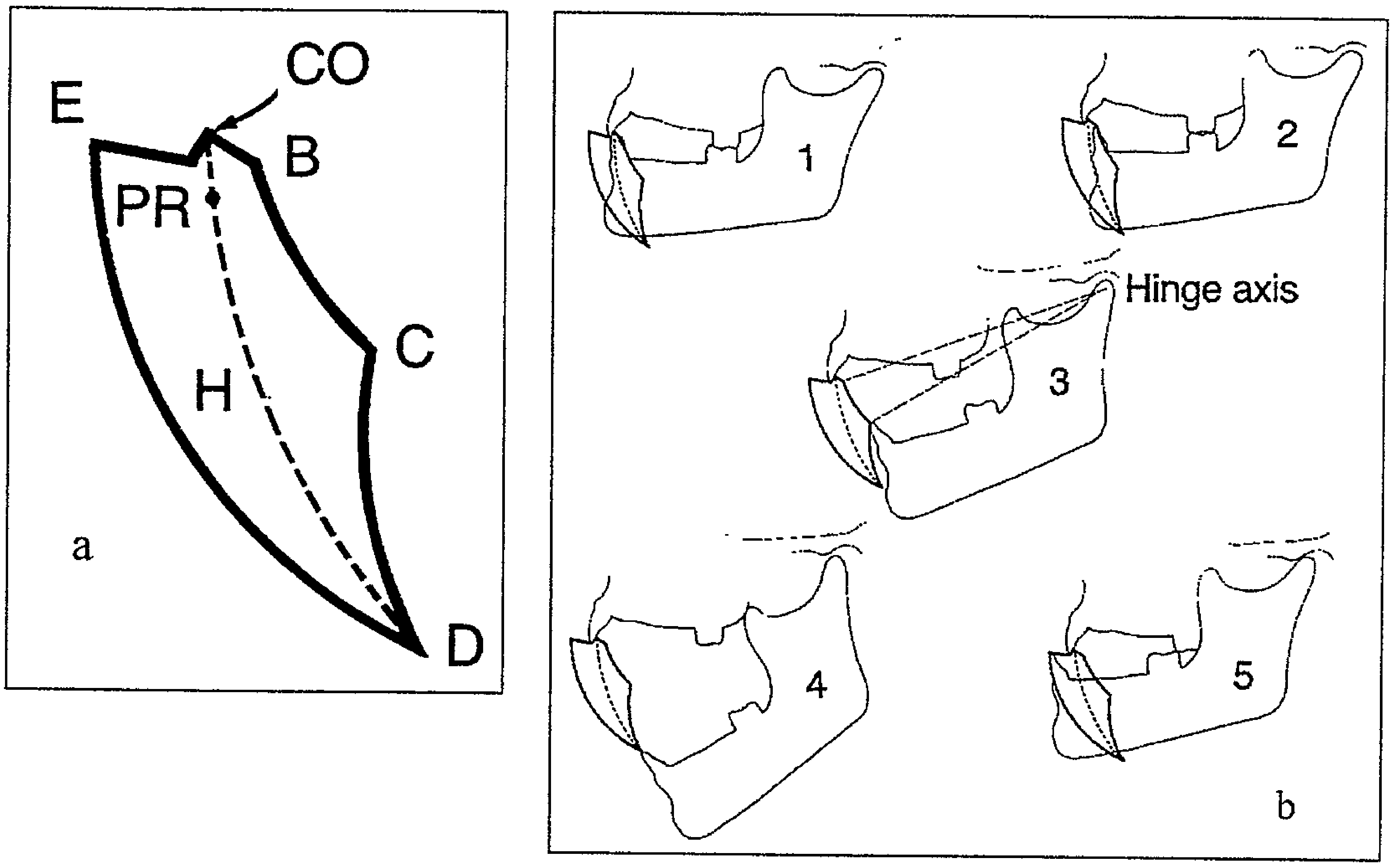


Fig. 1.2-8 (a) Mandibular border movements in the sagittal plane. Centric occlusion (CO) and the other most superior portions are tooth-determined positions. The retruded contact position (B) and the maximum protrusion with tooth contact (E) are determined by teeth and structures of the joint. Other border positions - the rotational hinge movement opening (line B to C), the translation phase of opening (line C to D), the protrusive smooth arch (line D to E) - are determined by structures of the joint and associated ligaments. Note that postural rest position (PR) and the path of habitual closure (H) are not located on any of the borders. (b) (1) Note the position of the mandibular incisal point in centric occlusion. (2) This point moves inferiorly and posteriorly as the mandible is retruded with posterior occlusal contact. (3) The incisal point arcs downward and backward during retruded rotational opening. (4) Note the position of this point during maximum opening with condylar translation. (5) Maximum protrusion with tooth contact brings the incisal point to a reverse incisal overbite position (from Rugh and Johnson, 1988).

The sagittal plane border movement in Posselt's diagram, also known as the median vertical envelope, is a tracing of the maximum vertical and anterior-posterior movements of the mandibular central incisors with respect to the maxillary teeth, as shown in Fig. 1.2-8. Key structures directly affecting border movements are also shown. The following determine border movements of the mandible in the sagittal plane: incisors, posterior occlusion, TMJs, disk, and, not shown in Fig. 1.2-8, the muscles and ligaments. However, as previously mentioned, pure rotation opening (Fig. 1.2-8 (a) line B to C) or pure translation opening (Fig. 1.2-8 (a) line C to D) might not exist in some subjects.

Frontal plane border movements

Frontal plane border movement is a tracing of the maximum vertical and lateral movements of the mandibular central incisors with respect to the maxillary teeth, as shown in Fig. 1.2-9. As in the sagittal plane, the most coronal aspects of the movements are determined by the teeth. When the mandible performs lateral movement from the centric position with tooth contact, the inclines of the working side teeth guide the mandible in a lateral and inferior direction. Notice that the maximum lateral and vertical opening varies among individuals. The lateral movement capabilities are determined by structures of the joint, muscle and ligaments. The border movement tracings in Fig. 1.2-9 show that lateral movements are reduced when the mandible is opened wide.

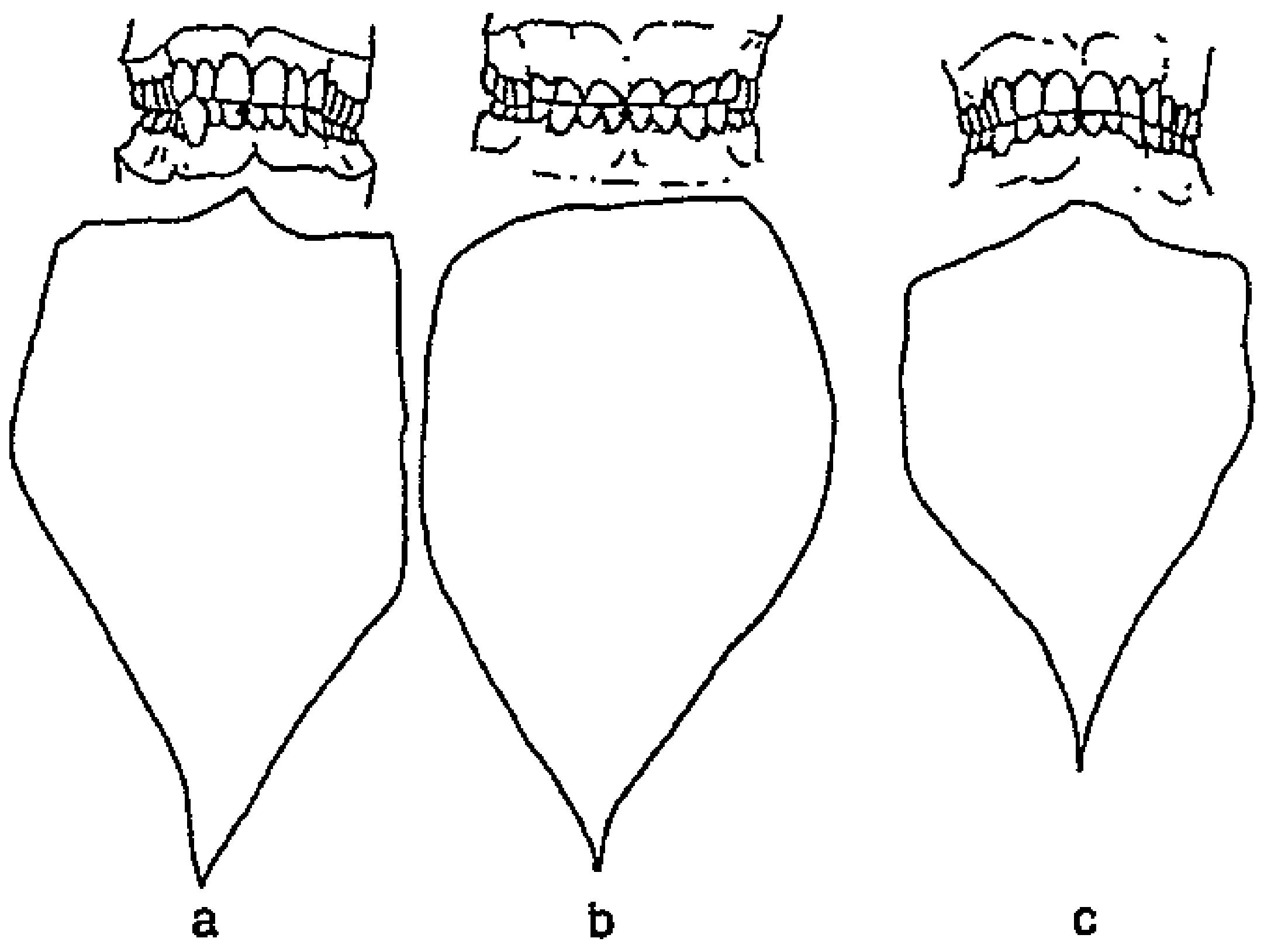


Fig. 1.2-9 Tracings of frontal plane mandibular border movements in three patients with different occlusal conditions. Tracing (a) is from a patient with a relatively steep occlusal guidance and a very specific intercuspal position. Tracing (b) is of a bruxer with very severe tooth wear. The tooth wear provides a relatively flat occlusion that results in a comparatively flat coronal movement tracing for this patient. Tracing (c) is a more common tracing; however, the vertical opening is somewhat restricted (adapted from Gibbs and Lundeen, 1982).

Horizontal plane border movements

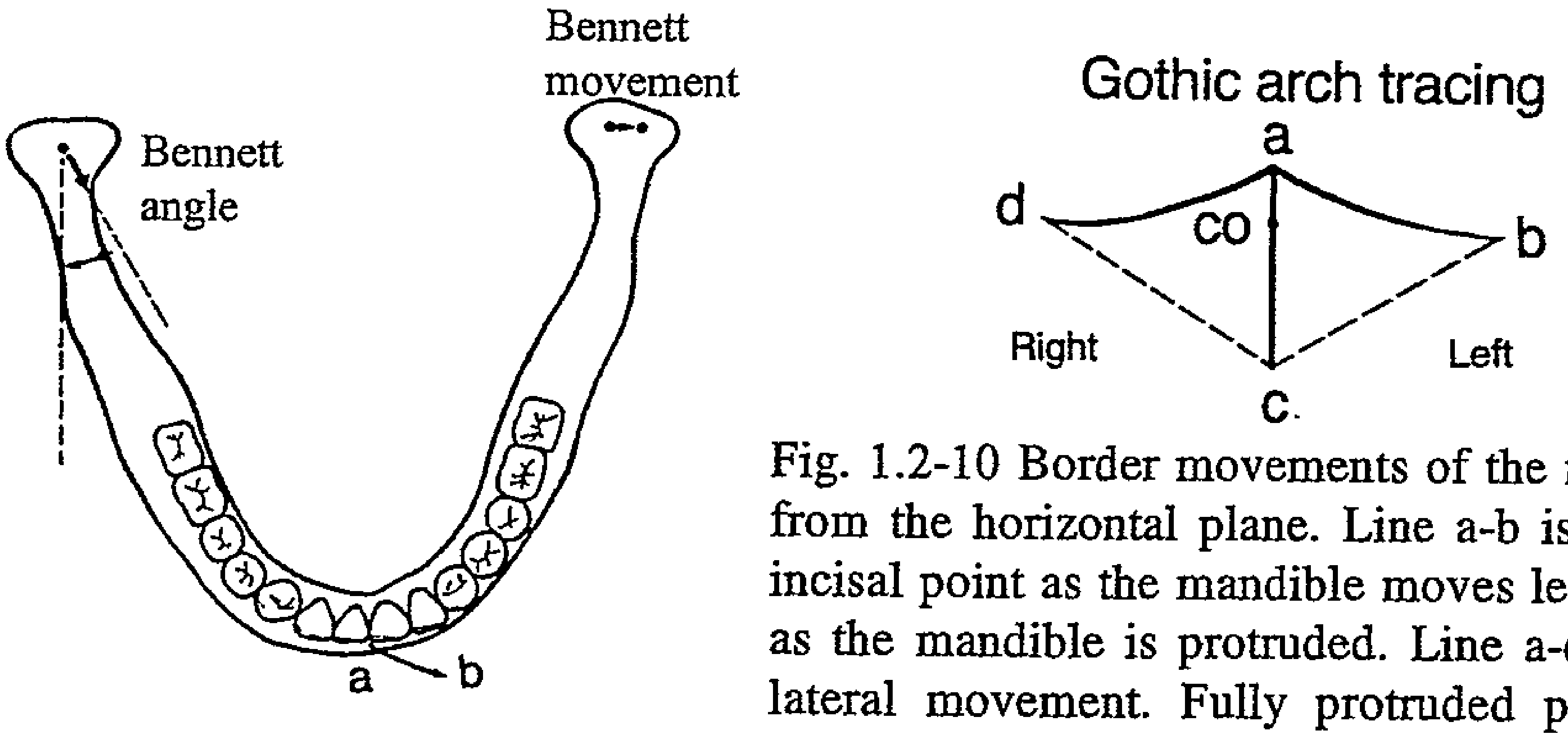


Fig. 1.2-10 Border movements of the mandible as viewed from the horizontal plane. Line a-b is recorded from the incisal point as the mandible moves left. Line a-c is made as the mandible is protruded. Line a-d represents a right lateral movement. Fully protruded position (c); centric occlusion (CO; from Rugh and Johnson, 1988).

Horizontal plane border movements, also known as the horizontal envelope, is a tracing of the maximum lateral and antero-posterior movements of the mandibular central incisors with respect to the maxillary teeth, as shown in Fig. 1.2-10. The Gothic arch tracing of Gysi (1910) recorded from this plane show lateral and antero-posterior movements of the jaw. This tracing usually begins with the mandible at the most retruded position, known as centric relation (CR) position. This point is usually 1 mm posterior to the centric position. As in sagittal and frontal border movements, the Gothic arch tracing varies between individuals, mainly due to individual variability in the shape and size of the condyle and fossa and to muscular and ligament characteristics (Mongini and Capurso, 1982).

1.2.2.3 Posterior and anterior determinants

As discussed above, the superior aspects of mandibular movement are limited primarily by the teeth and the joints morphology. The shape, relative position, and anatomy of the teeth and joint are the determining factors of the movements that the mandible may make. Because the mandibular movements and their relation to occlusal and joint anatomy are interdependent, it is important to be familiar with the relationship among these three factors, before the discussion of the jaw movements in detail.

The anatomical differences between individuals of the TMJ components, known as the ***posterior determinants***, can influence the mandibular movement. These determinants include the shape of the articular eminence, the anatomy of the medial walls of the mandibular fossae, the form of the mandibular condylar process, the intercondylar distance, the ligaments, the jaw muscles, the disc, etc. For example, subjects with a steeper slope of the articular eminence would be likely to have a larger downward component of condylar movement during lateral and protrusive excursions if the contour of the disc was not a factor. Further, as the movement of the mandible is controlled and limited by the muscles and ligaments, any changes of these soft tissues could conceivably change the path and the range of mandibular movements.

It was generally believed that condylar guidance was individual and immutable (Ingervall, 1972; Pelletier and Campbell, 1990; Alsawaf and Garlapo, 1992). Therefore, it was widely accepted that occlusal guidance and the occlusal form of a prosthesis should be restored in harmony with condylar guidance (McCollum, 1939; Ash and Ramfjord, 1995). A number of clinical procedures have been formulated to reflect this philosophy. However, most of these procedures actually record condylar "movements" and not the condylar "guidance". Condylar guidance is *"the mandibular guidance generated by the condyle and articular disc traversing the contour of the glenoid fossae"* {The Glossary of Prosthodontics Terms - Seven Edition, 1999}. The condylar path (or movement) is *"the path traveled by the mandibular condyle in the TMJ during various mandibular movements"* {The Glossary of Prosthodontics Terms - Seven Edition, 1999}. And condylar movements are not only influenced by the condylar guidance but also by other posterior determinants, such as muscles. In addition, recent studies suggest that condylar movements could be changed by an occlusal alteration (for details, see Section 1.2.5.5). Thus, there is a need to be cognisant of the difference between the "posterior determinants", "condylar guidance" and "condylar movements".

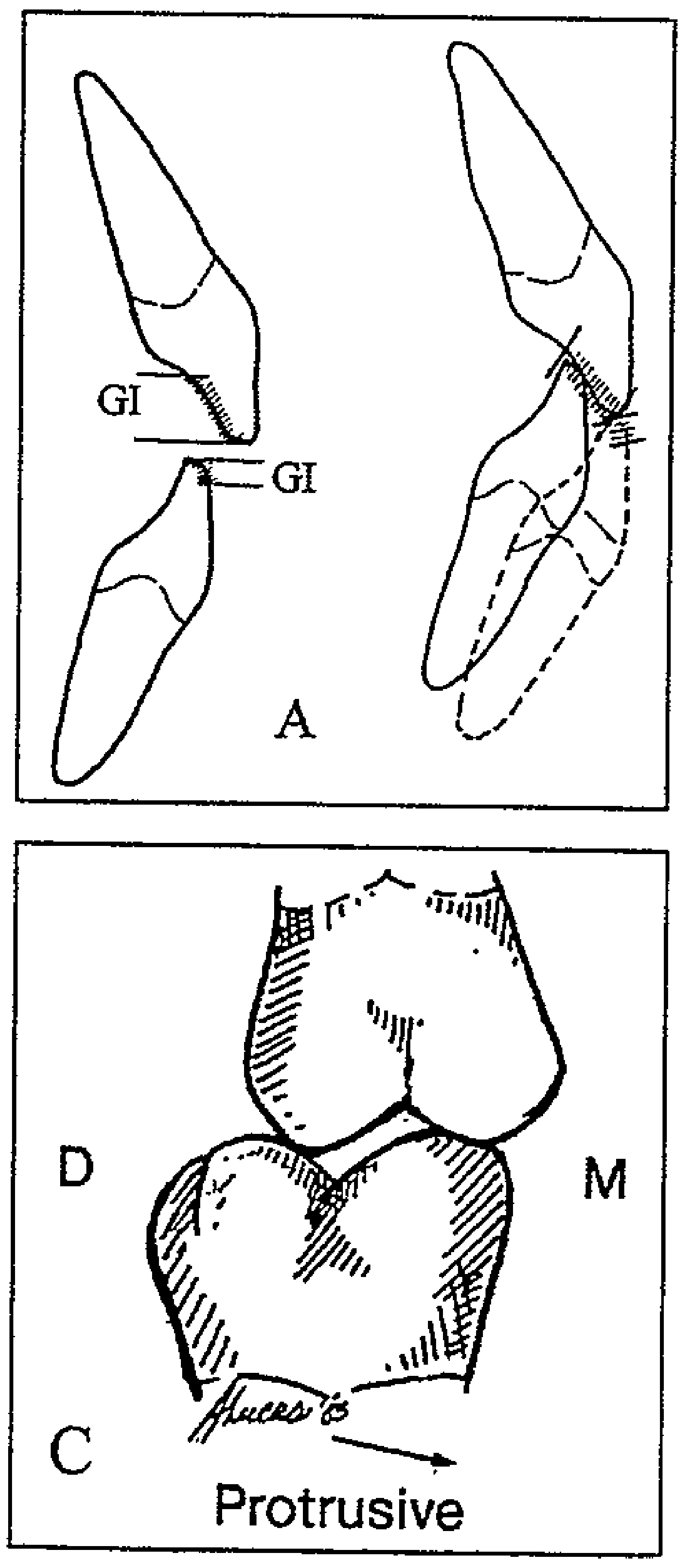
Similarly, the anatomical differences of the teeth, known as the ***anterior determinants***, can influence mandibular movements. These factors include the vertical and horizontal overlap and the shapes of the palatal concavities of the anterior teeth as well as the cusp height and inclination of the posterior teeth. For example, a greater vertical overlap causes the direction of mandibular opening to be more vertical during the early phase of a protrusive or chewing movement as well as causes a more vertical pathway at the end of the chewing stroke. Since anterior guidance can be altered either by clinical dental practice or by pathologic conditions such as caries, oral habits, or tooth wear, it is considered as a variable rather than a fixed factor.

1.2.2.4 Occlusal contact during mandibular border movements

The superior contact border movement is determined by the characteristics of the occlusal surfaces of the teeth. Throughout this entire movement, tooth contact is present. Since this border movement is solely tooth determined, changes in the teeth result in changes in the border movements. It is important to have an understanding of the types and locations of tooth contacts that occur during the basic mandibular movements. The term "eccentric" is used to describe any movement of the mandible from the intercuspal position that results in tooth contacts. The three basic eccentric movements are protrusive, laterotrusive (as well as mediotrusive) and retrusive border movements. In here, only the static relationships of the posterior and anterior teeth are discussed. However, one should keep in mind that the masticatory system is extremely dynamic.

Protrusive mandibular movements

The protrusive movement is defined as the movement of the mandible forwards from the intercuspal position (IP). Any tooth contact, which occurs within this movement, is considered as protrusive contact. In normal occlusal relationships, this mainly happens on the anterior teeth, while the incisal and labial edges of the mandibular teeth move against the lingual fossa areas and incisal edges of the maxillary teeth. These are considered as the guiding inclines of the anterior teeth (Fig. 1.2-11 (A)). On the posterior teeth, contacts can occur between the distal inclines of the maxillary palatal cusps and the mesial inclines of the opposing fossae and marginal ridges. Posterior protrusive contacts can also occur between the mesial inclines of the mandibular buccal cusps and the distal inclines of the opposing fossae and marginal edges (Fig. 1.2-11 (B) and (C)).



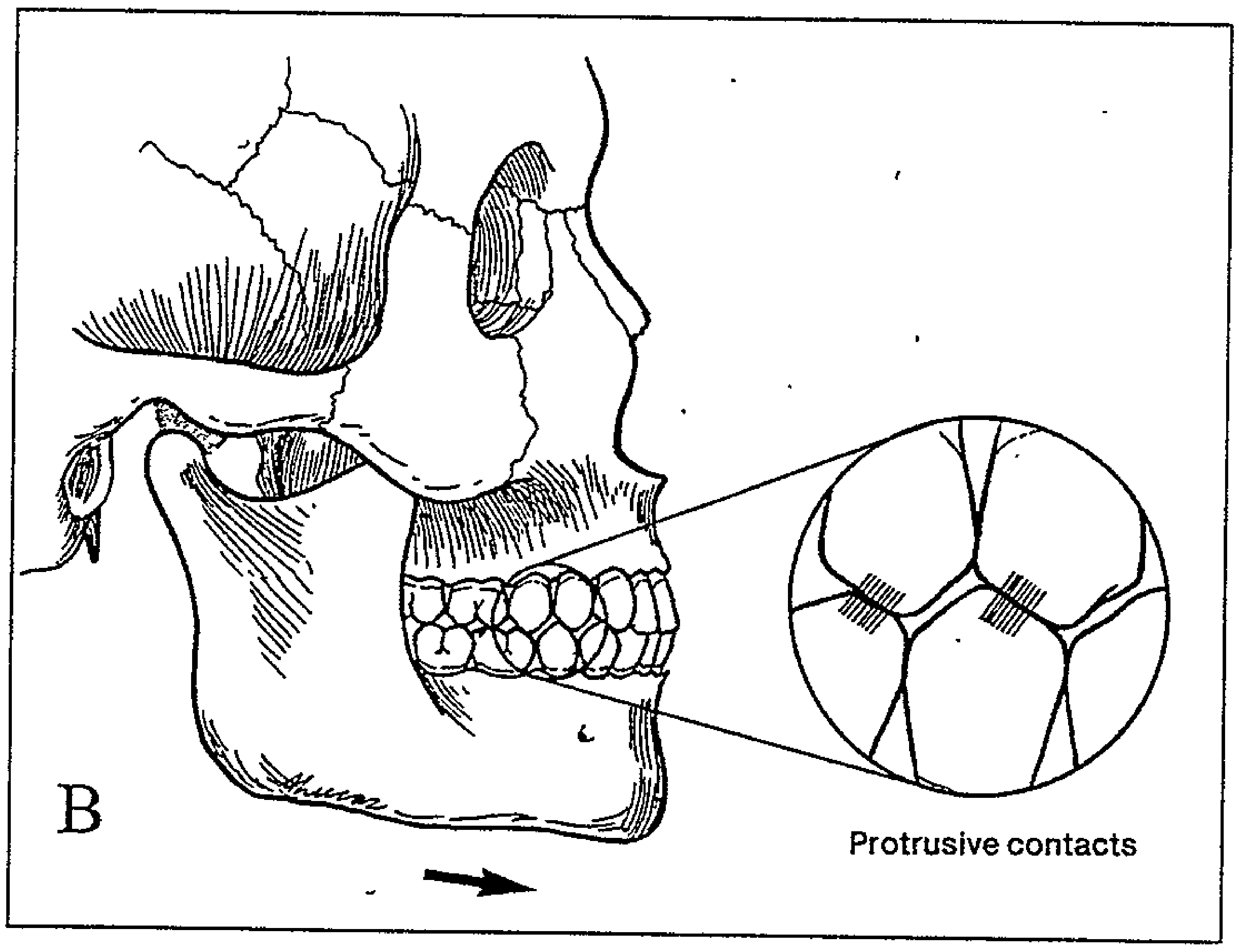


Fig. 1.2-11 (A) Anterior guiding inclines (GI) during protrusion. (B) and (C) Posterior protrusive contacts can occur between the distal inclines of maxillary teeth and the medial inclines of mandibular teeth. D: distal; M mesial (adapted and modified from: Okeson, 1998).

Laterotrusive and mediotrusive mandibular movements

During lateral movements of the mandible, the left and right mandibular teeth move across their opposing teeth in different directions. Two types of occlusal contacts can occur: laterotrusive contacts on the working side and mediotrusive contacts on the balancing side.

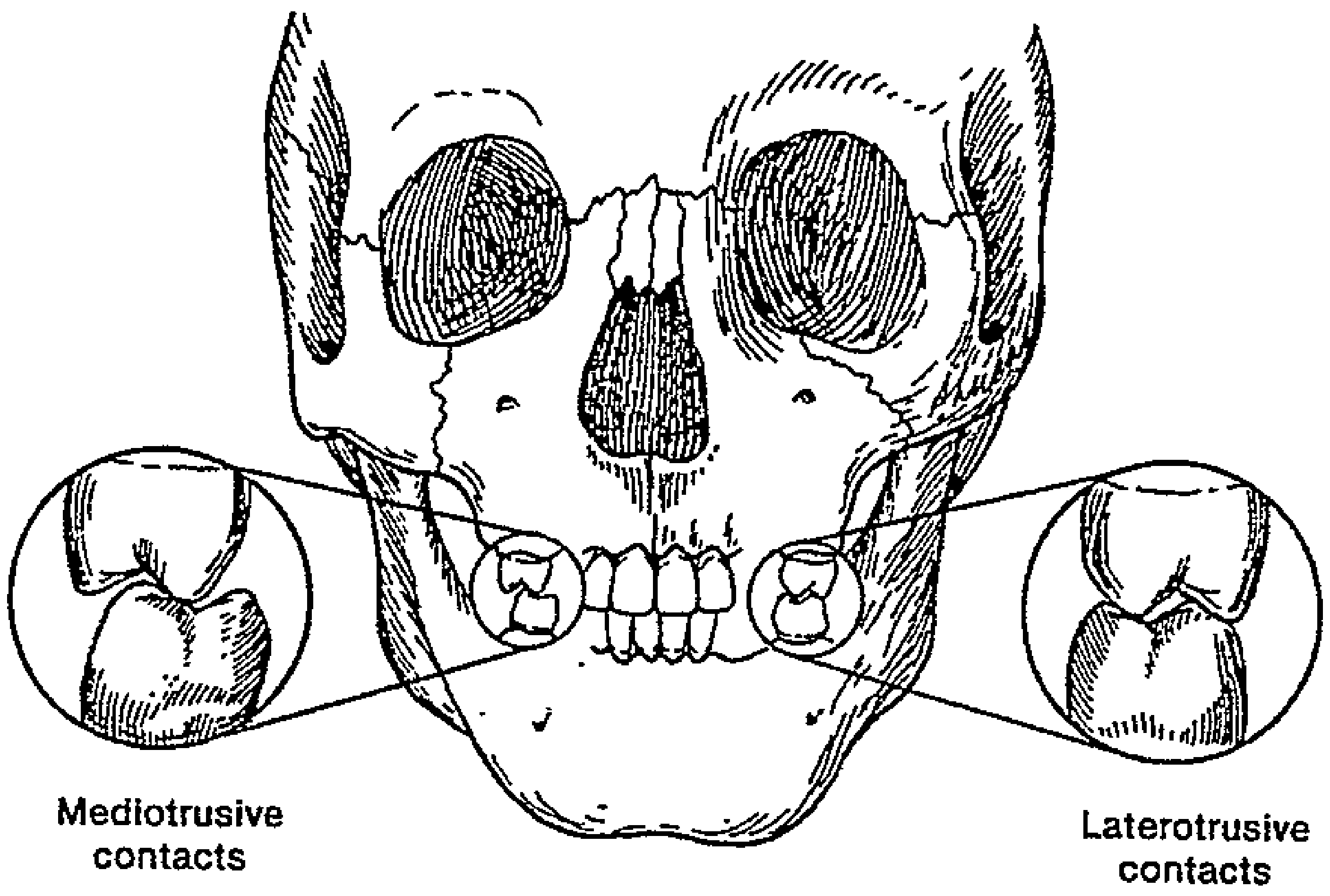


Fig. 1.2-12 Occlusal contacts during left laterotrusive movement (adapted from: Okeson, 1998).

In Fig. 1.2-12, for example, while the mandible moves toward the left side, contacts can occur on two incline areas. One is between the inner inclines of the maxillary buccal cusps and the outer inclines of the mandibular buccal cusps. The other is between the outer inclines of the maxillary lingual cusps and the inner inclines of the mandibular lingual cusps. Both contacts are known as laterotrusive contacts or working contacts, while, for differentiation, the later one is also known as lingual-to-lingual laterotrusive.

At the same time, the right mandibular teeth pass across the opposing teeth in the medial direction. The potential tooth contacts, called mediotrusive contacts, are located between the inner inclines of the maxillary lingual cusps and the inner inclines of the mandibular buccal cusps. As this happens on the balancing side, they are also termed balancing contacts or non-working contacts.

As previously mentioned, the anterior teeth may play an important guiding role during mandibular lateral movements. During lateral movement, the laterotrusive contacts could occur between the mandibular and maxillary canines only. If so, this is known as canine guidance, and the contact is located between the labial surfaces and incisal edges of the mandibular canines and the lingual surfaces and incisal edges of the maxillary canines.

Retrusive mandibular movements

Opposite to protrusive movements are retrusive movements that occur when the mandible moves posteriorly from the intercuspal position. The range of this movement, while compared with other mandibular movements, is relatively small (~1 mm) due to the limitation of the ligaments. In this movement, the mandibular buccal cusps move distally across the occlusal surfaces of the opposing maxillary teeth. Areas of potential contact occur between the distal inclines of the mandibular buccal cusps (centric) and the mesial inclines of the opposing fossae and marginal ridges (Fig. 1.2-13).

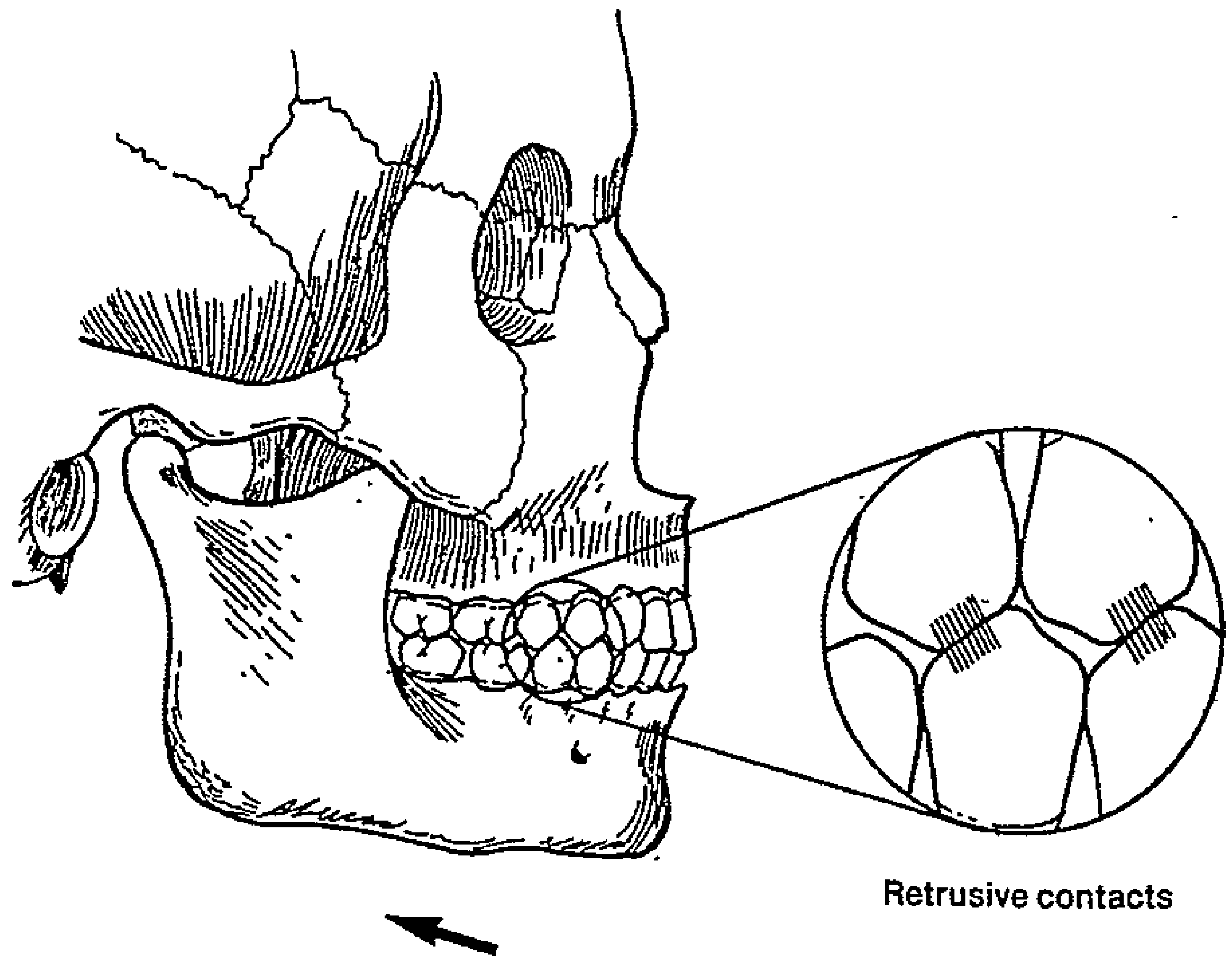


Fig. 1.2-13 Posterior retrusive contacts can occur between the mesial inclines of the maxillary teeth and the distal inclines of the mandibular teeth (adapted from: Okeson, 1998).

1.2.3 The influence of changes in the occlusion on the mandibular movement

During the jaw functions of mastication and swallowing, tooth guidance is thought to have an influence on muscle activity, and this altered activity may contribute to an altered pattern of mandibular movement (for review, see Clark *et al.*, 1999). Physically, the tooth guidance varies with tooth arrangement and interarch teeth relationships. Anterior guidance is determined by the overbite and overjet arrangements of anterior teeth and posterior guidance by the relationship of the inclines of bicuspid and molar supporting cusps. In this section, the studies of mandibular movement, which involve an alteration of occlusion, are reviewed.

Ahlgren's early study (1966) indicated that, with 'normal occlusion', the subjects showed a simpler and more regular chewing pattern. Subjects with malocclusions demonstrated chopping, reversed, contralateral, and irregular masticatory strokes. Later in 1976, he reported that the occlusion of the teeth was of significant importance for the development of masticatory movements. This supported the proposition that occlusal morphology had a close relationship with mandibular movement during the last few millimeters of the closing cycle and was in agreement with the review of masticatory function reported by Bates and coworkers (1975). Therefore, it was likely that an alteration of guiding cuspal forms could change jaw movements.

Wood and colleagues (1981) studied jaw movement patterns using the Kinesiograph. The jaw movement patterns of five subjects with reconstructed occlusions were compared with those of 10 dentate subjects with largely unrestored dentitions. The mean linear separations between opening and closing pathways and deviations around these pathways for the reconstructed group were consistently smaller than those for the control group. The results suggest that reconstructed subjects use displacement patterns which show less variation than do subjects with natural dentitions.

Hannam and colleagues (1981) studied the immediate effect of working-side occlusal interferences on muscle activity and jaw muscles in normal human subjects. The results suggested that chewing pattern, jaw displacement and muscle activity could be influenced by the occlusion. Later in 1985, Belser and Hannam studied the influence of altered working-side occlusal guidance on masticatory muscle activity and related jaw movement during chewing. The results suggested that the occlusal alteration narrowed the envelope of border movements in the frontal plane, especially in the area close to the intercuspal position.

Shiau and Ash (1989) studied the immediate and delayed effect of a working-side interference on normal subjects. Changes were observed in EMG activity and chewing patterns after the placement of the interference. These changes included an immediate slight decrease of the opening velocity, a significantly increased closing velocity of jaw movement, and premature contraction of the closing muscles. Later in 1995, Shiau and Syu studied the effect of a working-side interference on bruxers and non-bruxers. The results showed that the occlusal alteration changed the pattern of border movements in both bruxers and non-bruxers. The closing velocity was often decreased immediately after the placement of the interference.

Two recent studies also provided related information about the influence of the occlusal modifications on the mandibular movement. After the prosthodontic rehabilitation on patients with extensive tooth wear (Ekfeldt & Karlsson, 1996), increased duration of the masticatory mandibular opening movement and decreased mandibular movement velocity was noticed following rehabilitation. The mandibular closing angle, near occlusal contact, became steeper after prosthodontic treatment, indicating a changed mandibular movement pattern. In another investigation involving healthy children with incisor crossbite (Sohn *et al.*, 1997), a broader jaw movement pattern in the frontal view and faster jaw movement velocity in the lateral direction, at a level close to the habitual maximum intercuspation position, was shown in the post-treatment record ($p < 0.05$). The duration of the muscle activity and the incidence of silent periods in the masseter muscle during chewing significantly decreased after treatment ($p < 0.005$).

According to these studies, the introduction of an occlusal alteration could alter the mandibular movement. Thus, it raises the question as to the influence of an occlusal alteration on the condylar path, as the condyle is part of the mandible. The following section reviews condylar movement and the influence of an occlusal alteration on condylar movement.

1.2.4 Condylar movement

The movements of the condyle are more complex in the human than horizontally oriented quadrupedal animals, even some bipedal animals, like anthropoid apes, because of the limitation of the body axis, the bony structures, and the ligaments. For example, the horizontally oriented body axis allows quadrupedal animals to rotate open their mouth widely without infringing upon the submandibular and retromandibular structures of the neck. Therefore, to have a wider range of mandibular movements in humans, most of the rotation movements are combined with the translation movements, and thus likely to result in a significantly altered condylar movement path in comparison with other animals. In the following section, the balancing and working side condylar movement during lateral jaw movements under the natural tooth guidance are reviewed.

1.2.4.1. Balancing-side condylar movement

Lundeen and coworkers (1978) reported that the balancing side (i.e. contralateral or non-working) condylar head generally moves downward, forward and inward during lateral jaw movement to the side contralateral to the balancing-side condyle. The amplitude of the displacement of the balancing-side condyle, approximately 10-14 mm (Slavicek, 1988), is larger than that of the working-side condyle. The lateral jaw movement is a unilateral translation of the balancing side condyle with minimal condylar rotation within the inferior concavity of the disc, as the superior aspect of the disk translates across the temporal bone.

Peck and colleagues (1999b) reported that in all 44 subjects, all balancing-side condylar points moved downward, forward and medially (to the side of jaw movement), and these data were recorded with a six-degrees-of-freedom jaw-tracking device. During laterotrusion, the balancing side condyle moved 7.2 mm anteriorly, 5.9 mm inferiorly and 2.3 mm medially. These values were comparable to those reported by Slavicek (1988) who noted an anterior translation of 7.2 mm and an inferior translation of 5.6 mm. The average rotation angles were 3.5° in the horizontal plane and 1.2° in the sagittal plane at maximal laterotrusion (Peck *et al.*, 1999b). These rotation angles in each plane were approximated by directly measuring the angle between the condylar shapes at the beginning and the end of the movement.

1.2.4.2. Working-side condylar movement

The working-side condyle rotates and translates during various lateral movements. Previous studies (Hobo, 1984; Lundeen *et al.*, 1978; Colaizzi *et al.*, 1988; Peck *et al.*, 1999a) suggested that during laterotrusion, the condyle moved laterally (known as "Bennett movement"), with some variation in the amplitude and in the direction antero-posteriorly and/or supero-inferiorly. However, some studies (De Pietro, 1963; Landa, 1958) argued that the backward, upward and inward pantographic tracing of the working-side condyle may simply be the result of a rotating condyle that projected this rotational movement as a translation onto the laterally positioned recording table. Therefore, these authors suggested a purely rotating working-side condyle during lateral jaw movement.

A recent study (Peck *et al.*, 1999a) supported the existence of Bennett movement during lateral mandibular movement. The authors studied the working-side condylar movement during laterotrusion with a six-degrees-of-freedom jaw-tracking device. The working-side condyle showed a clear lateral displacement (mean ± SD, 1.4 ± 0.7 mm) in most of the subjects. The mean horizontal displacement was 2.0 mm and the mean sagittal displacement was 1.5 mm. In 32 of 44 subjects, the condyle moved upward, backward and laterally; in eight subjects, the condyle moved downward, forward and laterally; in the remaining four subjects, the condyle moved upward, forward and laterally. In addition, the study showed considerable variability compared with the amount of translation in each subject between different condylar points during a single working-side lateral movement. In other words, the selection of the condylar point may influence the result of the working-side condylar tracing during laterotrusion. Thus, "*a single condylar point and even a clinically determined condylar shape may provide a misleading interpretation of condylar movement during working-side excursive jaw movements. To accurately describe the movements of the working-side condyle, the trajectories of at least 3 radiogaphically determined condylar points should be calculated from mandibular movement recorded with six degrees of freedom*" (Peck *et al.*, 1999a).

1.2.5 The influence of changes in the occlusion on condylar movement

There is controversy as to the relationship between an occlusal alteration and condylar guidance. Some studies using articulators (Page, 1955; Schulte *et al.*, 1985) or pantographs (Clayton *et al*, 1971; Dupas *et al.*, 1987) suggested that a change in the occlusion had no effect on condylar guidance. On the other hand, some pantographic studies (Kamimura, 1983; Gross *et al.*, 1985, 1993) indicated that an occlusal alteration could change condylar tracings. However, in these articulator-based studies, the articulators cannot fully simulate human condylar and mandibular movement. Further, the pantographic tracings were recorded from sites far away from the actual condylar position, thus, the rotation of the condyle would have a significant effect on the tracings. In addition, recent studies (Zwijnenburg *et al.*, 1996; Peck *et al.*, 1997, 1999a, b) have indicated that points approximately 5 mm away from the selected condylar path could show a different path during working-side laterotrusion. As the recording site of the pantographic device was likely 20 mm or more away from the condyle, the condylar tracings recorded in these studies (either the articulator studies or the pantographic studies) are very likely to be very different to the actual condylar movement.

Recently, four studies, using six-degrees-of-freedom jaw-tracking devices, suggested that an occlusal alteration could change the condylar path during laterotrusion. These studies are reviewed in this section. But before that, the concept and problems associated with six-degrees-of-freedom jaw-tracking devices is discussed.

1.2.5.1 Definition of six degrees of freedom

The expression *six-degrees-of-freedom* refers to the description of the motion of objects in terms of translation and rotation with respect to axes in three-dimensional space. A device that can record movement in six degrees of freedom is the equipment which can record the three translatory and three rotatory movements of an object and apply the recordings in the calculation of the movement of any point within or on the target object.

1.2.5.2 Basic principle of six-degrees-of-freedom devices

In a rigid object, which is subject to Newton's law of translation and rotation, the total movement of any point of interest within it can be calculated, if appropriate data is available. The data includes (1) the positional relationship between the point of interest and the referencing point in each axis; (2) the amount of the rotatory movement of the object about each axis; and (3) the amount of the translatory movement of the referencing point within the object along each axis.

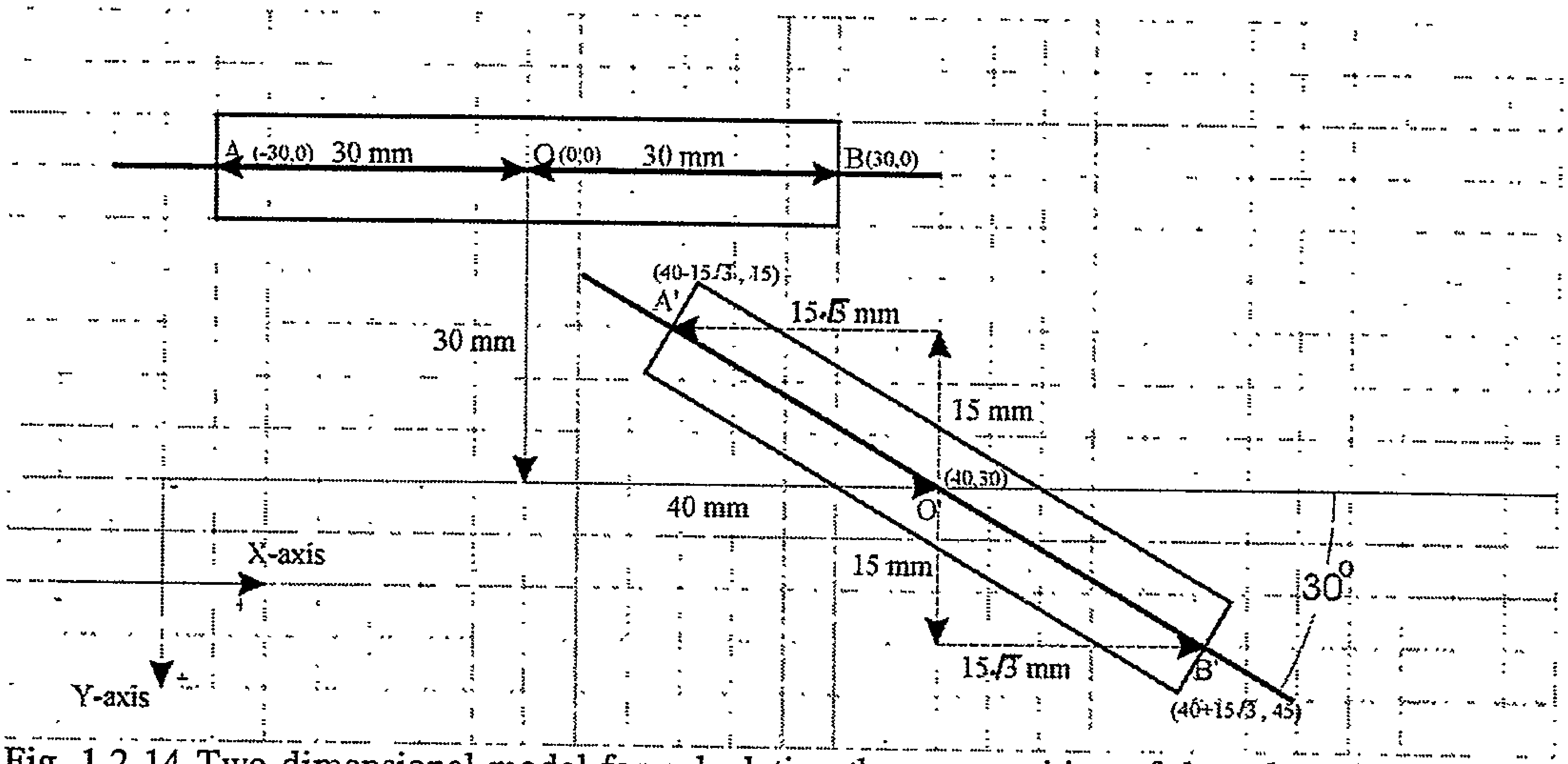


Fig. 1.2-14 Two-dimensional model for calculating the new position of the selected points on a solid object after translation and rotation.

For example, in Fig. 1.2-14, the positional relationship between the points of interest, A and B, and the referencing point O is -30 mm and +30 mm along X-axis, and 0 mm and 0 mm in Y-axis, respectively. The amount of the rotatory movement is 30°. In addition, the amount of the translatory movement of the referencing point O is 40 mm and 30 mm along X-axis and Y-axis, respectively. According to the translatory data, the new position O' (40,30) of the point O is known. Then, combining with the positional relationship data and the rotatory data, the new position of the points of interest A and B can be calculated: A' ($40-15\sqrt{3}$, 15) and B' ($40+15\sqrt{3}$, 45). Therefore, the total movements of the point A and B are 70-15$\sqrt{3}$ mm (or 70-30 cos30°) and 10+15$\sqrt{3}$ (or 10+30 cos30°) mm along X-axis and 15 mm and 45 mm along Y-axis, respectively.

1.2.5.3 Six-degrees-of-freedom application to study of condylar movement

Given the assumption that the mandible is a rigid body, the movement of any point within the mandible can be calculated accordingly if mandibular movement is recorded in six degrees of freedom (Hannam, 1992). Since the mandible is a three-dimensional object, the movement of any jaw point (i.e., on condyles, coronoid process, teeth, etc.) includes rotatory as well as translatory movements within three-dimensional axes. For both mathematical and biomechanical reasons, two-dimensional recordings and/or projections may introduce errors in estimations of the actual three-dimensional movement amplitudes. To avoid such errors, the amplitudes of mandibular movements have been quantified as three-dimensional movement amplitudes, since this parameter is unbiased by projection errors (Eriksson *et al.*, 1998).

Theoretically, it is possible to describe these rotatory and translatory movements within three-dimensional axes according to conventional kinematics. After defining the three orthogonal axes that pass through the referencing point, the total motion of the translational and rotational variables along each axis could be expressed. Then according to the data from this simple set of six descriptors and the time recorded, the motion of any other definable point and surface within the mandible as well as other properties, such as velocity, acceleration, etc., could be computed. To achieve this objective, various forms of clutches are attached to the dental arches, since these arches are conveniently accessible anchorage points.

From these clutches, the electronic or opto-electronic devices could record the lower dental arch motion, relative to the upper arch. For analyzing the motions, it is necessary to define reference planes and origins. Quite accurate measurements of motion can be made this way (Hannam, 1994).

There is an important literature describing condylar point trajectories from data expressed this way. Most studies have used the "Replicator system", first reported by Gibbs and coworkers (1971, 1982). This classic description of the varied patterns expected during mastication included predictable differences in the timing of the two condylar head positions, evidence suggesting the wrench-like actions of the jaw muscles around vertical axes during jaw closing, and the demonstration of different computed trajectories between opening and closing paths on the working side, but not on the balancing side (Hannam, 1994).

1.2.5.4 Problems encountered in the application of a six-degrees-of-freedom device in the study of mandibular and condylar movement

Before applying the six-degrees-of freedom principle to the study of mandibular and condylar movement, three basic problems should be noticed. One problem relates to the measurement of the positional relationship between the condylar points of interest and the recording device. The second relates to the limitations of the recording device. Third is the possible mandibular deformation under masticatory muscle activity.

(1) Problem of the measurement of the positional relationship

It is impossible to measure directly the positional data between the points of interest and the recording device, because of the covering soft tissues. Therefore, an alternative method must be used. The "Replicator system" (Gibbs and Lundeen, 1982) as well as the electronic mandibular measuring system (Hobo and Takayama, 1989), developed by Hobo and Mochizuki (1983), calculates the hinge axis by computer, and the condylar points, whose movements are to be plotted, are chosen on the hinge axis 20 mm medial to the skin for adults. The "JAWS-3D system" uses an extra light-emitting-diode (LED) pointer to indicate the position of any point of interest, and the point of interest on the condyle can be defined as 15 mm medial to skin of the palpated lateral condylar pole in a plane parallel to the Frankfort horizontal plane. In addition, the three-dimensional "Mandibular Movement Analyzing System" (Ogawa *et al.*, 1998), developed in Kyushu University, Japan, uses a three-dimensional digitizer to input the relative position, and the arbitrary hinge condylar point is located 5 mm vertically inferior to a point 13 mm anterior to the posterior border of the tragus of the ear on the canthus-tragus line.

The major problem of these alternative methods is the use of an average value condylar point. The advantage of an average value is the convenience, however, the individual differences in the thickness of the covering soft tissues or the size of the bony structures are ignored. For instance, in the JAWS-3D system, Salaorni and Palla (1994) states that a *"depth of 15 mm was considered enough to record the movement of an intracondylar point (Krenkel & Grunert, 1988)."* However, this point could be close to the lateral border of the condyle in one subject, and the medial border of the condyle in another, depending on the individual differences. Such a difference in locations of the determined condylar points may cause a difference in condylar tracings between subjects, even while the condyles perform the same movement quantitatively and qualitatively. Thus, this uncertainty, as to the possible error brought about by this limitation, would increase the difficulties in summarizing and interpreting the condylar movements between subjects. Further, an average value point does not have any clinical or anatomical meaning other than it is an intracondylar point.

According to recent studies, the selection of the condylar point influences the results of the trajectory of movement recorded, therefore, unless the selected point is clinically relevant and can be actually located, the recording itself will be meaningless. In the horizontal axis, according to Hobo (1984), if the calculated point is located laterally to the rotational centre of the hinge axis in the working side condyle, the trajectory generated becomes progressively more backward, lateral, and upward as the distance laterally increases. In contrast, it moved forward, laterally, and downward, if the point was medial to the rotational centre. Therefore, individual differences can cause quantitative and qualitative changes to the calculated condylar point trajectory. Thus it is possible that the trajectory generated could be more forward and downward for subjects with thinner covering soft tissues than those with thicker covering soft tissues, even though the condyles in these subjects may be performing the same movement quantitatively and qualitatively. Moreover, in the parasagittal and horizontal planes, according to Peck and colleagues (1997, 1999a, b) and Zwijnenburg and colleagues (1996), for all movements except protrusive movements and possibly for balancing-side condylar points, the three-dimensional excursions of the condylar points strongly depended upon the choice of condylar reference point.

Since the position of the condylar point influences the calculated results of the condylar point trajectories, the clinical importance of the referencing points must be investigated while defining the condylar points. In addition, the accuracy and the reproducibility of the referencing point determination on each individual subject must be considered. Otherwise, it would be possible that the points recorded in the experiments were not the points that are claimed of clinical importance.

(2) Limitation of the recording device

A limitation of the six-degrees-of-freedom device is the distance-dependent increase of the measurement error. Since the calculation of condylar point movement is based on the recordings of movement and positional data, any imprecision of the recording can affect the calculated results. Further, the error increases as the distance between the recording device and the points of interest is increased.

To minimize this limitation, two methods can be used. One is to decrease the measurement error of the system by improving the equipment. The other is to decrease the distance between referencing LED points and the points of interest by changing the positional design of the LED and clutches.

(3) Problem of mandibular deformation

When the masticatory muscles function, the generated force can lead to deformation of the mandible in a complex manner. This deformation phenomenon may cause some problems in the condylar motion studies, of which the basic assumption is that the mandibular bone is a rigid beam. These studies not only include the six-degrees-of-freedom studies but also include those studies, which use the pantographic device.

According to Hylander (1988), under the contraction force during function, the primary deformation of the mandible includes twisting about the long axis of the body of the jaw, bending in both the parasagittal and transverse planes, and symphyseal shear. Human clinical studies also demonstrated changes in lower posterior dental arch width during function (Goodkind and Heringlake, 1972; Omar and Wise, 1981; Grant, 1986). In addition, Finite Element Analysis (Korioth and Hannam, 1994) suggests that the human jaw deforms elastically during symmetrical and asymmetrical clenching tasks in a complex manner, which includes the rotational distortion of the mandibular corpora around their axes, and a parasagittal and transverse deformation. All these possible deformations result in an inconsistent positional relationship between mandibular points during function.

However, most condylar motion studies are based on the assumption that the mandible is a rigid object. No matter how the condylar referencing points are determined anatomically or mathematically, these points are assumed to have a fixed positional relationship with the recording device. The tracings of these points were then recorded or calculated, based on the formulae of rigid body mathematics. Since the mandible can be bent during some functional movements, the resultant tracings may not represent the true trajectories of the points of interest.

Jiang (1992) investigated the influence of the difference of the biting pivot positions, vertical dimension and mandibular positions on condylar displacement during clenching. The bending deformation of the mandible was also measured by a multi-vision and image-analyzing system. The results indicated that when clenching on the unilateral 2nd molar, the mandible on the non-pivoting side had an inward and upward bending deformation and the arch width decreased. It can be inferred that the actual condylar displacement was more inward and upward than that measured by the Pantograph.

The problem of mandibular deformation would become a major issue in the condylar motion studies especially at high force levels. Thus, researchers should be aware of the possible deformation phenomena while analyzing the condylar tracings in their studies.

1.2.5.5 Study of the influence of an occlusal alteration on condylar movement with a six-degrees-of-freedom recording device

To date, numerous of studies about the relationship between a change to the occlusion and condylar movements have been done. However, only four of them (Coffey *et al.*, 1989; Hobo and Takayama, 1989; Sarinnaphakorn *et al.*, 1997; Ogawa *et al.*, 1998) have used a six-degrees-of-freedom recording device.

Coffey and colleagues (1989) studied the effect of a lateral retrusive (LR) working-side canine guidance on the working-side condylar movements of the lateral pole in eight patients. Four of them were lateral retrusive patients, defined as the mandibular mesial cusp ridges contacting distal cusp ridges of maxillary teeth during lateral mandibular movements. The other four were lateral protrusive (LP) patients, defined as the mesial cusp ridges of maxillary teeth contacting the distal cusp ridges of the mandibular teeth during lateral mandibular movement. The lateral pole of the condyle, the point 8 mm medial to the skin and 5 mm anterior to the hinge axis parallel to the axis orbital plane, was selected as the condylar referencing point. The Replicator system, mentioned above, was used to record electronically the condylar movement in the horizontal plane. The movements of the condyle were recorded under three conditions. First were the horizontal-range-of-motion movements, using the central bearing screw and plate to separate the teeth with minimal increase of the vertical dimension. Second were the natural-tooth-guidance movements performed during lateral movement. And third were the lateral-protrusive (LP) and lateral-retrusive (LR) splint-guidance movements during lateral movements with splints which altered the tooth guidance with minimal increase in vertical dimension.

A comparison between the recordings of LP patients' horizontal-range-of-motion movements, natural-tooth-guidance movements, lateral-protrusive splint-guidance movements and lateral-retrusive splint-guidance movements was done. The results showed that the lateral pole of the working-side condyle during natural-tooth-guidance movements were within the range of the horizontal-range-of-motion movements. The lateral-protrusive splint-guidance tracings were almost similar as natural-tooth-guidance movements. The lateral-retrusive splint-guidance recordings exhibited a more posterior pathway than the horizontal-range-of-motion, natural-tooth-guidance and lateral-protrusive splint-guidance movements. These findings suggested that a force in a posterior direction occurred in the TMJ during the lateral-retrusive splint-guidance movements, compared with horizontal-range-of-motion movements. Therefore, the data suggest that lateral movements of the lateral pole of the working-side condyle were affected by the lateral tooth guidance. Moreover, the lateral pole of the working condyle during the lateral-retrusive splint-guidance movement often exceeded horizontal-range-of-motion tracings in lateral and posterior directions, which indicated that lateral retrusive tooth guidance could cause a displacement of the mandible beyond tracings made during guided movements of the mandible. Therefore, the possibility arose that occlusal forces generated during the lateral-retrusive splint-guidance movements caused the working condyle to extend posterior to movements generated during horizontal-range-of-motion movements.

Another study which examined, with a six-degrees-of-freedom device, the influence of an altered occlusion on the working-side condylar movements, was done by Hobo and Takayama (1989) on 10 males. The condylar referencing point was the centre of the condyle, defined as the point 20 mm inward from the skin surface along the terminal intercondylar axis. The anterior reference point was defined as the point 43 mm above the edge of the right maxillary central incisor. Left and right lateral movements were performed and the three-dimensional displacements of the centre of the working condyles and the incisal point were measured. The recordings of the lateral movements were performed under two conditions. First was under the occlusal condition (natural canine guidance). Second was under the paraocclusal condition: the vertical dimension was maintained by a central bearing point on the central bearing plate and during lateral movement, the mandible could be guided in a relatively horizontal direction, following the geometry of the central bearing plate.

The results showed that the working-side condylar recordings varied significantly under the influence of the canine guidance between subjects, therefore, the results supported the hypothesis that the working-side condylar movements were affected by anterior canine guidance. However, there were no remarkable changes on the balancing side. This could be explained because the working condyle had a relatively closer position to the canine guidance than the balancing condyle.

Second, the working-side condyle under the paraocclusal condition exhibited small sagittal displacements and showed a tendency to move straight laterally along the transverse horizontal axis. Conversely, under the canine guidance conditions, the working side condyle moved laterally and deviated sagittally in various directions. It was suggested that the working condylar path was affected by anterior tooth guidance and both condylar and anterior guidance were interdependent factors. When canine guidance is not coincident with the working condylar path, there is a sagittal displacement of the working path created to compensate for the lack of harmony. Therefore, the need to establish harmony between condylar and anterior guidance was suggested.

Moreover, the working condylar path in the sagittal plane under the paraocclusal condition varied qualitatively and quantitatively in comparison with that under the canine guidance condition. This finding might be related to the Coffey and coworkers study (1989) that the working side condylar path in the sagittal plane was influenced by the LR or LP guidance to varying degrees. However, the nature of the canine guidance (LR or LP guidance) was not measured in this study (Hobo and Takayama, 1989). Therefore, further discussion about the relation between these two studies is difficult.

In the balancing-side condylar study (Sarinnaphakorn, 1997; Sarinnaphakorn *et al.*, 1997), the quantitative effects of an occlusal alteration on condylar movement during a lateral excursive jaw movement was evaluated in seven subjects. The posterior condylar referencing point was defined as a point 15 mm medial to the skin over the palpated lateral condylar pole in a plane parallel to the Frankfort plane. The anterior referencing point was the mid-incisor point (MIPT), defined as the point midway between the edge of mandibular right and left central incisors. The referencing points' tracings were recorded by an opto-electronic recording system (JAWS-3D, Metropoly AG, Zurich, Switzerland), which measured the motion of any point on the mandible with six degrees of freedom in real time. The trajectories of the non-working side condylar points during lateral excursive movement under natural tooth guidance (as the control condition), were compared with those after the placement of the metal overlays, without altering the vertical dimension in the centric occlusion, onto the bilateral maxillary first molars (as the guidance condition). Qualitative and quantitative analyses were performed to see whether there was any difference under control and guidance conditions both at the full extent of the lateral excursive movement, i.e., to edge-to-edge tooth contact, and at a standardised (3-mm) displacement of the MIPT movement.

The results showed that the introduction of the posterior tooth guidance altered the trajectory of the balancing-side condylar points as well as the mid-incisor point. While performing the full extent of the mandibular movements as far as the edge-to-edge tooth contact, the trajectories of the balancing condylar point movements were statistically significantly increased by the introduction of the metal overlays in comparison with control. In contrast, when assessed at the first 3-mm displacement of the MIPT movement, the trajectories of the balancing condylar points were statistically significantly decreased. The introduction of the posterior tooth guidance also altered the trajectories of MIPT movements by increasing the departure angle of the mid-incisor point in the front plane.

This study (Sarinnaphakorn, 1997) also provided some preliminary data about the influence of an occlusal alteration on the working side condylar movements. A variable change of the condylar point trajectories was found due to the alteration. However, according to the limitations of the study, that is, the close proximity of the selected condylar point to any instantaneous rotational centre on the working side as well as the single arbitrary referencing point in each condyle, no quantitative evaluation was available. Therefore, for further investigation of the influence on the working-side condyle, the use of a complex radiographical imaging system, such as afforded by the computer tomography (CT) scan, for determining anatomical condylar points as well as the multiple condylar-refererencing points, is suggested.

Ogawa and colleagues (1998) investigated the effect of an altered inclination of the canine guidance on the pattern of the condylar movements during laterotrusion in 20 subjects. The condylar reference point in each subject was located at a position 5 mm vertically inferior to the point 13 mm anterior to the posterior border of the tragus on the canthus-tragus line. The inclination of the canine guidance was steepened approximately 10° by attaching a metal overlay to the palatal surface of the maxillary working-side canine. The condylar movements during laterotrusion before and after the insertion of the overlay were compared.

The results showed that there were significant differences in the anterior and inferior components of the working-side condylar path before and after the alteration of the canine guidance. The anterior displacements before and after the occlusal alteration were 0.12 mm and 0.30 mm, respectively, and the inferior displacements were 0.17 mm and 0.27 mm. In some cases, the occlusal alteration changed the direction of condylar movements supero-inferiorly and/or antero-posteriorly. No significant difference was found in the lateral component of the condylar path. On the balancing side, the anterior component of the condylar movement significantly decreased after the canine guidance was altered and this is consistent with the findings from the Sarinnaphakorn and coworkers (1997) study.

The major limitation of these four studies was that they used a single condylar point to represent movement of the condyle which is a three dimensional object. However, recent studies (Hobo, 1984; Zwijnenburg *et al.*, 1996; Peck *et al.*, 1997, 1999a, b) indicated that, except for the protrusive movement and possibly the non-working condyle during contralateral excursion, the three-dimensional movements of the condylar points strongly depended upon the choice of the condylar reference point, which means that no single point can fully represent the whole condylar movement. As previously mentioned, Hannam (1992) indicated that the trajectory of motion of one point has no more meaning than that of another unless it represents a point of specific anatomical significance.

To address this issue, one approach is to study the movement of condylar points with specific anatomical significance. For example, Coffey and colleagues (1989) stated that *"movements of the lateral pole of the working condyle are particularly important since autopsy studies have shown that TMJ deviations from the normal rounded contour of the articular surface of the temporal and condylar components with deformations in the articular disk are located primarily in the lateral portion on the joint (Hansson and Oberg, 1977; Hansson and Nordstrom, 1977; Solberg et al., 1985)."* However, the question was whether the condylar tracings recorded in this study were the condylar paths of the lateral pole. In the Coffey and colleagues (1989) study, the lateral pole of the condyle was determined as the point 8-mm medial to the skin and 5-mm anterior to the hinge axis parallel to the axis orbital plane. According to this method, the actual condylar points recorded during the experiment may not be the lateral pole of the condyle in the same subjects, due to individual differences. For example, a point 8-mm medial to the skin might be lateral to the actual lateral pole in one subject and medial to the lateral pole in another, and this would depend of the thickness of the soft tissues between the condyle and the skin surface. In other words, although the authors stated that the lateral pole of the condyle might have some clinical importance, the tracings recorded in the experiment might not be the path of the actual lateral pole.

In the other three studies (Hobo and Takayama, 1989; Sarinnaphakorn, 1997; Ogawa *et al.*, 1998), the authors also used average values in the determination of condylar points. However, the major conceptual problem of this approach was that the assumption of the morphology was mainly based on average data from the previous research. Therefore, individual differences, such as the thickness between the condyle and skin surface and the skeletal size of the head, were not considered. Further, the relationship between the hinge or arbitrary axes and the condylar structure was not fully addressed. Thus, the projected trajectories, their numerical quantification, and comparison between them, all depended greatly on the method. To solve the problem, the usage of complex radiographic images, would be necessary.

In addition, another issue in the Coffey and colleagues (1989) and Hobo and Takayama (1989) studies was the altered vertical dimension by the central bearing plate and screw or the mandibular acrylic resin splint. In a recent study, Hagiwata and coworkers (1994) evaluated the effects of controlled anterior guidance on right-sided condylar motion at two different vertical dimensions (3 mm and 10 mm). The results indicated that standardized sliding movements on appliances with anterior guidance did not affect condylar translation equally in all subjects. Major increases in vertical dimension could also change vertical-axis rotation of the working-side condyles in some subjects. The results suggested that appliances might have effects on the articulation which were difficult to predict without direct measurement. Thus, the findings in these two earlier studies (Coffey *et al.*, 1989; Hobo and Takayama, 1989) could be due to the alteration of the occlusion and/or to possible effects due to increases of the vertical dimension.

Further, none of these studies have investigated the influence of an occlusal alteration on the working-side condylar path during the return phase of laterotrusion. Since the condylar path could be different during the return phase, the influence of the occlusal alteration at the return phase remains unclear.

1.2.6 The condylar referencing points

As previously mentioned, the location of the condylar point influences the path of this point during jaw movements. Therefore, before further study about the influence of an occlusal alteration on condylar movement can be done, the issue of the reference points selected should be addressed. This section discusses how the location influences the recorded path and then discusses the issues of the condylar point selection and their determination.

1.2.6.1 The expression of movements

When studying movements, the difference in the tracing between a point and an object should be noticed. The description of single point movement includes the translatory movements along each axis (Fig. 1.2-15 (A)). Whereas the expression of a solid object tracing includes not only the translatory movements but also the rotatory movement along each plane (Fig. 1.2-15 (B)).

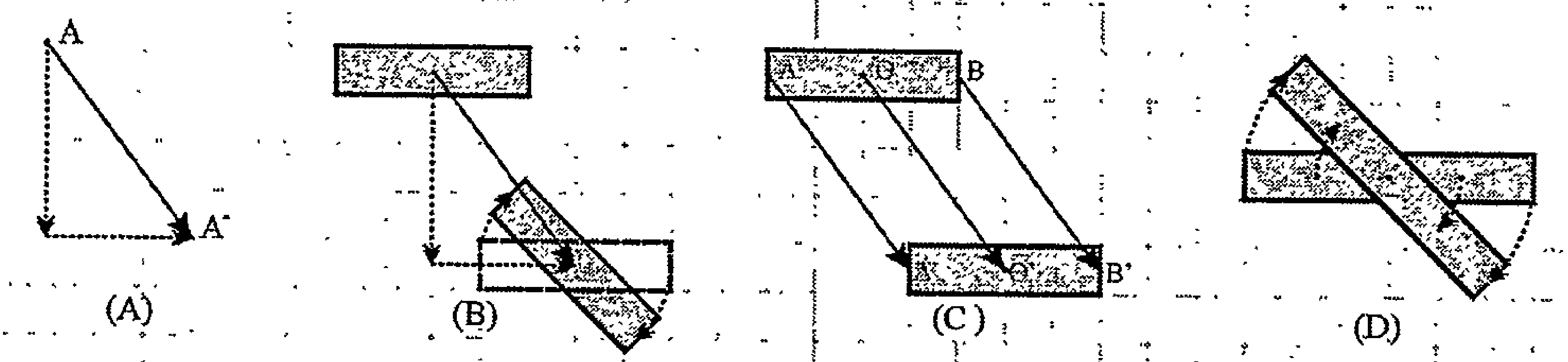


Fig. 1.2-15 Two dimensional model for movement expression. (A) translatory movements of a single point, (B) translatory and rotatory movements of a solid object, (C) translatory movements of a solid subject, (D) rotatory movements of a solid subject.

The translatory movements of a solid object represent the ***general movement pattern*** of the object. Every point within the object performs the same degree of movement regardless of its position within the object (Fig. 1.2-15 (C)). On the other hand, the rotatory movements of a solid object cause ***point-characterised movement***. Every point within the object moves toward different directions with varying velocities, according to its relative position to the rotational centre (Fig. 1.2-15 (D)). Only the rotation centre is not influenced by rotatory movements, therefore, it displays the general movement pattern of the object, whereas the rotatory movement is ignored.

Due to the influence of the point-characterised movement, the tracings of a single point cannot represent the movements of other points within the object unless pure translation is performed. This is because the trajectories of single points could only register the translatory movement of the point along each axis. From the tracings of single points, one could not differentiate which part of the record is under the influence of translation, rotation, or a combination of both. Therefore, when trying to analyse the movements of an object by using single referencing points, the locations of the referencing point becomes an important issue.

1.2.6.2 The referencing points selected in condylar studies

Most previous studies of TMJ dynamics have used a single referencing point to express the movement of the condyle, a three-dimensional body. Some studies have used points defined radiographically in terms of condylar anatomy {termed here anatomical points, e.g. the lateral condylar pole defined radiographically (Peck *et al.*, 1997, 1999a, b) or the radiographic centre of the condyle (Rohrer *et al.*, 1991)}, or those defined in terms of the palpated lateral condylar pole (Merlini and Palla, 1988; Siegler *et al.*, 1991; Naeije *et al.* 1995; Peck *et al.* 1997, 1999a, b), or those defined in terms of condylar or jaw movement features {e.g. a point along the hinge axis (Hobo, 1984; Hobo and Takayama, 1989; Ogawa *et al.*, 1998), or a point along the so-called kinematic axis (Naeije *et al.*, 1999; Yatabe *et al.*, 1995)}. Others have developed techniques to record and animate the motion of the whole condyle within the fossa (Krebs *et al.*, 1994, 1995; Palla *et al.*, 1997; Gallo *et al.*, 2000).

The studies that have employed single points to describe condylar movement have, however, a number of limitations. First, as described above, as jaw movements involve complex rotatory and translatory movements, the location of the point chosen influences the shape of its trajectory (Hobo, 1984; Zwijnenburg *et al.*, 1996; Peck *et al.*, 1997, 1999a, b).

Second, most points have a questionable inter- and intra-operator reproducibility. For example, on repeated assessment, the coordinates of the palpated lateral condylar pole may vary up to 7 mm in the sagittal plane (Peck *et al.*, 1997). In addition, the relationship between any of these points and condylar anatomy is variable. For the kinematic centre or axis, the relation to the rotation centre of the condyle during lateral movements remains unclear. As far as radiographically defined condylar points are concerned, there is little information as to the accuracy (i.e. the overall error or the systematic error) with which these points can be determined. Thus, there is always the doubt that the recorded points might not be the intended points of interest.

Therefore, in order to describe condylar movement accurately, it is necessary to record the movement of points that are defined in terms of condylar anatomy and that are recorded with a six-degrees-of-freedom jaw-tracking device. However, in order to do this, an accurate and reproducible method is needed for registering the location of radiographically defined condylar points in the coordinate system of a jaw-movement recording device. This can be achieved via a fiducial marker that can be radiographically imaged as well as registered in the coordinate system of a jaw-tracking device (Hannam, 1992; Krebs *et al.*, 1994, 1995; Peck *et al.*, 1997, 1999a, b). The accuracy of these methods however remains unclear. Our previous study (Swintara *et al.*, 2001) that used a unilateral fiducial marker, reported that the error with which a condylar point could be registered could be

>1 mm. The present study employed a distributed fiducial marker to determine whether this error could be reduced.

1.3 Jaw muscle activity during laterotrusion and the influence of an occlusal alteration

Previous studies suggest that an occlusal alteration can influence condylar movements during laterotrusion. However, there is a lack of information regarding the influence of an occlusal alteration on the EMG activity of the jaw muscles during laterotrusion, especially the lateral pterygoid muscles which are thought to play an important role in the generation and control of lateral jaw movements (Murray *et al.*, 2001). Before studying the influence of an occlusal alteration on jaw-muscle EMG activity, a detailed understanding of the activity patterns of the jaw muscles during lateral movement is needed. Therefore, this section reviews the gross anatomy and EMG activity of the jaw muscles during laterotrusion, as well as the influence of an occlusal alteration on these muscles during laterotrusion.

1.3.1 Gross anatomy of the jaw muscles

More than twenty muscles attach to the human mandible. In the terms of the size, force development and functional movement of the mandible, the most important muscles are the temporalis, masseter, and medial pterygoid (known as jaw-closing muscles) as well as the lateral pterygoid and digastric muscles (known as jaw-opening muscles) (Fig. 1.3-1). These muscles are also known as masticatory muscles, which are one of the components of the masticatory system. The masticatory muscles are involved in basic jaw movements (including jaw opening, jaw closing and lateral jaw movements as well as protrusion and retrusion), parafunctional movements (including grinding), functional movements (including masticating and speech jaw movements), as well as temporomandibular-joint stabilization and maintenance of mandibular posture. Anatomical studies suggest that all masticatory muscles, except possibly the digastric muscle, have irregular shapes, large attachment areas and a complex internal architecture. This section reviews the gross anatomy of these muscles.

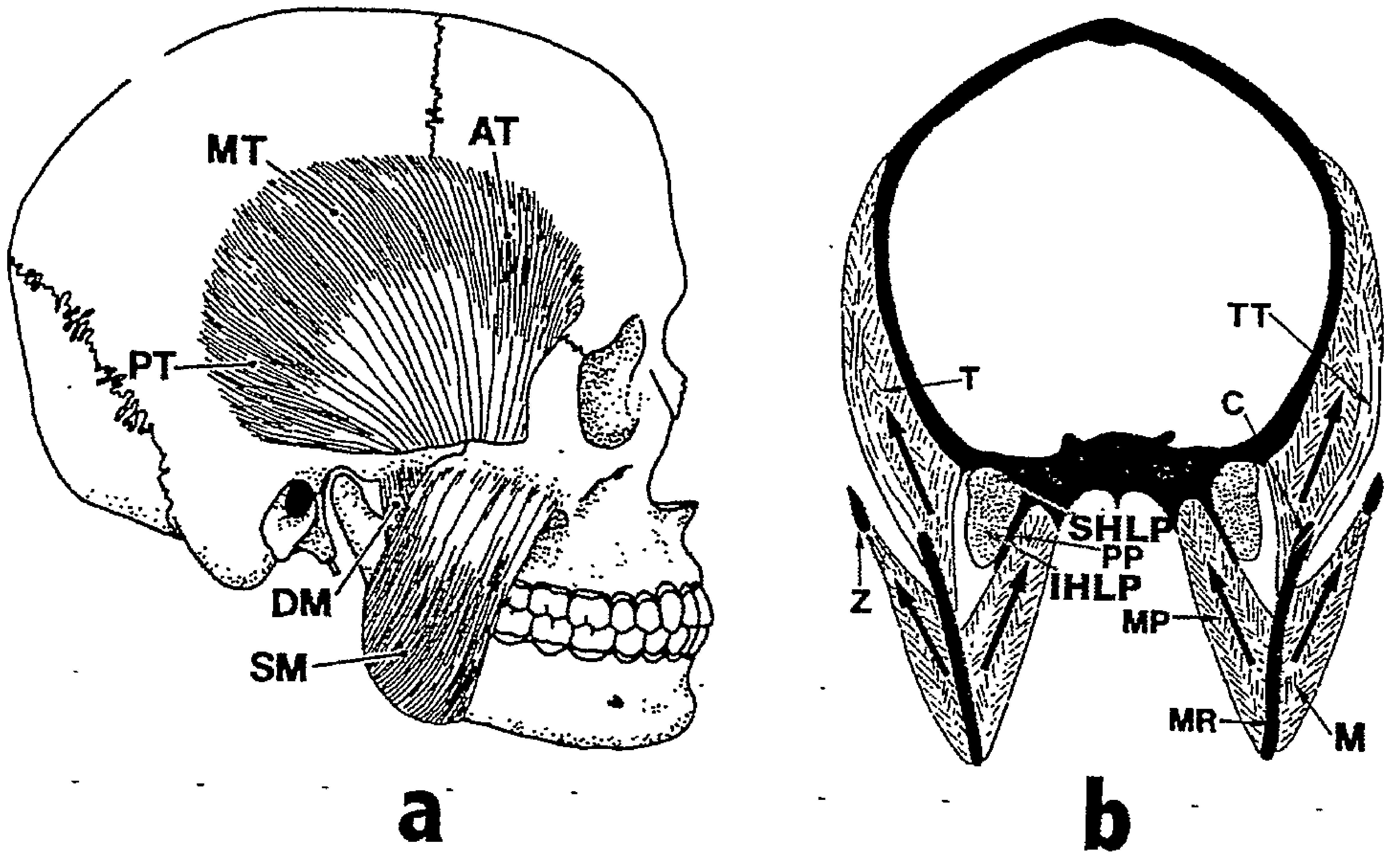


Fig. 1.3-1 Gross anatomy of masticatory muscles. (a) The masseter and temporalis muscles: deep masseter (DM), superficial masseter (SM), anterior temporalis (AT), middle temporalis (MT), and posterior temporalis (PT). (b) Coronal section of the muscles of mastication: temporalis (T), tendon of temporalis (TT), zygomatic arch (Z), coronoid process (C), mandibular ramus (MR), masseter (M), medial pterygoid (MP), pterygoid process (lateral) (PP), lateral pterygoid-superior head (SHLP), and lateral pterygoid-inferior head (IHLP). The large arrows indicate the general direction of pull of the anterior temporalis, superficial masseter, and the medial pterygoid muscles (modified from: Hylander, 1992).

1.3.1.1 Temporalis muscles

The temporalis muscle is a broad fan-shaped muscle, which takes origin from the lateral surface of the skull and projects inferiorly to the mandible (Miller, 1991; Hannam and McMillan, 1994). The origin attaches medially to the temporal fossa (from the inferior temporal line to the infratemporal crest) and laterally to the temporal fascia. The majority of this fan-shaped muscle converges into a conspicuous, flat tendon that inserts onto the anterior, medial and posterior borders of the coronoid process and the anterior border of the ascending ramus.

This muscle is separated into superficial and deep layers by an internal central aponeurosis extending from the tendon. The synergistic contraction of both superficial and deep fibre groups produces principal tension. However, differential activation of the superficial and deep fibres can occur depending on the requirements of the tasks. At the lateral view, the superficial fibres are oriented in different directions with the anterior fibres directed diagonally, caudally and laterally, and posterior fibres are oriented almost horizontally (e.g. Fig. 1.3.1 a). The deep fibres are directed vertically and medially toward the greater wing of the sphenoid bone. The orientation of the muscle fibres suggests that differential muscle activation occurs (Wood, 1986; Blanksma and van Eijden, 1990). Orientation of the fibres suggests that temporalis is capable of elevating the mandible, retruding the mandible and laterally displacing the mandible, with varying activities in different regions of the muscle depending on the biomechanical demands of the tasks.

1.3.1.2 Masseter muscles

The masseter is often divided anatomically into three overlapping and only partially separated layers: a superficial, an intermediate and a deep part. The superficial part arises via a thick, multileaved aponeurosis from the anterior two thirds of the lower border of the zygomatic arch as far anteriorly as the zygomatic process, and inserts from the angle of the mandible anteriorly to the ascending ramus. The intermediate part extends from the medial aspect of the anterior two thirds of the zygomatic arch and the lower border of its posterior third and inserts into the central part of the ascending ramus and the coronoid process. The deep part takes origin from the deep surface of the zygomatic arch and inserts onto the upper part of the ascending ramus and the coronoid process.

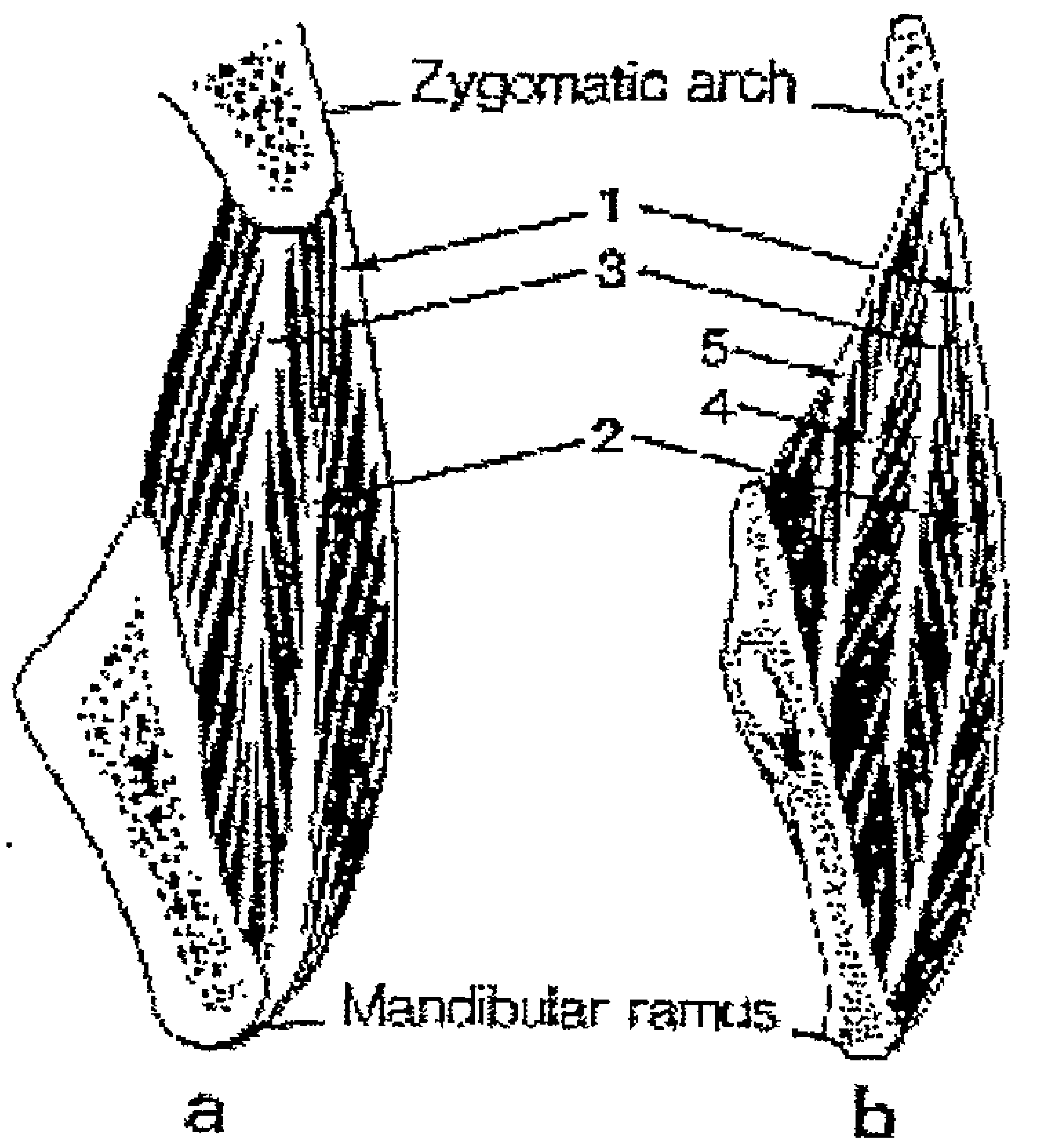


Fig. 1.3-2 Frontal view of the longitudinal section from a human masseter muscle. Muscle fibres are drawn in black and aponeuroses tissues are drawn in white. (a) Ebert's version (1939) and (b) Schumacher's version (1961). Both have been redrawn (from Stålberg and Eriksson, 1987).

The masseter reveals a multipennate character with at least four internal aponeuroses (Lam *et al.*, 1991). These aponeuroses are aligned roughly parasagittally, and are attached individually to the zygomatic arch and the mandible in order to form interleaving septa, which provide anchorage for most of the muscle fibres (Fig. 1.3-2). These aponeuroses can be visualized by Magnetic Resonance imaging (Lam *et al.*, 1991). Differences in fibre, tendon and sarcomere lengths within the masseter has been reported by van Eijden and Raadsheer (1992). These differences in regional morphology clearly imply functional differentiation. The functional partitioning of activity is possible in at least three regions (deep anterior, deep posterior and superficial) and perhaps in four (Blanksma *et al.*, 1992). Generally, the superficial fibres, which are more obliquely oriented, become activated most during movement tasks of jaw elevation, elevation with protrusion, or movements on or toward the side contralateral to the muscle. The deep fibres contribute strongly to jaw elevation, and become active more vigorously on jaw retrusion, on the side ipsilateral to the muscle (Hannam and McMillan, 1994).

1.3.1.3 Medial pterygoid muscles

The medial pterygoid muscle is a quadrilateral muscle. It takes origin mainly from the pterygoid fossa at the medial side of the lateral pterygoid plate. It descends posterolaterally to form a strong tendinous lamina attached posteroinferiorly to the medial surfaces of the mandibular ramus and angle. A small inferior head arises from the tubercle of the palatine bone and the maxillary tuberosity and passes over the lower part of the lateral pterygoid before joining the main fiber group. Thus, these two heads envelop the lateral pterygoid muscles. This muscle is very heavily pennated. Schumacher (1961) reported at least six aponeuroses (up to eight) in the muscle, and they form interleaved septa. Like their masseter counterparts, the septa are not always parallel and not all of them run through the whole muscle; some extend about two-thirds of the way. From the frontal view, the muscle has very little geometry to suggest the possibility of various angles of pull. However, from the lateral view, fibre angulations are sufficiently variable to suggest different actions and this is due to the more anteroposteriorly disposed and wide mandibular insertion (Hannam and McMillan, 1994). Due to the difficulty of recordings and the complex architecture of this muscle, it is not known whether differential contraction occurs.

1.3.1.4 Lateral pterygoid muscles

Conventionally, the lateral pterygoid muscle is considered to be one muscle with two origins and consists of two heads, a superior (SHLP) and an inferior (IHLP) head (Grant, 1973) (Fig. 1.3-3). The inferior head originates from the lateral surface of the lateral pterygoid plate, sometimes including the pyramidal process of the sphenoid bone and then projects laterally and posteriorly. The superior head originates from the upper one-third of the pterygoid plate and from the infratemporal fossa (formed by the greater wing of the sphenoid bone and the squamous part of the temporal bone) and then projects caudally, laterally and posteriorly. The inferior head is about twice the cross-sectional size of the superior head, which is a thin flat band of fibers when viewed laterally. Both heads are separated at their origins by fibrous and adipose tissues and blend together to form a central pterygoid tendon at the point of insertion on the condylar neck (Honée, 1972; Wilkinson, 1988).

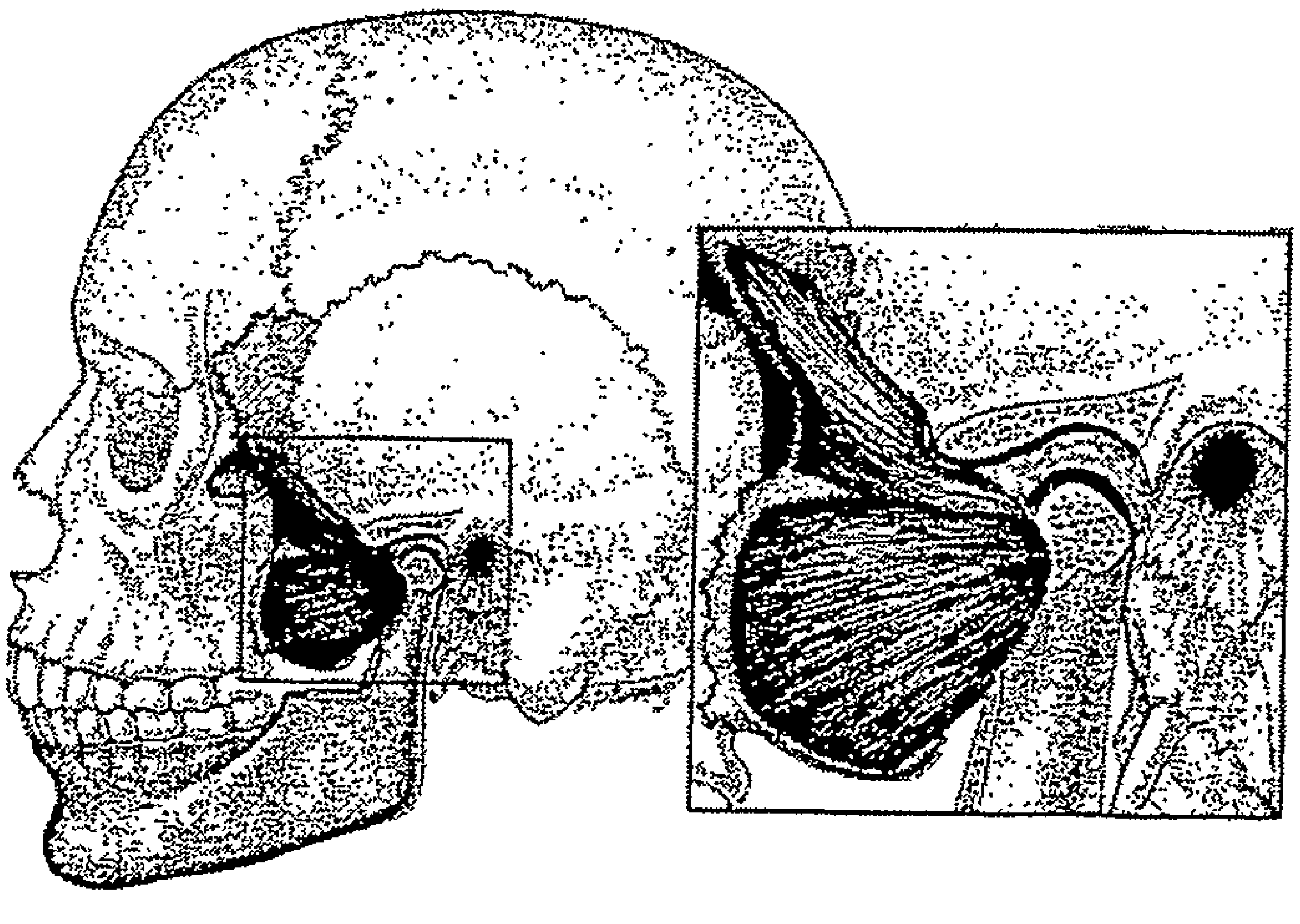


Fig. 1.3-3 Attachment of the two heads of the lateral pterygoid muscle (from Travell and Simons, 1983).

Generally, there is an agreement that both parts of the muscles, when tensed, exert traction on the subcondylar region at the fovea. However, there is controversy as to the exact insertion of the superior head of the lateral pterygoid muscle. Porter (1970) and Honée (1972) reported that the superior head muscle fibres insert mainly into the joint capsule and the disc in all subjects. On the other hand, many anatomical studies suggested that the majority of the superior head fibres insert either directly to the pterygoid fovea of the condyle or indirectly by fusing with tendons of the inferior head of the muscle. Only a small portion of the superior head fibres, about 20% of the uppermost fibres, insert into the antero-medial part of the disc-capsule complex (Wilkinson, 1988; Wilkinson and Chan, 1989; Bittar *et al.*, 1994; Schmolke, 1994). The recent review (Bertisson and Ström, 1995) of 89 original articles (from 1879 to 1994) reported that about 60% of the articles indicated that the lateral pterygoid muscle has three attachments and inserted into the disc, the temporomandibular joint capsule and the condyle. Of the 89, 30% suggested that the lateral pterygoid muscle fibres mainly inserted to the condyle, and only a few muscle fibres inserted into the temporomandibular joint disc. Whereas, the remaining 10% of articles showed that the lateral pterygoid muscle inserted into the condyle only. The importance of the actual insertion of both heads is to contribute to the understanding of the possible mechanisms involved in temporomandibular disorders. For example, if the superior head inserted mainly into the condylar disc, and the inferior head inserted into the neck of the condyle, then incoordination in onset and/or duration between both heads might cause dysfunction (Klineberg, 1991a). Otherwise, the small portion of the superior fibres inserting into the disc are unlikely to cause the disc to move independently of the condyle, since the majority of the SHLP fibres insert on the condylar neck (Wilkinson, 1988; Bittar *et al.*, 1994).

The internal architecture of the human lateral pterygoid muscle is much simpler than the jaw closing muscles, since the muscle is comprised of relatively long fibres that are not multipennated. The lateral pterygoid fibres are aligned in the same direction as the bulk of the muscle, therefore, the muscle is most suitable for shortening over long distances. In other words, it offers a better propensity for near-isotonic than for near-isometric conditions requiring power (Hannam and McMillan, 1994).

The difference between the fibre orientations of the two heads in the parasagittal and horizontal planes leads to a biomechanical difference between two heads (Miller, 1991). The inferior head is more efficient in lowering the mandible. It pulls the ipsilateral (to the muscle) condyle anteriorly, inferiorly, and contralaterally. Anatomically, the inferior head appears important to condylar translation, but minimally to mandibular rotation (Carlsoo, 1956). On the other hand, the superior head has been suggested to have more of a tendency to close the mandible. Anatomically, the superior head is capable of moving the condylar head, articular disc, and joint capsule anteriorly and slightly superiorly to position the condyle and disk along the articular surface of the temporal bone (McNamara, 1973).

1.3.1.5 Digastric muscles

The digastric muscle consists of two parts (the anterior and the posterior bellies) which are separated by an intermediate tendon. The anterior belly originates from the digastric fossa that is located at the inner and inferior border of the anterior mandible. It projects posteriorly and inferiorly to the tendon, and the posterior belly projects superiorly and posteriorly from its tendonous attachment to the mastoid notch of the temporal bone. The central tendon is attached to the body of the hyoid and greater cornu by a fibrous loop (Williams *et al.*, 1989). The anatomical orientation of the two bellies suggests that the anterior digastric is capable of mandibular opening movement and retrusion and the posterior digastric is capable of elevating the hyoid bone.

1.3.2 Jaw muscle activity during laterotrusion

Before studying the influence of occlusal alteration on the EMG activity of jaw muscles during laterotrusion tasks, a detailed understanding of the normal activity pattern of these muscles is necessary. Therefore, this section reviews the studies about the EMG activity of jaw muscles during laterotrusion.

1.3.2.1 Electromyography

Electromyography is a recording of electrical signals that originate from the muscle fibres. These signals exhibit various durations and shapes depending upon the type of electrode and electrode placement, such as over the belly of the muscles (as surface electrodes) or within the muscle (as intramuscular electrodes). Signals are usually recorded with a pair of electrodes connected to an amplifier, which renders an algebraic summation of the signal that occurs simultaneously at both electrodes. If the signal source is closer to one of the two electrodes, it will be recorded at one electrode before the other. The amplifier will produce a signal representing the difference in voltages at each electrode at each time point and the EMG potential emitted from the amplifier is the difference between the signals at the two electrodes. Spurious signals from more distant sources, such as other muscles or radiofrequency interference, reach the two electrodes at about the same time, and the amplifier can cancel such signals by algebraic summation.